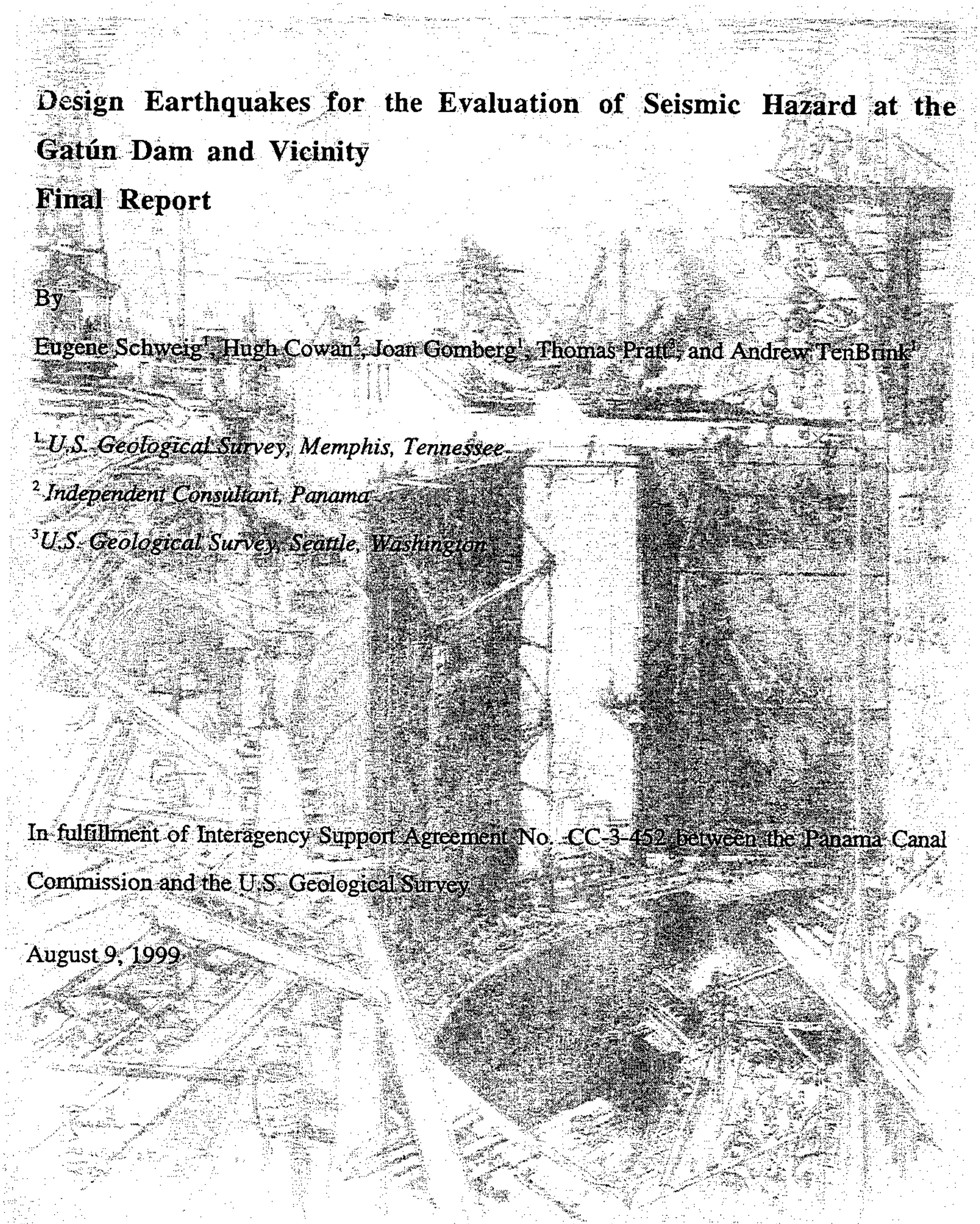

Design Earthquakes for the Evaluation of Seismic Hazard at the Gatún Dam and Vicinity
Final Report

By

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1. INTRODUCTION

1.1 Background

This report describes the results of work conducted between 1996 and 1998 by the U.S. Geological Survey (USGS) for the Geotechnical Branch of the Panama Canal Commission (PCC) under Interagency Support Agreement CC-3-452. The report fulfills the requirements of the third and final phase of investigations associated with the characterization of potential earthquake sources most likely to affect the Gatún Dam.

The primary objective of this work is to advise the PCC on appropriate design earthquakes to be used in their evaluation of the seismic hazard at Gatún Dam. The tasks associated with this study include:

- Geological surveys in the Panama Canal Zone and vicinity, together with high-resolution seismic reflection profiling beneath Lake Gatún, Gatún Dam and Limón Bay, to evaluate the location, kinematics, and age of tectonic faults (Figure 1.1).

- Geological surveys of sandy fluvial deposits at localities susceptible to liquefaction, to identify possible evidence of earthquake induced paleoliquefaction.

- Monitoring of background seismicity in the Canal Zone and vicinity for a period of six months, using a portable seismograph network to identify contemporary seismically active zones, and to further constrain tectonic models impacting potential source characterization (Figure 1.2).

The first section of this report presents the recommended design earthquakes of this study. The rationale for each design earthquake is then described. Finally, recommended strong ground motion records are described and the reasoning for their selection described.

1.2 Work Program 1996-1998

USGS representatives (Eugene Schweig, Thomas Pratt, Joan Gomberg, and Mark Holmes) spent two weeks in Panama during February, 1996, as part of Interagency Support Agreement (ISA) No. CNP-93786-NN-29. That visit was directed toward obtaining preliminary estimates of earthquake hazard at the Gatún Dam, and the identification of tasks that would enable such hazard estimates to be refined. The work included the acquisition of sub-bottom profiling data in Lake Gatún, a review of the archives of the Panama Canal Commission, and a geological field reconnaissance of active

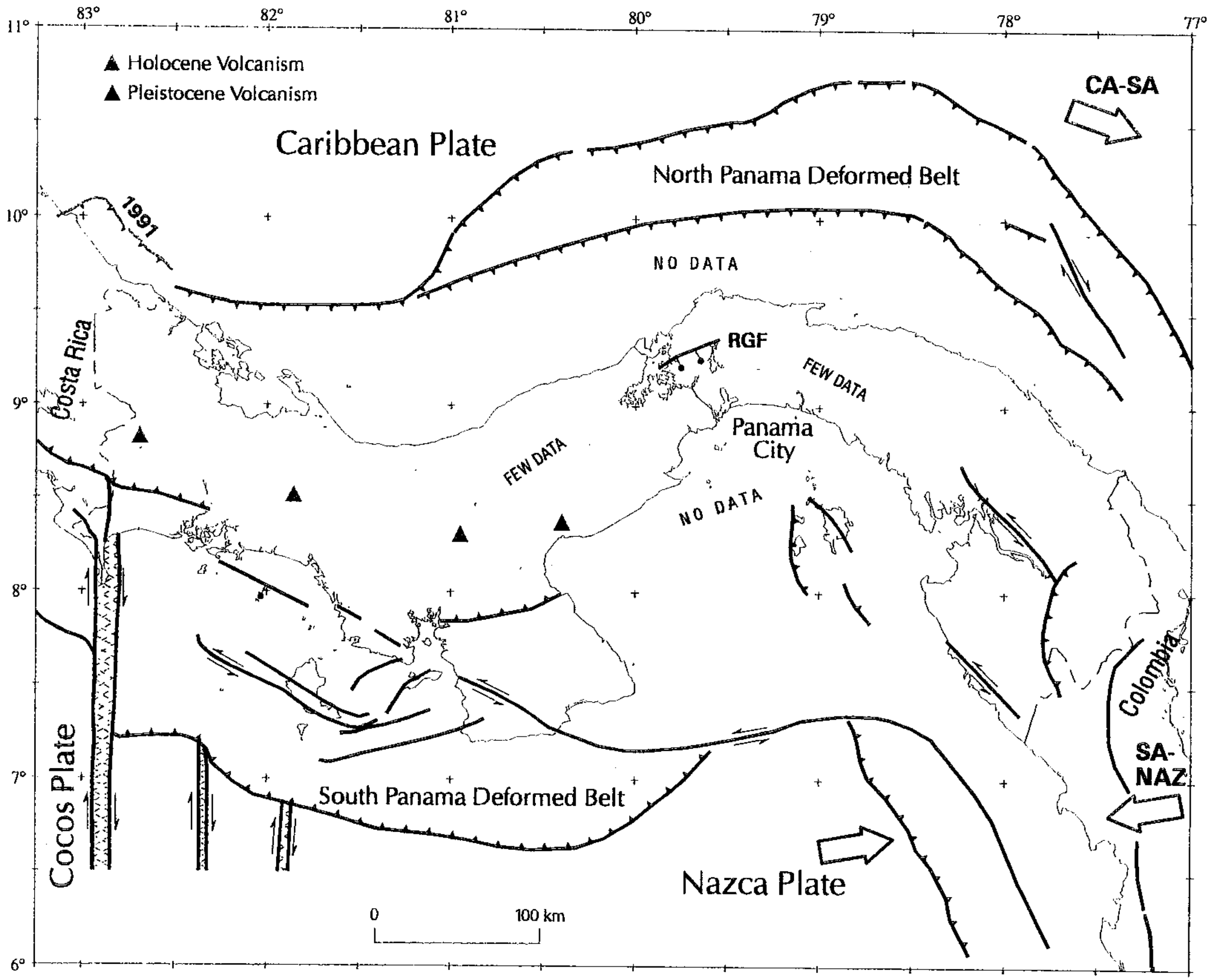

Figure 1.1: Major structural elements of the Panama Block and surroundings (after Cowan, 1998). Panama is located at the intersection of the Nazca, Cocos, Caribbean and South America plates, and is converging against South America across the northern Andes. The active boundaries of the Panama Block are therefore characterized mainly by compressional tectonics. Note that the Panama Canal is located in the interior of the block, but few data are available to define the active geological structures. (RGF=Rio Gatun Fault)

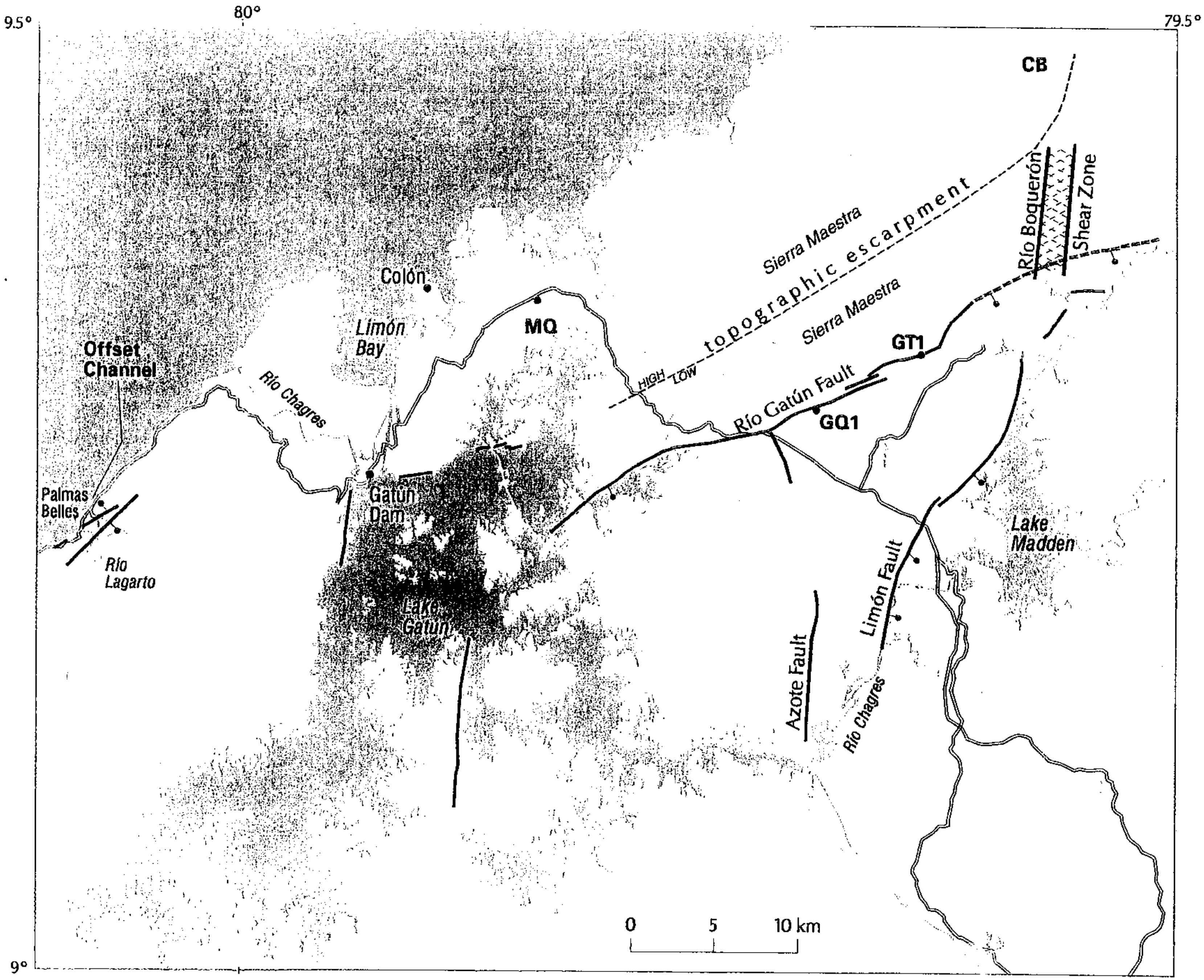

Figure 1.2: Structural features in the Lake Gatún area. MQ, Margarita Quarry; GQ1, quarry in Figures 4.3 and 4.4; GT1, site of two trenches across Río Gatún fault; CB, Cerro Bruja.

faulting (see Schweig et al., 1996; Pratt et al., 1996). Based on analyses of data gathered it was recommended that:

- a design earthquake of M 8.0, located 50 km from the Gatún Dam site within the North Panama deformed belt, should be adopted;
- a design earthquake of **M** 7.1 located in the Río Gatún fault zone, about 10 km from the Gatún Dam, should be adopted;
- a densely spaced, portable seismograph network should be deployed to monitor seismicity associated with faulting in the Canal Zone and vicinity;
- additional permanent seismic stations should be installed near Gatún Dam as part of the network currently operated by the University of Panama;
- accurate (GPS) timing should be added to strong-motion K2 accelerometers installed on Gatún Dam;
- a search should be conducted for geological evidence of surface rupture associated with prehistoric earthquakes on the Río Gatún fault and other structures; and
- a search should be conducted for geological evidence of liquefaction induced by strong shaking in prehistoric earthquakes, regardless of their source.

A new agreement, Interagency Support Agreement No. CC-3-452, was signed March 11, 1997, under which Eugene Schweig, Thomas Pratt, Joan Gomberg were to conduct geological, seismological, and geophysical investigations in order to provide recommendations for design earthquakes for Gatún Dam. Hugh Cowan, an independent consultant in Panama, was retained as a consultant and worked on all phases of the current agreement. Andrew TenBrink, a USGS student employee at the University of Memphis, assisted in the geological aspects of the project as part of his Masters degree program.

1.2.1 Task I, Geological Investigations

Under the previous agreement, we had identified areas where further geological studies might result in estimates of the dates of large prehistoric earthquakes. These included areas that were likely to preserve indirect evidence of earthquakes (such as liquefaction) that would indicate that local strong ground shaking had occurred *regardless* *of the earthquake source*. We also identified areas where excavation of fault traces might be possible in order to obtain evidence for prehistoric activity on those particular faults. Finally, we identified possible active faults, other than the previously identified North Panama deformed belt or the Río Gatún fault zone, that might be a threat to Gatún Dam.

In 1998 we increased the scope of paleoseismological work in an attempt to establish closer bounds on the recurrence of large earthquakes. This work concentrated on the Río Gatún fault and a search for evidence of paleoliquefaction west of Limón Bay. Our earlier analysis suggested that the Río Gatún fault is at least 50 km long and capable of generating an earthquake of at least **M** 7.0. We were also concerned about a fault system identified parallel to the coast near Palmas Bellas, 15 km west of Gatún Dam, and extending an unknown distance to the east and west. We had earlier identified this area as one promising for paleoliquefaction studies. Details of this work are contained in Schweig et al. (1998).

1.2.2 Task II, Seismic Reflection Profiling: Limón Bay and Gatún Dam

The objectives of the seismic reflection profiling were to determine: 1) whether shallow faults lie beneath or near Gatún Dam; 2) the trends of faults imaged beneath Limón Bay during seismic profiling carried out in 1996; and 3) the age of motion on these faults. The 1997 seismic reflection profiling consisted of a grid of closely-spaced (1500 feet apart) marine seismic profiles in southeastern Limón Bay to determine the trends of the faults imaged there in 1996. Specifically, we sought to determine whether any of the faults have a trend that indicates they extend beneath Gatún Dam. We also acquired three land seismic profiles along the center of Gatún Dam and another land profile perpendicular to the dam just west of the spillway to determine whether faults lie directly below the dam. In addition to the profiling, we examined pre-dam topographic maps of the Gatún area and descriptions of boreholes from Gatún Dam to interpret the strata we imaged beneath the dam. Details of this task are contained in Schweig et al. (1998) and Pratt et al. (1999).

1.2.3 Task III, Monitoring of Seismicity

Under the previous agreement, we searched the seismological literature, the archives at the PCC, and spoke with experts at the University of Panama (UPA) to compile all available information on instrumental and historical earthquakes in the vicinity of the Canal Zone. This search yielded little information due to a lack of any instrumental data from within Panama prior to the installation of the UPA network in the early 1990s. Comparison of the UPA catalog with the one we produced as a result of our 1997-1998 monitoring indicated that, although the UPA network may provide some general measure of the seismicity rates in central Panama, it is too sparse to provide locations accurate enough even to identify gross-scale patterns in the distribution of earthquakes. From

October, 1997, until April, 1998, we installed and operated 14 temporary seismic stations in the vicinity of the northern portion of the Canal. Each station operated independently, and all were maintained by USGS contractor Hugh Cowan, with assistance from PCC personnel from the Geotechnical Branch and the Meteorological and Hydrological Branch.

Data were mailed to Joan Gomberg every 3-4 weeks for analysis and archiving. The average station spacing of about 15 km permitted us to locate earthquakes with enough accuracy to resolve clear spatial variations in the seismicity. Although various interpretations of the distribution of earthquakes both laterally and with depth are plausible when considered alone, a relatively unique and reasonable interpretation may be constructed when results of all three tasks are combined. See Schweig et al. (1998) for details.

2. DESIGN EARTHQUAKES

We recommend three design earthquakes for consideration of the seismic hazard at Gatún Dam. The character of ground motion associated with each source is likely to be distinct. The design earthquakes include a moment magnitude (M) 7.7 thrust earthquake located at the Caribbean plate-Panama Block interface, 35 km beneath the Gatún Dam (Source 1), a M6.8 earthquake on the Río Gatún fault (Source 2), and a M5.0 or M6.0 earthquake on a crustal fault near Gatún Dam (Source 3).

The design earthquake parameters presented in the table are followed by an explanation of the evidence and reasoning from which they were derived. The data that went into the reasoning are in the following chapters.

Source Zone	Moment Magnitude (M)	Site Distance (km)	Slip per Event (m)	Fault Area (km^2)	Recurrence Interval (years)
Source 1	7.7	35	3.3	3300	330-1000
Source 2	6.8	13	0.8	450	10,000 - 20,000
Source 3a	5.0	2	0.2	12	200
Source 3b	6.0	2	0.5	100	2000

2.1 North Panama Deformed Belt (Source 1)

The seismic network deployed for six months during this study detected mainly intermediate-depth earthquakes beneath central Panama. We interpret the spatial distribution of seismicity as defining the surface of the subducted Caribbean plate beneath the Panama Block, dipping south from the North Panama Deformed Belt (NPDB) (Figure 1.1) at about 16 degrees. The plate interface is located about 35 km beneath the Gatún area (which forms the basis for the site distance in the table above) and deepens to about 60 km farther to the southeast. The subducted plate has a large surface area potentially available for rupture and is assigned a larger magnitude than the other design earthquake sources.

We have revised our original estimate of magnitude (M8.0) for the NPDB source (Schweig et al., 1996) because our geologic studies have not revealed evidence for a past event of this size. In our initial report we recommended a M8.0 earthquake for the NPDB, based on our understanding of the 1882 Panama earthquake offshore, in the northeastern sector of the NPDB. The 1882 earthquake was associated with liquefaction at settlements along the north coast of Panama, and produced a tsunami that drowned more than 60 persons in the province of San Blas (Mendoza and Nishenko, 1989; Camacho and Viquez, 1993). The 1882 event has been described as a possible "great" earthquake (M8 or larger), but that interpretation is constrained only by felt reports that were largely restricted to the north coast of Panama. The vertical movements and ground motions that accompany great earthquakes are normally associated with liquefaction and measurable changes in coastline morphology. Our search for such features did not reveal any such evidence.

Our choice of a design earthquake magnitude for Source 1 is, therefore, lower than M8, but is larger than the 1991 Limón, Costa Rica, earthquake (M7.5) in the western part of the NPDB. This is because the Limón earthquake rupture was restricted to the vertical thickness of the Panama Block, overlying the Caribbean plate interface (Plafker and Ward, 1992). In northern Panama this scenario would correspond to one of the offshore faults in the NPDB. In contrast, the plate interface that lies beneath the NPDB and dips south beneath the Panama isthmus has a larger surface area available for rupture. We therefore recommend a design magnitude of M7.7 for the Source 1 earthquake.

The lack of evidence of paleoliquefaction in the areas we inspected does not eliminate the possibility that large earthquakes have shaken the Gatún area. This absence of evidence in some cases may reflect the lack of conditions conducive to liquefaction or a stratigraphic record of sedimentation that may be shorter than one seismic cycle. An approximate recurrence interval for Source 1 earthquakes can be estimated from empirical information on earthquake source parameters (Wells and Coppersmith, 1994) together with information on regional plate convergence rates. An empirical relation for slip as a function of moment magnitude is:

$$\log(\text{average slip}) = 0.69(\text{magnitude}) - 4.8$$

This relation gives a slip of 3.3 m for a M7.7 event. 3.3 m of slip in turn suggests a minimum recurrence interval of 330 years, given the approximately 1 cm/year convergence rate between the Panama and Caribbean plates (Kellogg and Vega, 1995). This recurrence interval also represents a minimum value, because some part of the convergence may be relieved aseismically. The occurrence of two large historical events (1882 and 1991) in different parts of the NPDB implies that the recurrence interval for rupture of individual sections of the underlying thrust zone may be hundreds of years, not thousands of years. This interpretation and the fact that the calculated recurrence interval of 330 years is approximate and probably a minimum, led us to estimate an upper bound on the recurrence interval of 1,000 years.

2.2 *Río Gatún Fault (Source 2)*

The Río Gatún fault (Figure 1.2) is the largest recognized crustal fault in the Canal area. The presence of the Río Gatún fault just 13 km from Gatún Dam indicates that large crustal faults could be a threat to the Dam. However, our geological studies have revealed that there has been no motion on the Río Gatún fault for at least 10,000 years or more. Thus, crustal faults could produce moderate to large earthquakes but probably very infrequently.

A fault length of approximately 30 km is indicated for the Río Gatún fault based on a number of observations. The northeast extent of the fault is constrained by the Río Boquerón valley, a structural depression that trends perpendicular to the Río Gatún fault and displays no obvious evidence of lateral or vertical displacement by the Río Gatún fault. The western limit of the Río Gatún fault was previously inferred to be in the western part of Lake Gatún, based on topographic and bathymetric features (Schweig et al., 1996). Several lines of evidence now indicate that the fault is shorter.

Examination of the Río Gatún fault as part of this study has revealed that it is a normal fault that has predominantly vertical motion (down to the south) rather than a strike-slip fault with horizontal motion (cf. Mann and Corrigan, 1990). The topographic and bathymetric features beneath the lake are an order of magnitude smaller than the scarps that delineate the Río Gatún fault east of Gatún Lake. Furthermore, Tertiary rock units (including Caimito Fm, and undifferentiated Late Eocene marine rocks) that are only a few tens of meters in total thickness are mapped on both sides of the fault in Gatún Lake. East of the lake, hundreds of meters of vertical motion can be demonstrated across the Río Gatún fault, so the fault must terminate near the east edge of Gatún Lake. Alternatively, the fault could be segmented such that the sub-lake portion of the fault has accommodated much less displacement than the segment east of the lake. In either case, it appears unlikely that a single earthquake would rupture a 60-km long Río Gatún fault. Empirical relations (Wells and Coppersmith, 1994) indicate that a fault 30 km in length can be expected to produce a M6.8 earthquake. This implies a fault area of about 450 km^2 (30 km by 15 km).

As explained in Chapter 4, our studies indicate long recurrence intervals between events on the Río Gatún fault, on the order of 10,000 to 20,000 years, because:

1 There is no obvious evidence for recent faulting on seismic profiles or in trenches and fault-associated shear zones in the basement rocks are strongly lithified and could be tens of thousands of years old;

2 Unfaulted alluvial deposits that straddle the Río Gatún fault are highly weathered to a depth of 5 meters or more indicating ages greater than 10,000 years. The age of these deposits is unknown, but alluvial deposits that have been dated at 10,000 years from a region of similar climate in western Panama show much less intense weathering (Cowan et al., 1997).

3 We have not observed any offset of alluvium in any of the many streams that cross the Río Gatún fault along the Sierra Maestra front;

4 The geology of the Sierra Maestra block indicates that the long term rate of uplift across the Río Gatún fault is slow with the Río Gatún fault and the Río Boquerón structural depression bounding the south and east margins of the Sierra Maestra, respectively. Both fault zones evidently controlled the uplift of the mountains, which are composed of pre-Tertiary (>65 million years) basement rocks, tilted to the northwest. Marine sediments of late Miocene age (11-8 million years) unconformably overlie the basement rocks on the western flank of the Sierra Maestra (Stewart et al., 1980), thus implying that the Sierra Maestra had been partially uplifted and stripped of its Tertiary sediment cover prior to the late Miocene. A minimum long-term uplift of about 900 m in 10 million years may be inferred from the topographic offset across the Río Gatún fault, thus indicating a maximum long term uplift rate of 0.1 mm/year (10,000 years to accumulate 1 m of displacement).

5 Lastly, the predominance of intermediate-depth earthquakes and paucity of upper crustal earthquakes recorded during this study (section 4.3) suggests that more of the plate convergence may be accommodated by the subduction thrust zone, than by shallow crustal faults.

This evidence indicates that the recurrence interval of large earthquakes on the Río Gatún fault is tens of thousands of years, not hundreds or thousands of years. We thus suggest using a recurrence interval of 10,000 years for moderate crustal earthquakes on the Río Gatún fault.

2.3 Caribbean Coast Faults near Gatún Dam (Source 3)

We recommend two design earthquakes to account for the range of possible small to moderate crustal earthquakes near Gatún Dam (Figure 1.2). These earthquakes are considered separately from the Río Gatún source zone because small events are more common than large events and small events could occur on faults very near, or even beneath Gatún Dam.

One of the main conclusions from the seismic reflection profiling in southern Limón Bay is that there is a high density of shallow faults in the area north of Gatún Dam and probably all around the Dam. On some of the profiles the faults are only 250 meters apart, and we estimate that at least one of these faults is 8 to 13 km in length. These shallow faults could have different orientations, and any buildup of strain in the crust could produce a small to moderate earthquake on one of these shallow faults. The seismic profiles document several faults within 2 km of Gatún Dam, so it is important to account for the possibility of a small, shallow earthquake occurring very close to Gatún Dam.

The recurrence intervals for small to moderate crustal earthquakes near Gatún Dam are difficult to quantify and we have no direct evidence that would constrain this parameter. We did not find evidence of surface faulting or liquefaction near Gatún Dam, and the seismic profiles do not prove that any of these shallow faults moved during the last 6,000 years. However, because of the high density of shallow faults and the lack of age constraints on the observed displacements, the possibility of seismogenic faulting near the Dam must be considered. Given the lengths of the observed faults, and the lack of evidence for longer local faults, we feel that magnitude 6 is a reasonable upper bound for local earthquakes. Based on the arguments above, a standard Gutenberg-Richter distribution of magnitudes and a b-value of 1.0, and our geologically constrained estimates of recurrence for earthquakes on the Río Gatún fault, we would estimate a recurrence interval for a M6.0 earthquake to be on the order of 2000 years. This implies that tectonic stresses accumulate similarly in both source regions 2 and 3, which is reasonable geologically, and is consistent with the seismicity distribution we have observed. Similarly, based on a Gutenberg-Richter magnitude frequency distribution, corresponding earthquakes of magnitude 5 would occur about every 200 years.

3. Source 1: North Panama Deformed Belt

M = 7.7, Site Distance = 35 km, Slip = 3.3 m, Fault Area = 3300 km^2, Recurrence Interval = 330-1000 years

3.1 Early work

At the outset of this project, one of the design earthquakes considered by the PCC was a magnitude 7.5-8.0 earthquake occurring in the Northern Panama deformed belt (NPDB) (Figure 1.1). The NPDB is an arcuate zone of distributed folding and thrust faulting that extends eastward from the border region of Costa Rica and Panama to the Gulf of Uraba, Colombia. The NPDB is being generated by compression between the Caribbean plate and the Isthmus of Panama, and has been the source of several large earthquakes during the historical period (Mendoza and Nishenko, 1989; Camacho and Viquez, 1993). The rates of convergence between the two plates are poorly known, but the Caribbean plate is apparently being thrust beneath Panama as a poorly developed subduction zone.

From very sparse GPS data, Kellogg et al. (1995) estimated a rate of 11 mm/yr. Their data support a model in which Panama and Costa Rica are part of the same rigid Panama microplate as proposed by Adamek et al. (1988). A consistent but more sophisticated model of regional deformation comes from modeling of geodetic data by Lundgren et al. (1995). Their model shows that the Panama block moves northward at a rate that increases westward along the NPDB from 10 mm/yr to 20 mm/yr, consistent with clockwise rotation, thrusting in the NPDB, and left-lateral strike-slip faulting in central Costa Rica. This is also consistent with Plafker and Ward's (1992) estimated 90 mm/y convergence rate between Cocos and Caribbean plates with 2-11 mm/y taken up between Panama and the Caribbean (obtained in their study of coastline morphology in the vicinity of the April 22, 1991, Costa Rica earthquake).

The main rationale for choosing this design earthquake was the Mendoza and Nishenko (1989) report on the 7 September 1882 earthquake, which was the most damaging historic earthquake to affect the Gatún Dam region of Panama. Mendoza and Nishenko documented the effects of the earthquake, and estimated that it was a great (M~8) earthquake located in the NPDB at approximately 10°N, 78°W. They describe severe effects including widespread liquefaction in the north-central portion of the isthmus, including in the town of Gatún, now under Lake Gatún, and a large tsunami on San Blas Islands to the east.

The NPDB presented a unique challenge. Although the PCC initially considered an **M** 7.5-8.0 design earthquake, they had not decided on a source distance. We (Schweig et al, 1996) initially recommend using **M** = 8.0 as the design magnitude, based on our initial reading of Mendoza and Nishenko (1989). Mendoza and Nishenko had estimated an 1882 epicentral location well east (about 220 km) of the Gatún Dam site. We inferred that the available information about the 1882 earthquake could be attributed to rupture on any fault within the broad zone that defines the NPDB, as mapped by Silver et al. (1990, 1995). We also pointed out that the faults in the deformed belt are likely thrust faults dipping to the south, thus the rupture surface from a magnitude 8 event could extend under Gatún Dam. In view of these factors, Schweig et al. (1996) recommended a design distance from the site of 50 km.

With the NPDB being offshore, the methods of further evaluating this source were limited. Marine seismic work or deep continental seismic reflection studies were considered too costly or impractical. Direct observation of the faults is impossible because they are under water or beneath the crust of Panama. Therefore we used two methods. One was the deployment of a temporary seismic network, to better constrain the rates of seismicity and to see if the spatial pattern of seismicity could give us more information of what geologic structures were most active.

We considered a search for prehistoric liquefaction (paleoliquefaction) would also be useful in that such data could indicate that local strong ground shaking had occurred regardless of the earthquake source. If earthquakes similar to the 1882 earthquake had recurred repeatedly during the past few thousand years, it was hoped that a record might be preserved in the geologic record of liquefaction. Conversely, if we could find obvious and widespread evidence of 1882 liquefaction, but *not* prehistoric liquefaction, that might indicate very long repeat time for NPDP earthquakes affecting the Gatún area.

3.2 Results

3.2.1 Seismic Network Deployment

More details of the seismic network deployment are given in Schweig et al. (1996). Figure 3.1 shows the location of the 15 seismic stations deployed between October 18, 1997 and April 1, 1998. The main guiding principles for reliably monitoring local earthquakes are to surround the probable epicenters with stations, and to record at least a few seismic phases for each earthquake at distances no greater than the focal depth of likely events. These objectives were balanced with practical considerations like the number of available instruments, security, remoteness from sources of seismic noise, and accessibility. We were hoping to record earthquakes associated with the NPDB, as well as shallow crustal earthquakes associated with the Río Gatún fault or other crustal faults near the dam site.

Table 1 lists all our stations and their locations. Many stations were located inside buildings maintained as hydrologic monitoring stations by the Meteorological and Hydrological Branch of the PCC. The noise levels of these stations and two stations elsewhere (BS and SA) were very low, so that the minimum magnitude detection threshold for most of the network should be nearly uniform. Those stations in Table 1 with no descriptions listed are some of the stations of Panama's permanent seismic network operated by the University of Panama (UPA). We list those UPA stations that provided additional data constraining the events recorded on our network.

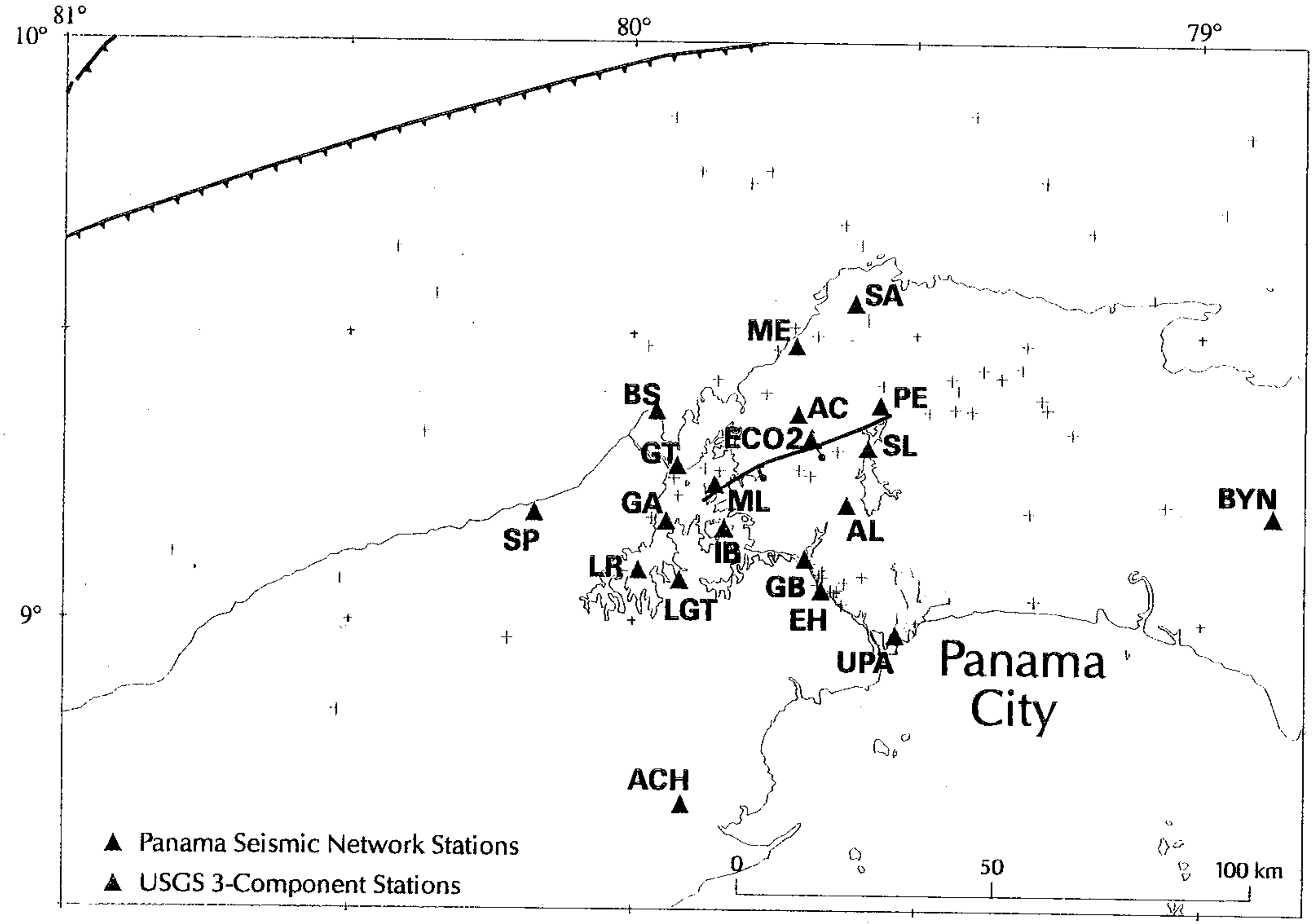

Figure 3.1: Earthquakes recorded by the 3-component USGS seismic network. Also shown are the Panama Seismic Network stations (UPA) within the map area. The Gatún Dam site is at station GT.

Table 1. Seismic Stations

Station Code	Geographic Name	Longitude (W)	Latitude (N)	Elev (m)	Description
AC	Agua Clara	-79.706547	9.365003	499	Met. & Hyd. Station
AL	Alajuela	-79.620556	9.206482	49	Met. & Hyd. Station
BS	Battery Stanley	-79.956477	9.369697	33	Abandoned bldg. at Fort Sherman
EH	Empire Hill	-79.66464	9.058173	102	Met. & Hyd. Station
GA	Gaucha	-79.938986	9.177346	51	Met. & Hyd. Station
GB	Gamboa	-79.696962	9.115964	63	Garage in private home
GT	Gatún	-79.919725	9.274582	27	Supply bldg. at Canal Protection Division Headquarters
IB	Isla Barro Colorado	-79.836614	9.16584	42	Office bldg. at Smithsonian Inst.
LR	Los Raices	-79.988018	9.09159	47	Met. & Hyd. Station
ME	Meiche	-79.71088	9.483076	24	Private farm building
ML	Monte Lirio	-79.853347	9.241164	72	Met. & Hyd. Station
PE	Peluca	-79.561107	9.381814	117	Met. & Hyd. Station
SA	San Antonio	-79.606226	9.558164	28	Abandoned IRHE station
SL	Salamanca	-79.582218	9.306513	91	Met. & Hyd. Station
SP	Salsipuedes	-80.171669	9.190646	27	Storage shed in private home
UPA	Univ. of Panama	-79.5338	8.9810	41	
DVD	David	-82.4557	8.4340	50	
ARM2	Armuelles	-82.8667	8.1000	10	
IPE	Ipeti	-78.4933	8.9772	50	
LGT	Lagarita	-79.9150	9.0745	50	
ECO2	Sierra Maestra	-79.6837	9.3218	450	
BYN	Bayano	-78.8750	9.1910	50	
CNI	Chang	-82.5168	9.4167	20	
AZU	Azuero	-80.2740	7.7917	14	
FTA	Fortuna	-82.2647	8.6815	629	
ACH	Campana	-79.9098	8.6878	600	

In the six months of the deployment, 86 events (blasts and earthquakes) were recorded on three or more stations, the minimum required to obtain a location. Of the 86 locatable events, 64 were deemed to be located with enough accuracy to be used in our interpretations. Most of the events omitted were recorded more than ~50 km outside our network; the distance and lack of azimuthal distribution of data for these events is reason to not trust their accuracy. Of the 86 events located, we are confident that the 14 located in the vicinity of the Gaillard Cut are blasts (one is a few km east of the Cut, but the waveforms have the same character as the other blasts). Although only three of these have been associated with blasts noted in the Canal Commission records provided to us, the character of the waveforms and their apparently shallow focal depths enable us to identify them as blasts with confidence.

The seismicity we recorded provides only a minimum estimate of the true rate for a number of reasons. First, more events were recorded on just one or two stations, but not included in our database because they could not be accurately located. A second reason that events may be missed is the use of triggered recording, necessary to minimize data storage so that stations need only be visited every few weeks. Triggering criteria must be tuned to local site conditions and characteristics of the local earthquake signals. Thus, as these factors vary spatially and temporally, some earthquakes inevitably do not get recorded. Finally, equipment failures also reduce the potential to reliably record and locate earthquakes.

We estimate that we probably captured ~75% of the true seismicity above magnitude 2.5 within ~50 km of the network. This would correspond to a true rate of approximately one M>2.5 earthquake every two days. It should also be kept in mind that this is a gross average, as the seismicity rate varies spatially and temporally on scales smaller than those resolvable in our experiment.

3.2.1.1 Interpretation of hypocenter (latitude, longitude, and focal depth) distribution.

Table 2 lists the 64 events we believe to be reliably located. In addition to the hypocenters, measures of reliability are also listed. The map-view distribution of these events by event number (Table 2) and by location and depth are shown in Figures 3.1 and 3.3. Several features of the seismicity are notable. First, the region within the network is relatively aseismic, and only three of the earthquakes within the network perimeters occurred at shallow crustal depths (<20 km). Two of these shallow earthquakes are located southwest of Lake Madden (station SL) and may be associated with the Gatún fault system. The third is located west of Gamboa (station GB) and cannot be associated with any known fault. This paucity of earthquakes is not an artifact of the detection capabilities of the network as many events are detected from farther distances, which should be harder to detect than those within the network. All events southeast of stations GB in the immediate vicinity of the Canal are blasts.

Table 2

Reliably Located Hypocenters

Latitude (°N)	Longitude (°W)	Depth (km)	Event #	Date	Hr:Mn:Sec UTC	Rms (sec)	Min Dist (km)	#of P&S	# of S
9.0637	-79.6713	0.00	001	97/10/10	22:54:46.52	0.16	16.85	12	03
9.1563	-79.7667	0.00	003	97/10/15	04:35:35.07	0.17	15.60	07	03
9.0616	-79.6559	3.86	004	97/10/15	11:58:57.31	0.16	1.05	16	07
9.9178	-79.3682	45.07	005	97/10/15	22:57:53.09	0.09	47.80	12	06
9.0934	-79.6759	0.00	006	97/10/16	13:08:01.58	0.15	4.10	11	04
9.0636	-79.6443	4.23	007	97/10/17	13:02:51.09	0.15	2.35	15	07
9.0974	-79.6668	0.00	008	97/10/17	22:59:49.56	0.33	3.95	19	07
9.0746	-79.6524	0.00	012	97/10/24	22:22:52.22	0.09	2.25	09	04
9.0172	-79.6963	14.76	013	97/10/27	16:59:20.91	0.65	18.30	15	07
9.0776	-79.6888	4.49	014	97/10/29	13:07:27.92	0.08	3.40	07	03
9.4052	-79.3944	60.52	015	97/10/30	08:51:39.00	0.16	18.50	12	06
9.0758	-79.6628	10.22	017	97/10/31	13:13:20.49	0.09	15.25	10	03
9.3704	-79.3753	50.49	018	97/10/31	23:40:03.94	0.15	20.45	18	09
9.2754	-79.8813	37.03	020	97/11/04	05:34:46.49	0.20	4.20	26	13
9.5917	-80.4054	32.49	021	97/11/05	08:36:05.27	0.14	51.45	06	03
9.0908	-79.6514	4.98	022	97/11/06	16:23:14.43	0.20	3.90	04	01
9.7065	-79.6003	36.47	023	97/11/07	19:25:59.24	0.05	16.50	10	05
9.4267	-79.4061	42.55	024	97/11/08	13:49:17.58	0.11	17.75	10	05
9.4643	-79.2769	47.14	025	97/11/12	16:18:50.74	0.18	32.50	21	10
9.5239	-79.6544	38.83	026	97/11/17	08:11:07.23	0.09	18.55	17	08
9.0211	-79.6235	3.68	027	97/11/20	22:45:01.32	0.09	6.15	08	02
9.0527	-79.6662	1.73	028	97/11/24	14:29:15.98	0.11	0.65	08	01
9.5873	-79.6434	36.78	029	97/12/01	01:25:29.43	0.10	5.20	14	07
9.0690	-79.6307	5.11	031	97/12/02	22:37:44.03	0.25	3.95	05	02
9.3021	-79.6395	58.32	033	97/12/24	03:32:04.77	0.15	24.40	18	09
9.7770	-79.2150	45.29	034	97/12/27	09:16:48.45	0.01	49.35	05	02
9.3341	-79.1960	45.53	035	98/01/13	16:17:55.80	0.30	38.65	28	14
9.0705	-79.6608	0.19	036	98/01/16	22:50:55.78	0.03	1.40	17	06
9.0830	-80.5398	12.97	037	98/01/20	00:20:41.42	0.32	42.15	21	11
9.4452	-79.3573	26.78	038	98/01/21	05:12:25.27	0.21	23.45	26	13
9.5285	-79.7097	39.39	039	98/01/26	03:29:15.72	0.03	11.80	08	04
9.9013	-78.9091	9.99	040	98/01/27	23:35:43.22	0.06	79.05	26	13
9.8201	-79.8847	46.95	043	98/01/31	07:37:03.89	0.17	42.20	14	07
9.4157	-79.5402	61.62	044	98/02/02	20:57:28.34	0.02	4.45	06	03
8.8426	-80.5664	27.96	045	98/02/03	01:13:28.34	0.30	69.30	31	14
9.9213	-79.9003	16.42	047	98/02/03	20:03:17.30	0.08	61.65	06	03
9.6690	-80.4591	48.13	048	98/02/03	22:56:17.35	0.08	64.40	05	02
9.7982	-79.7763	9.57	049	98/02/04	08:53:10.62	0.32	52.00	06	03
9.3072	-79.7273	8.21	050	98/02/05	18:26:27.92	0.17	15.65	06	03
9.4918	-79.2782	18.92	051	98/02/06	02:52:47.21	0.11	33.40	24	12
9.1988	-79.1003	15.72	052	98/02/06	05:51:16.96	0.40	24.70	21	11
9.1748	-79.9931	34.13	054	98/02/07	11:40:55.86	0.20	5.95	07	03
9.4443	-79.8606	27.95	055	98/02/08	17:19:03.27	0.19	13.35	14	06
9.5473	-79.5497	36.93	056	98/02/13	10:16:35.85	0.09	6.35	33	16
9.3265	-79.2410	26.19	057	98/02/16	10:00:45.49	0.76	35.65	06	03
9.3610	-80.1813	1.19	058	98/02/17	11:27:08.94	2.19	18.95	08	04
9.5110	-79.9944	21.26	059	98/02/18	07:08:12.44	0.27	16.25	23	12
9.3937	-79.2423	45.88	060	98/02/18	20:36:52.08	0.03	35.00	11	05

9.3748	-79.2446	45.76	061	98/02/19	07:42:4.37	0.13	34.75	29	15
9.6780	-79.5695	33.08	065	98/02/26	20:00:1.72	0.22	13.95	30	15
9.5898	-79.0446	50.26	067	98/03/02	23:04:40.68	0.07	61.20	09	04
9.6181	-79.8630	29.55	070	98/03/09	15:05:0.81	0.43	29.45	07	04
9.2587	-79.6813	9.80	071	98/03/13	14:15:15.45	0.00	8.80	04	01
9.3469	-80.4227	33.33	072	98/03/15	08:00:15.69	0.26	32.60	23	12
9.7100	-79.1087	18.28	073	98/03/16	09:51:17.79	0.55	57.15	09	05
9.2446	-79.9596	47.38	074	98/03/17	07:25:49.50	0.05	30.80	05	03
9.3947	-79.7633	31.59	076	98/03/18	08:35:14.63	0.06	7.05	07	04
9.3734	-79.3994	52.31	077	98/03/20	10:37:13.29	0.05	17.80	12	06
9.7778	-79.8059	12.16	078	98/03/20	19:28:51.62	0.15	32.80	06	04
9.6988	-79.1761	20.16	079	98/03/22	15:15:36.87	0.15	55.00	20	10
9.4839	-79.7421	41.12	080	98/03/24	01:09:22.19	0.11	3.45	36	18
9.1895	-79.2624	57.52	082	98/03/28	01:55:17.51	0.27	39.15	10	05
9.3489	-79.3104	17.96	084	98/03/28	23:34:13.69	0.90	27.75	06	03
9.1154	-80.8105	44.38	086	98/04/01	00:26:4.94	0.36	70.65	24	09

With respect to the NPDB earthquake source, it is notable that the remaining earthquakes all appear to occur at depths well below typical shallow crustal seismicity, and because they deepen inland from the coast, are most likely associated with underthrusting of the Caribbean plate beneath Panama. A band of hypocenters along the coast extending beneath Gatún Lake to stations ML and GA have depths ranging between about 30-40 km. Focal depths deepen to about 45-60 km southeast of this band, consistent with the subduction zone dipping to the southeast beneath Panama. We have no explanation for why these deeper earthquakes are not observed southwest of station SL. This spatial variation in the deeper seismicity may be simply a consequence of our short monitoring duration. However, these deeper earthquakes occur where the topography is also highest, suggesting that the uplift of the terrain is related to a subduction process that changes from east-northeast of the network relative to the southwest in the vicinity of the Canal Zone.

Focal mechanisms, indicative of faulting type, are determined by plotting the direction of the first motion (polarity) of the P-wave on a lower hemisphere equal area projection. Unfortunately, most of the earthquakes from this study are outside of the network so that azimuthal coverage is generally poor. In many cases a unique best-fit mechanism could not be found, and the multiple optimal mechanisms differed quite significantly. In total, fourteen focal mechanisms were deemed adequately constrained to yield useful information. For some of these only the general character of the stress field can be inferred; e.g., the P-axis may be constrained to be approximately vertical and the T-axis poorly constrained so that the only information determined is that the faulting was dominantly normal (extensional). We observed a mixture of faulting types for the coastal

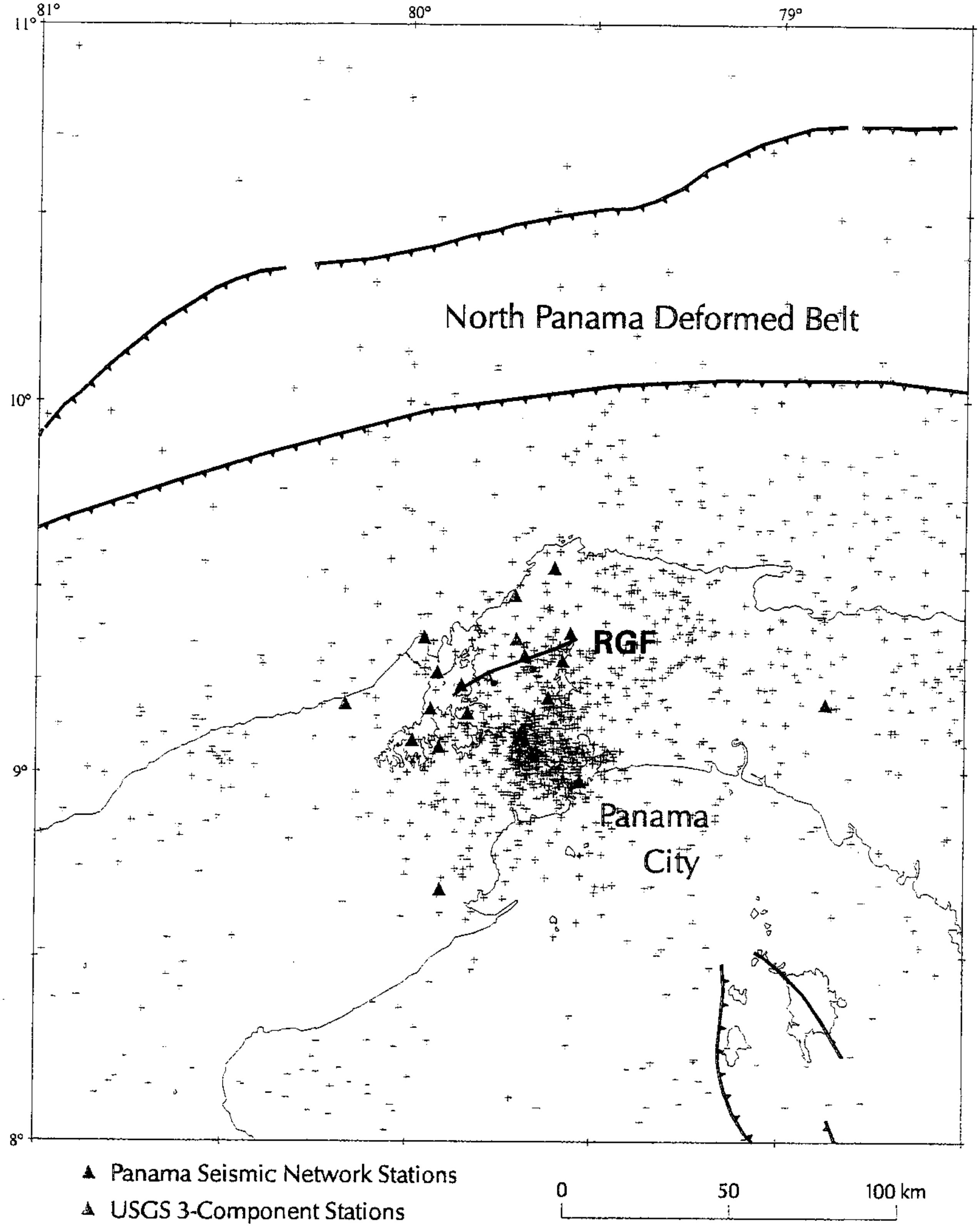

Figure 3.2: Seismicity catalog of central Panama from the University of Panama (UPA) seismic network. Also shown are the stations from the USGS seismic network deployment and UPA stations.

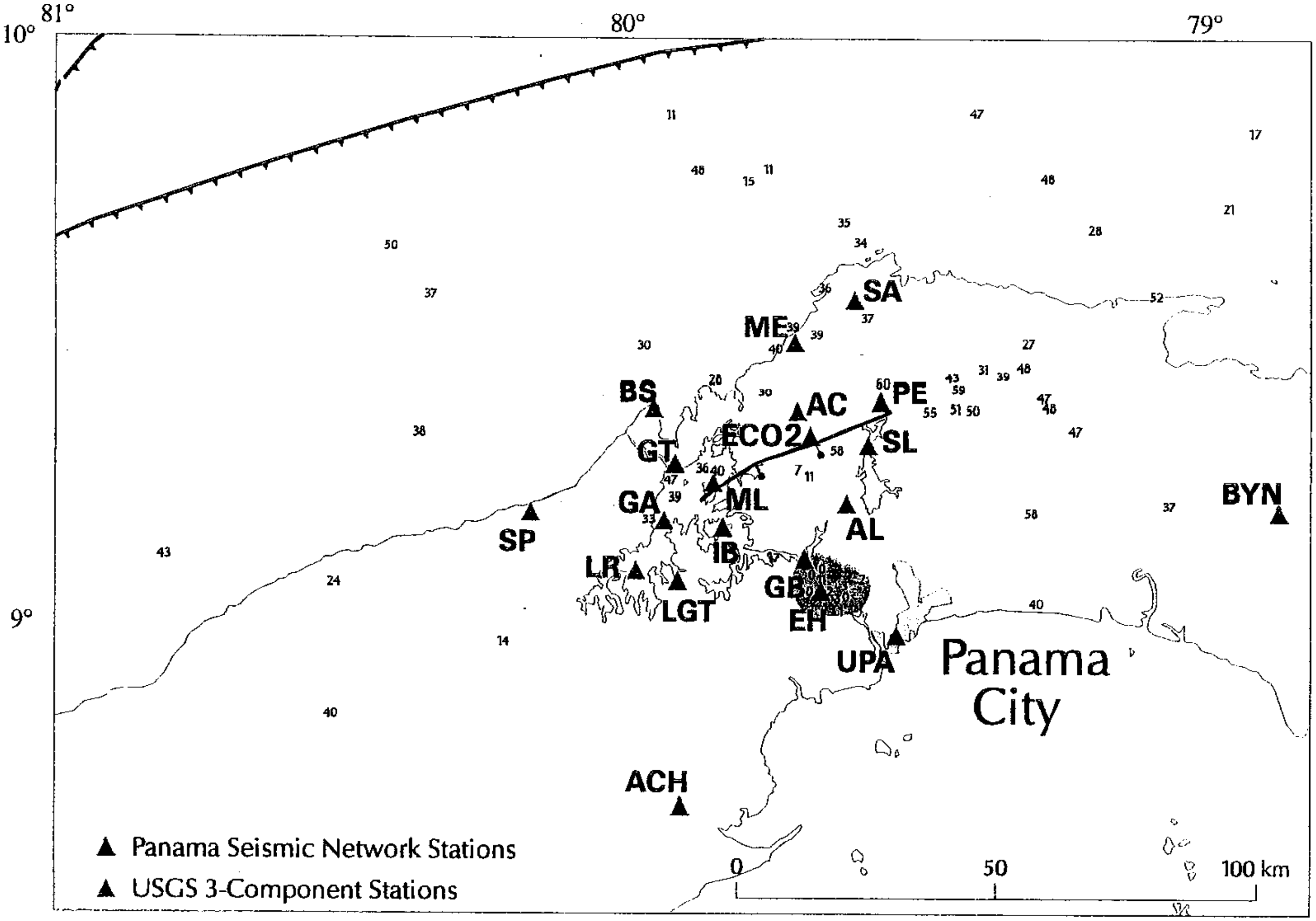

Figure 3.3. Epicenters (numbers, indicating estimated depths) of all well located earthquakes recorded by USGS (green triangles) and UPA (blue triangles) stations. Very low crustal deformation rates are implied by the fact that, at depths within the crust, only three earthquakes occurred within the network and five throughout the entire region. All shallow earthquakes in the southern half of the Canal Zone (shaded green area) are blasts. The deepening of sub-crustal earthquakes from the coast inland probably reflects subduction beneath the Isthmus. The reason for the clustering of the deepest events east of the Canal Zone is unknown, but the correlation with the highest topography suggests both are tectonically related. No evidence for a Canal Discontinuity is apparent in the seismicity or in the seismic velocity structure derived to locate the earthquakes.

earthquakes, all of which are deep (>20 km) and may be associated with subduction. This mixture is not surprising in the shallow reaches of a subduction zone. The deeper events to the east are dominantly thrust, perhaps reflecting compression of the subducting slab as it resists underthrusting beneath Panama. Several intermediate-depth earthquakes have been reported previously beneath eastern Panama (Adamek et al., 1988), including one of M ~7-7.2 in 1914 about 70 km beneath the Serranía de San Blas (Toral, 1998). To our knowledge, however, this project has provided the first evidence of active underthrusting beneath the isthmus in Central Panama.

We estimate that the seismicity rate of magnitude 2.3 to 3.8 earthquakes was approximately one event per two days. This estimate accounts for network downtime, noting that the network was fully operational for approximately 75% of the time. Magnitudes are taken from the UPA catalog for which there is only partial overlap with ours; thus, a few earthquakes with slightly greater magnitudes may be in our catalog. The sampling is too small and recording duration too short to extrapolate reliably to rates of larger magnitude earthquakes.

3.2.2 Paleoliquefaction Studies

As discussed earlier, the 1882 earthquake was reported to have caused widespread liquefaction in the north-central portion of the isthmus. Given this, and the success we have had using paleoliquefaction in the Central U.S., the Dominican Republic, and Puerto Rico, we thought it reasonable that 1) evidence of 1882 liquefaction should be clear in the field and 2) liquefaction ought to have recurred at or near the same sites in repeated earthquakes, as is typical elsewhere in the world.

In the first phase of this project (Schweig et al., 1996), we spent several days along the north coast both east and west of the Canal Zone looking for areas where liquefaction deposits, probably from large earthquakes in the North Panama deformed belt, might be preserved and accessible. We found a surprisingly large number of sites where there was a good potential for paleoearthquake studies, both in terms of access and the possibility of preservation of materials. We revisited and trenched a number of these sites, but never found liquefaction deposits.

One area that we had hoped would yield paleoliquefaction evidence was the paratrooper field northwest of Gatún Dam (site L1, Figure 3.4) along the Río Chagres. We excavated a total of seven trenches in this field. Although we recovered large quantities of organic material, which showed that the sediments are about 2000 years old, we discovered

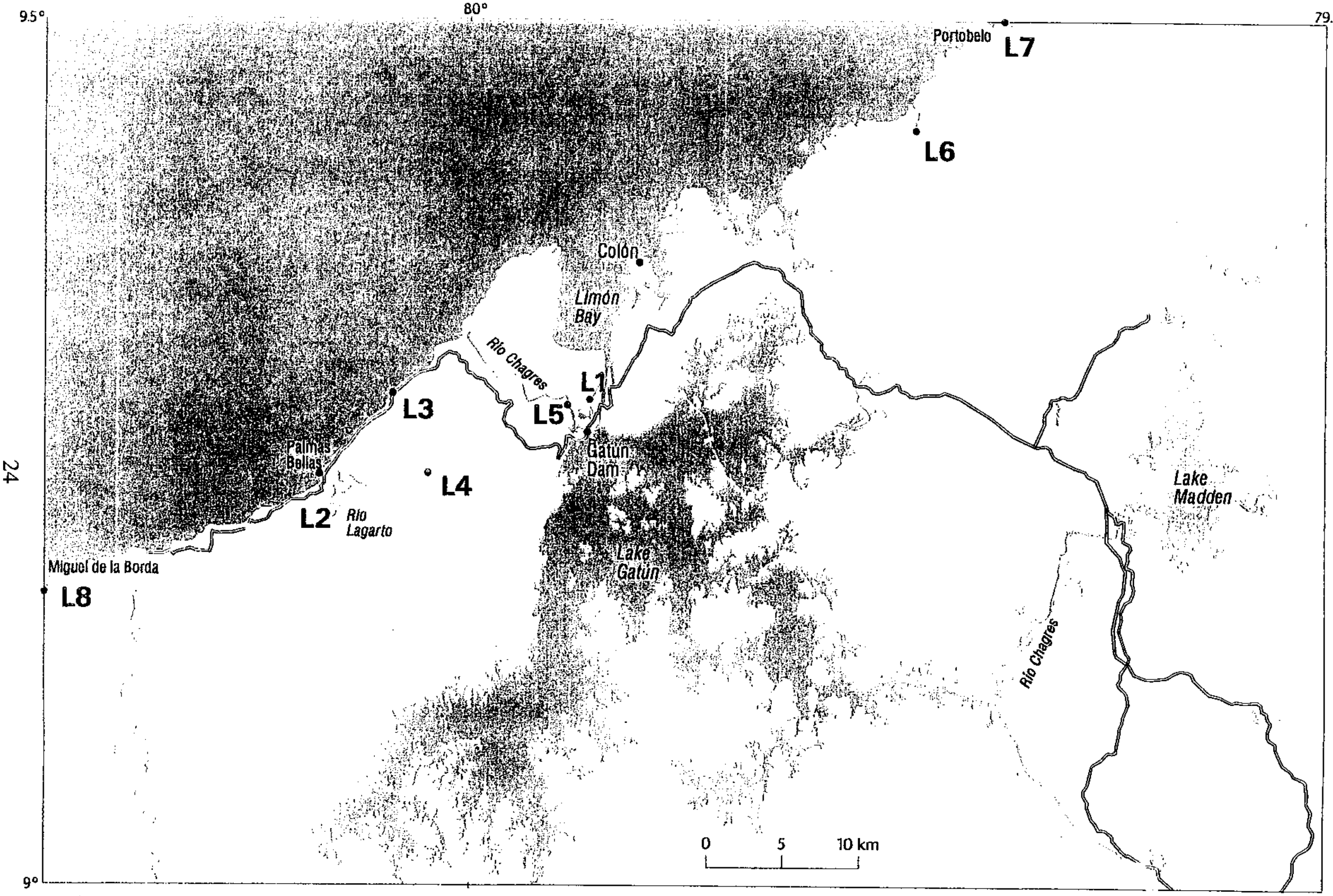

Figure 3.4: Liquefaction study sites. L1 (Paratrooper Field) had 5 trenches; L2 had 1 trench and pre-Columbian artifacts; L7 is on the Río Cascajal and is the site with liquefaction dikes shown in Figure 3.5.

that the sediments were so fine-grained as to make them not susceptible to liquefaction. Indeed, none of the sediments displayed evidence of liquefaction (or faulting). We suspect that the areas of liquefaction attributed to the 1882 earthquake occurred farther upstream along the Río Chagres, and are now submerged beneath Gatún Lake. Features that we originally thought might be attributable to earthquake-induced liquefaction are apparently due to precipitation of iron along desiccation cracks.

We also searched for evidence of earthquake-induced liquefaction along the lower reaches of rivers on the Costa Abajo (west of Gatún Dam on Figure 3.4) and in exposures of young coastal plain sediments exposed in wave-cut cliffs along the beaches (site L2 on Figure 3.4). Although conditions seemed reasonable for the formation and preservation of liquefaction features along the beaches, none were observed. Pre-Columbian artifacts were found in the sediments along the beach near an abandoned channel of the Río Lagarto (left side of Figure 1.2 and L2 on Figure 3.4), demonstrating that they were old enough to have experienced at least the 1882 earthquake. However, exposure is limited and the loose sands are extremely unstable, making excavation there difficult. Also, the loose, coarse grained sands may have been unable to maintain sufficient pore pressures to have produced surface-rupturing liquefaction near the free face at the beach where we trenched. Farther inland, the area was a swamp and excavation could not be accomplished by normal methods.

Historical documents describe liquefaction at Miguel de la Borda during the 1882 earthquake (site L8 on Figure 3.4). Due to the remoteness and inaccessibility of the village, we were only able to conduct reconnaissance excavations with hand tools. However, our investigation confirmed the liquefaction susceptibility of sediments and the suitability of the site for the preservation and dating of liquefaction deposits. Features that had been described to us as possible surficial sand blow deposits turned out to be sand deposited by burrowing crabs. Should funding become available in the future, we would recommend further paleoseismological studies in the Miguel de la Borda area.

We also searched for evidence of earthquake-induced liquefaction along the lower reaches of rivers along the Costa Arriba (east of the Gatún Dam on Figure 3.4). The sediments exposed at most of the rivers were considered too fine grained to liquefy. One exception is Río Cascajal, east of Portobelo (site L7 on Figure 3.4), where we discovered a site with a network of minor liquefaction dikes (Figure 3.5). The dikes do not appear to have breached the surface and there was no datable material to provide a context for determining the age of these features.

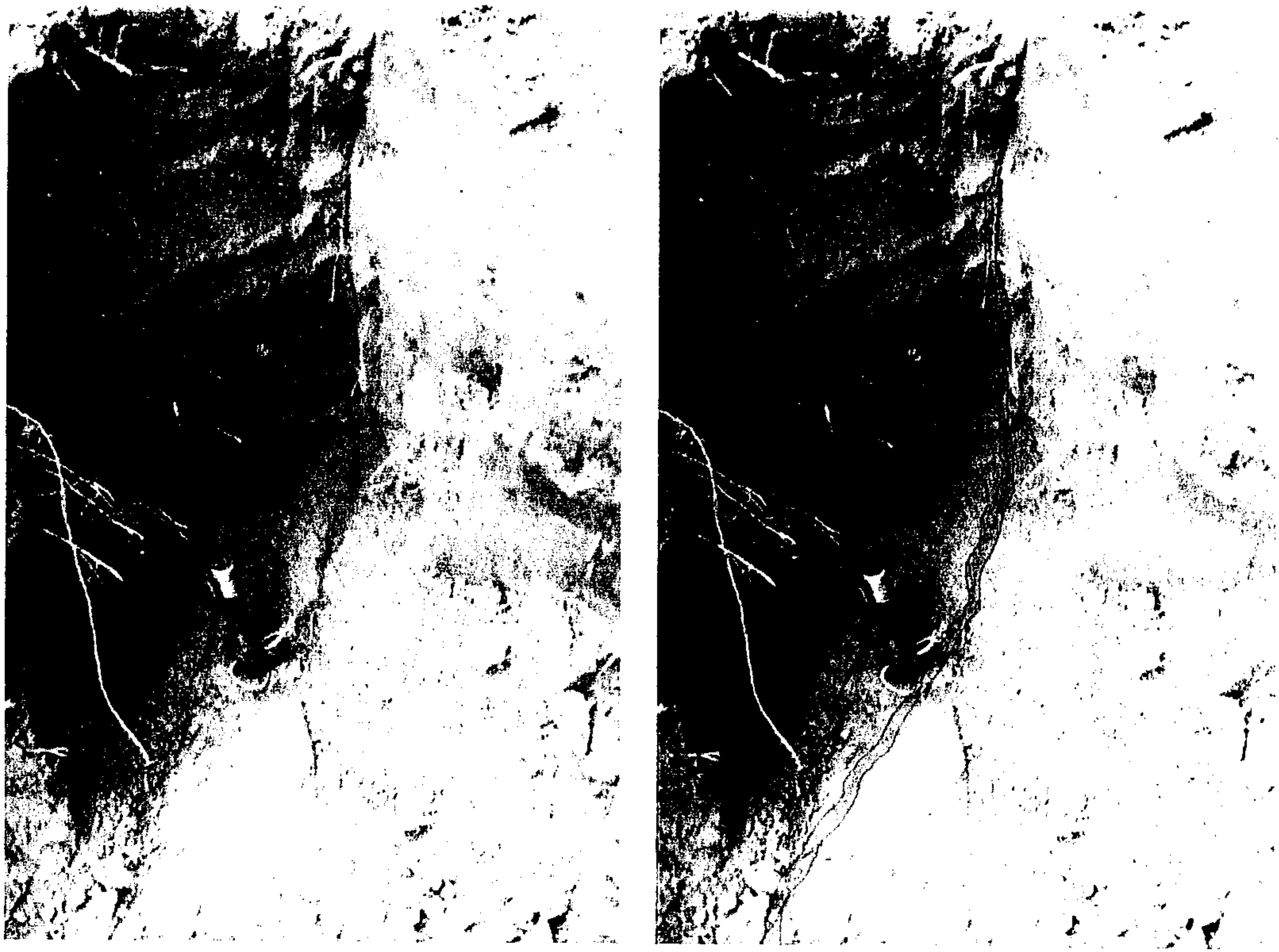

Figure 3.5: Small sand dike intruded into overbank silt in a hand excavation of the bank of the Río Cascajal, near Portobelo Site L7 on Figure 3.4). Photo on right shows the dike highlighted in color. The dike was discontinuous and did not penetrate the surface in our small excavation. No context for establishing the date of dike intrusion was found. Although time consuming, excavation in the adjacent field may yield datable materials.

In summary, it is likely that a record of paleoliquefaction exists along the Caribbean coast of Panama, but significantly more time and effort than we had allotted would be required to extensively investigate these areas.

3.3 Summary

1) The seismic network detected mainly intermediate-depth earthquakes beneath central Panama that we interpret as defining the surface of the subducted Caribbean plate beneath the Panama Block.
2) We found little evidence of prehistoric or 1882 earthquake-induced liquefaction.

4. Source 2: Río Gatún Fault

M = 6.8, Site Distance = 13 km, Slip = 0.8 m, Fault Area = 450 km^2, Recurrence Interval = 10,000 -20,000 years

4.1 Introduction

The Río Gatún fault forms the southern boundary of the Sierra Maestra highlands just east of Lake Gatún (Figure 1.2). The Sierra Maestra is the most conspicuous topographic feature in Gatún region, and the Río Gatún fault is the clearest tectonic feature in the region. Given its proximity to the dam site (~ 13 km), we (Schweig et al., 1996) recommended that the hazard from the Río Gatún fault be seriously considered and that a paleoseismological study of the fault be undertaken to determine if it was indeed active, and to estimate its rate of activity. We also expected the seismic network deployment to indicate if seismicity was occurring along the Río Gatún fault system.

The Río Gatún fault has been mapped previously by Jones (1950) and Stewart et al. (1980). Our work commenced with reconnaissance mapping of fault zones and associated rock units, guided by previous geological studies, of which the main sources were Jones (1950) and the "Geological Map of the Panama Canal and Vicinity, Republic of Panama" by Stewart et al. (1980). The Stewart et al. map represents a summary of data compiled during the 1940s through 1970s by workers whose primary interest was in the stratigraphy of the Canal Zone. Because our focus is the earthquake potential of the region, we felt it was important to reevaluate the tectonic framework in light of contemporary concepts of structural geology, sedimentology, and earthquake faulting.

We determined that the earlier mapping is deficient with respect to structural history (tectonic deformation) in the areas of critical importance to this study, which lie at the edge of the Canal Zone studied by Stewart et al. (1980). Among our discoveries in 1997 was that the region northeast of Lake Gatún has much greater structural complexity than previously indicated (Figure 1.2). One major focus of Andrew TenBrink's M.S. thesis work (TenBrink, 1999) was to sort out some of this structural complexity. One important aspect of the complexity is that the Río Gatún and related faults in the Sierra Maestra and Madden basin may not be continuous features, but rather may be broken into smaller segments. This segmentation has implications for estimation of maximum magnitudes, as faults may rupture in shorter sections. We further observed that the Río Gatún fault is dominantly a normal fault, with the area to the north being uplifted relative to the south, forming the Sierra Maestra.

4.2 Field Studies

We found that, contrary to the map of Stewart et al. (1980), but consistent with the regional Panama geological map (Dirección General Recursos Minerales de Panama, 1976) the region to the north of the Río Gatún fault consists of a sequence of sedimentary rocks, intruded by some large igneous bodies. The regional topography indicates that major faults may be present to the north of, and subparallel to, the Río Gatún fault. During our brief reconnaissance in the area north of the Río Gatún fault we noted at least one very broad (tens of meters wide), intensely sheared fault zone trending obliquely to the Río Gatún fault (Figure 4.1). Further investigation of the large escarpment to the north of the Río Gatún, particularly north of the Río Gatún Valley, was beyond the scope of this study.

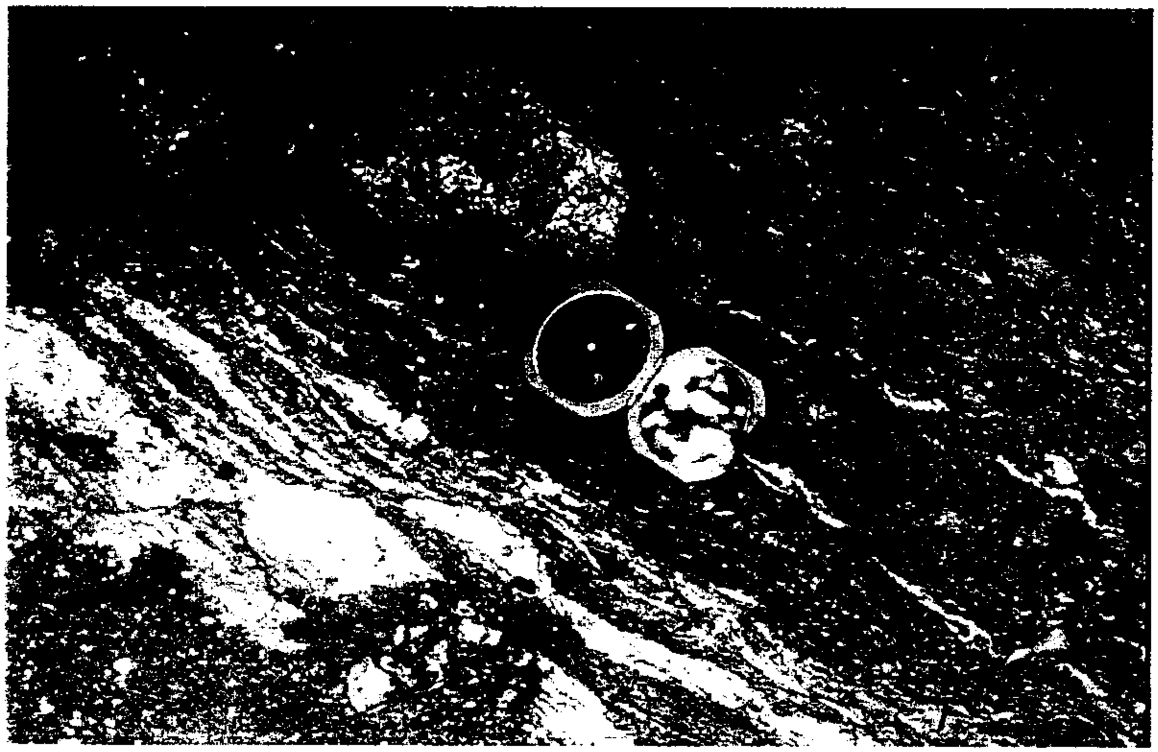

Figure 4.1: Close-up of intensely sheared rock in a fault zone parallel to and north of the Río Gatún fault, just south of "topographic escarpment" in Figure 1.2.

We were fortunate in that the Río Gatún fault was well exposed in numerous streams crossing the southern Sierra Maestra front. We excavated trenches along the Río Gatún fault zone and found no evidence of recent fault activity. Exposures of the fault zone in numerous streams and quarries revealed zones of intense shearing, indicative of significant movement. However, in all cases, these shear zones appeared to be strongly lithified, suggesting that the fault zones are currently much less active than in the geologic past (Figure 4.2).

Figure 4.2: Brecciated and relithified rocks in the channel of Río Gatuncillo, at the east end of the Río Gatún fault.

At the east side of Cerro Bruja (CB in Figure 1.2) and the Sierra Maestra, a north-northeast-trending fault zone may control the channel of the Río Boquerón. If so, it has important implications for maximum magnitude possible on the Río Gatún fault, as it may break the Río Gatún fault into shorter segments. Field observations suggest that the Río Gatún fault itself is dominantly a normal fault, with the area to the north being uplifted relative to the south, forming the Sierra Maestra. This observation is in contrast to earlier studies that had considered the Río Gatún to be a right- or left-lateral strike-slip fault with horizontal motion (e.g., Mann and Corrigan, 1990). We have observed one important exposure of the actual fault surface in a quarry, with kinematic indicators showing clear dip-slip fault motion (Figures 4.3 and 4.4). We have observed a broad fractured zoneassociated with the fault in many stream valleys crossing the fault.

Figure 4.3: Exposure of Río Gatún fault in quarry along the fault escarpment, which rises sharply from low topography 3 km north-northeast of Buena Vista, the nearest township on the Panama-Colon highway. Weathered Tertiary sedimentary rocks on the right have moved down relative to the older, less weathered rocks on the left. Note man for scale in center of photograph. Site marked as GQ1 on Figure 1.2.

Two trenches excavated along the fault zone at one site (Figure 4.5) also displayed normal faulting, but no age information could be obtained. Organic material is poorly preserved in the deeply weathered soils that overlie the Río Gatún fault zone, and there seems to be little deposition and preservation of sediments along the fault. Thus, there are few localities where faults might be observed breaking the youngest sediments. Finding the environments that will preserve paleoseismological data may entail a more detailed survey of the fault than the timing of this project has allowed. A number of observations, however, suggest that the Río Gatún fault is less active than we previously thought.

Figure 4.4: Exposure of Río Gatún fault plane in same quarry as Figure 4.3, showing striations indicating down dip normal fault motion. Hammer is for scale, not orientation.

First, no evidence for recent faulting has been documented in the excavations. All faults we observed in the basement rocks displayed shear zones are strongly lithified, indicating faulting that could be tens of thousands of years old. Second, in our trenches and in exposures adjacent to the stream valleys, alluvial deposits that overlie the Río Gatún fault are highly weathered to a depth of 5 meters or more. Although the age of these deposits is unknown, alluvial deposits that have been dated at 10,000 years from a region of similar climate in western Panama show much less intense weathering (Cowan et al., 1997). Third, we have not observed offsets in any of these weathered alluvial deposits nor in younger ones along the active stream channels.

Other observations suggest that even the long term rate of uplift across the Río Gatún fault is slow. The Río Gatún fault and the Río Boquerón structural depression bound the south and east margins of the Sierra Maestra, respectively. Both fault zones evidently controlled the uplift of the mountains, which are composed of pre-Tertiary (>65 million years) basement rocks, tilted to the northwest. Marine sediments of late Miocene age (11-8 million years) unconformably overlie the basement rocks on the western flank of the Sierra

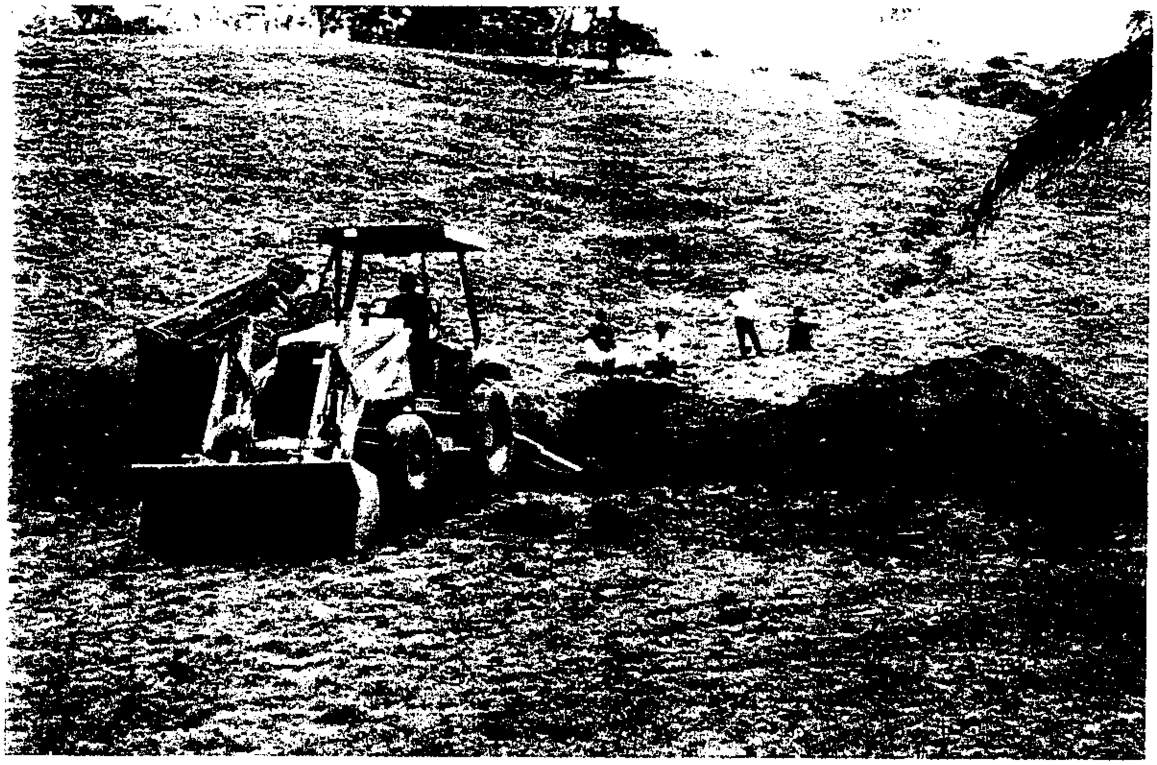

Figure 4.5: One of two trenches excavated across Río Gatún fault, about 12 km east of Panama-Colon Highway. View towards north up the steep frontal scarp at foot of Sierra Maestra. Note that even at 4 m depth, spoil is all intensely weathered soil. Location is GT1 on Figure 2.1.

Maestra (Stewart et al., 1980), implying that the Sierra Maestra had been partially uplifted and stripped of its Tertiary sediment cover prior to the late Miocene. A minimum long-term uplift of about 900 m in 10 million years may be inferred from the topographic offset across the Río Gatún fault, indicating a maximum long-term uplift rate of 0.1 mm/year (10,000 years to accumulate 1 m of displacement).

These observations appear to contrast the impressive topographic escarpment at the front of the Sierra Maestra. However, little is known about the rates of erosion of fault scarps in tropical environments. During all but the most recent part of their history, this escarpment was armored by a thick rainforest canopy, which likely prevented intense regional erosion of the scarp despite intense rainfall. The development of the thick weathering mantle on the alluvial deposits supports the idea that removal of material between streams may have been very slow, even while erosion within the stream channels was very rapid.

4.4 Evidence from Network Deployment

As discussed earlier, only 64 earthquakes were reliably located during the period of the study and, of these, only three occurred at shallow crustal depths. Two of these shallow earthquakes are located southwest of Lake Madden (station SL, Figure 3.1) and may be associated with the Gatún fault system. The lack of seismicity over such a short period is not sufficient information to make any definitive statement about the activity of the Río Gatún fault, but is consistent with the argument that it is not very active.

4.5 Summary of Results

Our review of literature and analysis of the local and regional stratigraphy indicates that the present topography and structural framework of central Panama reflects tectonic uplift and deformation during the last one to three million years. The lack of clear evidence of recent fault movement (last 10,000 years) along the Río Gatún fault implies that the rate of deformation there has slowed dramatically. As discussed in Schweig et al. (1996), faulting along the Caribbean coast west of Gatún Dam appears to be younger.

Our field studies focused on constraining the timing of significant deformation, through analysis of local stratigraphy, and on identifying the geometry and kinematics of the major faults. This information is critical to the evaluation of long term seismic hazard (maximum magnitudes), to the analysis of local microseismicity recorded on the seismic network, and to the interpretation of seismic reflection data collected for this project.

5. Source 3: Caribbean Coast Faults near Gatún Dam

M = 5.0-6.0, Site Distance = 2 km, Slip = 0.2-0.5 m, Fault Area = 12-100 km^2, Recurrence Interval = 200 -2,000 years

5.1 Introduction

It was recognized in the earliest phases of this project that, if they could be shown to be active, even small faults near or under the dam site could pose a hazard to the dam site. This and the fact that the areas of concern are almost entirely underwater were the rationale for sub-bottom profiling of Gatún Lake and Limón Bay in 1996 and 1997. The objectives of the seismic reflection profiling were to determine whether or not shallow faults lie beneath or near Gatún Dam and if so, the age of motion on any of these faults. The 1997 seismic reflection profiling consisted of a grid of closely spaced (1500 feet apart) marine seismic profiles in southeastern Limón Bay (Figure 5.1) to determine the trends of the

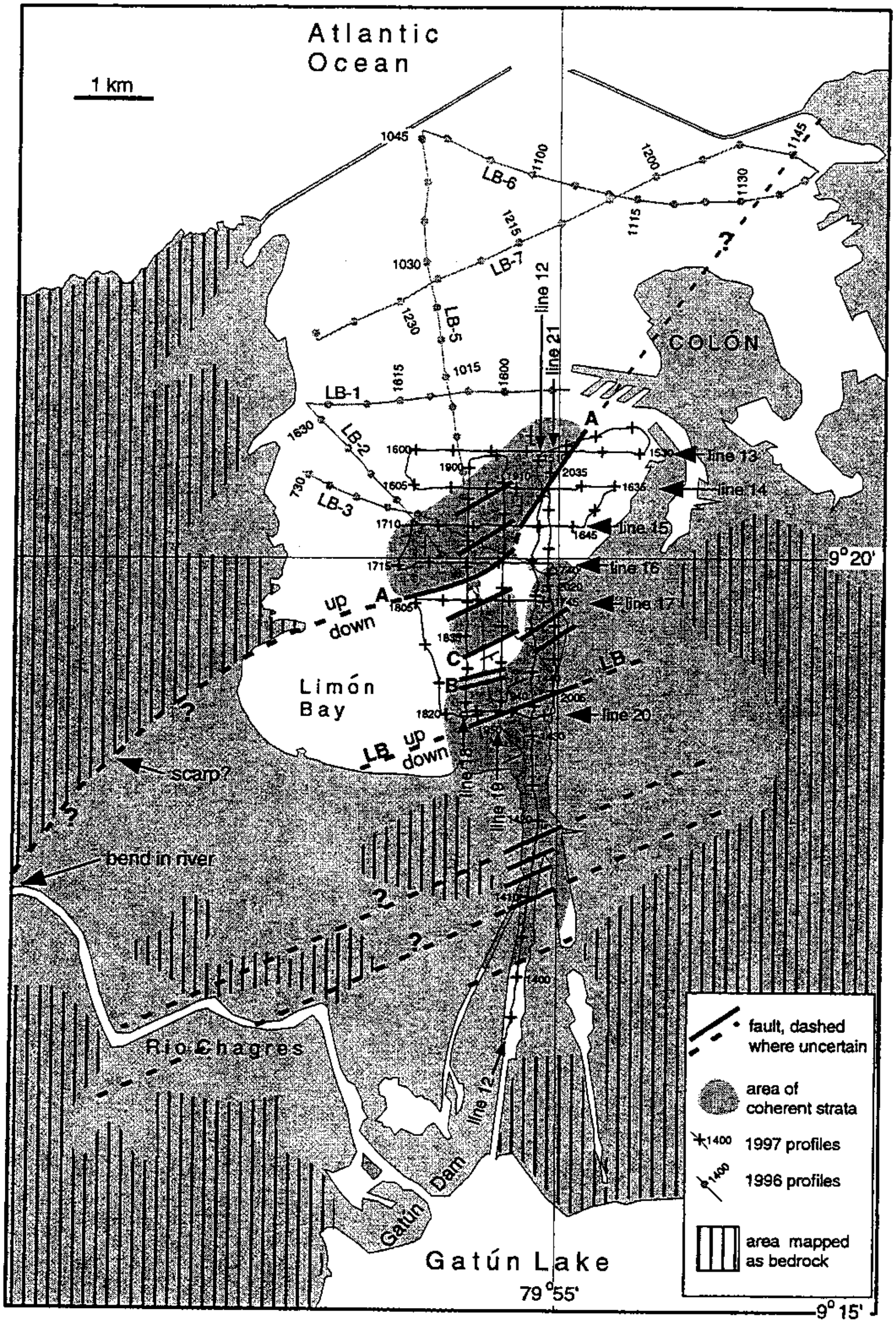

Figure 5.1: Map of Limón Bay showing the interpretation of features seen on the marine seismic reflection profiles. Faults that are visible on more than one seismic profile have a northeast trend; some faults align with bends in the river and with the edges of exposed bedrock if a northeast trend is assumed. The trends of many faults are unknown. A, B, C and LB are discussed in the text.

faults imaged there in 1996. Specifically, we sought to determine whether any of the faults have a trend that indicates they extend beneath Gatún Dam. We also acquired three land seismic profiles along the center of Gatún Dam and another land profile perpendicular to the dam just west of the spillway to determine whether faults lie directly below the dam. In addition to the profiling, we examined pre-dam topographic maps of the Gatún area and descriptions of boreholes from Gatún Dam to interpret the strata we imaged beneath the dam.

Details of this work and the actual seismic sections are given in Schweig et al. (1996 and 1998) and in Pratt et al. (1996, 1999). The following sections largely describe data from the 1997 campaign.

5.2 Limón Bay

A map summarizing our interpretation of faults beneath Limón Bay is shown in Figure 5.1. Limón Bay is underlain by sedimentary strata that dip to the west or northwest at 10 degrees or less. The strata consist of parallel beds that can be traced for up to a km, but are broken into coherent blocks by individual faults or by multiple faults in disrupted zones up to 500 m wide.

The horizontally bedded strata are most likely middle Miocene (11.8 to 8.3 million years old) Gatún Formation. Outcrops surrounding Limón Bay are mapped as Gatún Formation at sea level, overlain above sea level by the Toro Limestone and Chagres Sandstone. Southeast of Limón Bay, outcrops are composed entirely of Gatún Formation. The top of the bedded sequence is an erosional unconformity, above which are horizontally bedded silts and muds that are likely the same age as the Atlantic muck. In the south part of Limón Bay these muds form small, shallow ponds of sediment between bedrock knobs or ridges. We speculate, but cannot prove, that these muds were deposited at the same time as the upper layers of the 9000 to 6000 year old Atlantic muck that lie at the same elevation in the channels beneath Gatún Dam. As sea level rose after the last glaciation (about 15,000 years ago), the rising water probably deposited the muds.

5.2.1 Faults

There are numerous reflector truncations and offsets indicative of faults beneath Limón Bay and beneath the channel from Gatún locks to the bay. Faults are evident both as individual faults and as deformed zones that probably contain several faults. Thirteen distinct faults or fault zones are obvious on the 3.3 km length of profile 18 for an average of only 250 m between faults. All of the profiles from the southern part of the bay show a similar fault density, although there appear to be fewer faults in the northwest part of the bay.

Strata on the north and west sides of the faults commonly are elevated relative to the south and east side. Some faults, however, have the south sides up. The dips of the faults are unclear from the seismic profiles, although they appear nearly vertical, because they are obscured by zones of high-amplitude, chaotic reflectors, probably caused by bubbles of gas trapped at the faults. The faults could be high-angle reverse, normal, or strike-slip faults, or some combination of these. At least one of the faults is a normal fault indicative of extension.

Only a small portion of the faults have a distinctive enough appearance to be evident on two or more profiles, and these all have northeast trends (faults 'A', 'B', 'C', and 'LB' in Figure 5.1). The strata to the north of fault A form a coherent, west-dipping block with strata downdropped 30 m or more southeast of the disrupted zone. The feature is obvious on all profiles for a distance of 3.5 km, although it is subtle on profiles 13 and 14 (Figure 5.1). The edge of this block has a trend of N11°E to N25°E beneath the south-central part of the bay, but appears to change trend to N40°E beneath the east side of the bay (Figure 5.1).

Fault A may correlate with a prominent geologic and topographic feature mapped on shore west of Limón Bay (Figure 5.1). A point of land along the west shore of the bay, a relatively straight south edge of exposed bedrock, a prominent topographic scarp and a pronounced bend in the Río Chagres all suggest a fault zone with uplifted strata on its north side. These features seen on land lie at the westward projection of fault A interpreted from the seismic reflection profiles (Figure 5.1). If so, the length of fault A is at least 8 km. If fault A extends to the north east side of Limón Bay, where our 1996 profiles showed what could be a continuation of the fault, it has a length of about 13 km but is bent beneath the bay.

In addition to faults A, B, and C on Figure 5.1, a prominent fault at the south end of the bay (the Limón Bay fault of Pratt et al., 1996) can be interpreted to have a N18°E trend from four adjacent profiles ('LB' on Figure 5.1).

Faults are visible on the seismic profile acquired in the channel between Limón Bay and Gatún locks, although the trend of these faults cannot be determined from our single profile. Four faults with relatively small vertical offsets (<5 m) are visible 1.7 to 3.0 km north of Gatún locks (Figure 5.1). Two of the faults imaged beneath the channel north of Gatún locks are also in alignment with an exposed bedrock knob and prominent bends in the Río Chagres if these faults have a NE trend (Figure 5.1). We cannot determine whether the Río Chagres has these prominent bends because it follows old, easily eroded fault zones or because active faulting has recently diverted its flow.

5.2.2 Timing of faulting

We have only two constraints on the ages of motion of all the faults visible on the Limón Bay profiles: they are all younger than 8.3 million years old and many are likely more than 6000 years old. Where the strata beneath Limón Bay are cut by faults, the equal thickness and parallel bedding of strata on both sides of the fault indicates deposition was completed before the fault formed. The age of the Gatún formation is known from fossils (foraminifera) to be 11.8 to 8.3 million years old, and the faults must be younger.

The youngest age of faulting cannot be determined on many of the faults; however, some faults visible on the seismic profiles have a layer of apparently undisturbed mud above the bedrock unconformity. Assuming the muds above the unconformity in Limón Bay are equivalent in age to the Atlantic muck sediments below Gatún Dam, the faults must be older than 6000 years. Unfortunately, mud overlies a minority of the faults visible on the seismic profiles and those faults not capped by mud could have recent faulting. We also caution that our seismic data only show vertical displacements; we cannot eliminate the possibility that a strike-slip fault with primarily horizontal motion has displaced the Atlantic muck but left little or no resolvable vertical displacement.

The only profile that shows any potential faulting of the younger sediments is profile LB-5 where a slight disruption with about 1 m apparent vertical displacement occurs in the shallowest strata (about 10 m depth) above the Limón Bay fault. We are suspicious of this apparent displacement, however, because it is very near the limit of our resolution and a nearby profile across the Limón Bay fault does not show clear evidence of faulting. The Limón Bay fault could thus have been active within the past 6000 years, but the evidence is ambiguous.

Although we cannot document recent earthquakes on any of the faults beneath southern Limón Bay, they nonetheless form weaknesses that could rupture in an earthquake. The low numbers of earthquakes in this part of Panama and the lack of obvious features on our seismic data indicate most of the shallow faults are inactive or have very long intervals between earthquakes. However, the subduction zones bounding Panama provide obvious sources of stress and the Panama block is probably undergoing at least some internal deformation in response to its active tectonic setting. We conclude that earthquakes on these shallow crustal faults are likely, but our lack of positive evidence of recent motion (and the lack of geologic evidence) suggests they rupture infrequently.

5.2.3 Earthquake magnitudes

Earthquakes on shallow faults beneath Limón Bay likely would be small to moderate in size. Our data indicate that at least one fault 8 to 13 km in length lies beneath Limón Bay about 8 km north of Gatún Dam (fault A in Figure 5.1) and other faults probably have comparable lengths. There does not appear to be a pronounced topographic scarp extending for more than this distance around Limón Bay, so it is unlikely that any of these faults have lengths comparable to the ~30 km length we estimate for the Rio Gatún fault (Chapter 4). The global compilation of earthquake magnitudes and fault lengths in Wells and Coppersmith (1994) indicates a fault 8 to 13 km long can be expected to generate M5.0 to M6.0 earthquakes. We thus feel that a M5.0 to M6.0 earthquake is a reasonable estimate for the maximum size of events on these shallow faults.

We have no reliable way to estimate the recurrence interval of earthquakes on shallow faults near Gatún Dam. Seismometers have not been operating long enough in the Gatún area to provide a good estimate of the rate of shallow seismicity. The seismicity rate has definitely been low over recorded history (Camacho and others, 1997) and we see no direct evidence of active faulting, so we must assume the time interval between earthquakes is relatively long. We suggest a recurrence interval of about 200 years for a M5.0 earthquake and 2000 years for M6.0 events near Gatún Dam based on our limited data on the Rio Gatún fault (~10,000 to 20,000 year recurrence interval for M6.8 earthquakes) and assuming a reasonable Gutenberg-Richter distribution of magnitudes with a b-value of 1.0.

5.3 Gatún Dam

Faults are likely present beneath Gatún Dam. The profiles from southern Limón Bay show faults about 250 apart on average, and the profile just north of Gatún locks shows 4 faults within 3 km of the locks. One of our 1996 profiles shows a fault to the south of the dam, beneath Gatún Lake. This high density of faults near the dam indicates that faults likely lie beneath the ~2.2 km length of Gatún Dam. Furthermore, the Limón Bay profiles show that the faults are almost all overlain by channels or depressions in the bedrock surface, presumably caused by erosion of the fractured rock in the fault zone. The two deep channels beneath Gatún Dam may also have formed in fractured rock within a fault zone.

We looked for three features indicative of faulting on our profiles: 1) strata that show a vertical displacement across the fault zone, 2) an erosional notch or valley in the bedrock surface above the fault; and 3) arcuate diffractions caused by energy being scattered from the edges of the faulted strata. To confidently interpret a fault we require clear evidence of displacement plus one of the other features.

5.3.1 Borehole profiles and age dates

Numerous boreholes exist in Gatún Dam, and Figure 5.2 shows contrasting interpretations of the material beneath the dam compiled from this borehole information. The cross sections are both valid interpretations, given the information available at the time they that were made. The profiles show the same major features: the dam consists of dry and hydraulic fill sitting atop buried channels filled with muds, silts, and sands of the Atlantic muck. Bedrock is most likely the Gatún formation that is exposed in the surrounding hills. The upper cross section assumes no faulting - all changes in the depth to bedrock are assumed to be caused by erosion, and it assumes the Atlantic muck consists of layered muds, silts and sands deposited in old river valleys. The bottom cross section assumes that the river channels are fault-bounded, with faulting continuing during deposition of the lowermost layers of Atlantic muck (otherwise erosion would have removed the sharper topography). The lower cross sections make the point that the deeper channels could be caused by recently active faults that could rupture in the future.

Radiocarbon dates indicate that much of the Atlantic muck is between 9000 and 6000 years old. We obtained 9 radiocarbon (carbon 14) age dates on samples taken from cores penetrating the Atlantic muck beneath Gatún Dam. Figure 5.2 shows the approximate locations of the samples on the cross section. Five of the samples were taken from the middle or lower part of a channel and four of the samples were taken near the top of the Atlantic muck. The entire lower group of samples had ages between 9005 and 7655 years before present. Samples from the upper group were all between 6735 and 5895 years before present. Thus the bulk of the Atlantic muck is between 9000 and 6000 years old and most likely was deposited as sea level rose after the last glaciation about 15,000 years ago.

5.3.3 Reinterpretation of 1996 marine profile GD-3

We obtained marine seismic reflection profiles in Gatún Lake very near the shoreline at Gatún Dam in both 1996 and 1997 (Figure 5.3). The best profile, GD-3 from 1996, showed that the west part of the dam is underlain by acoustically transparent material, below which were three strong, nearly parallel reflectors. The borehole information indicates that the three parallel reflectors are most likely the top of an ~8 m-thick layer of overburden (soil?) at the base of the Atlantic muck (top reflector), the top of an ~8 m-thick layer of weathered bedrock beneath the overburden (middle reflector), and the top of solid bedrock at the base of the weathering (bottom reflector).

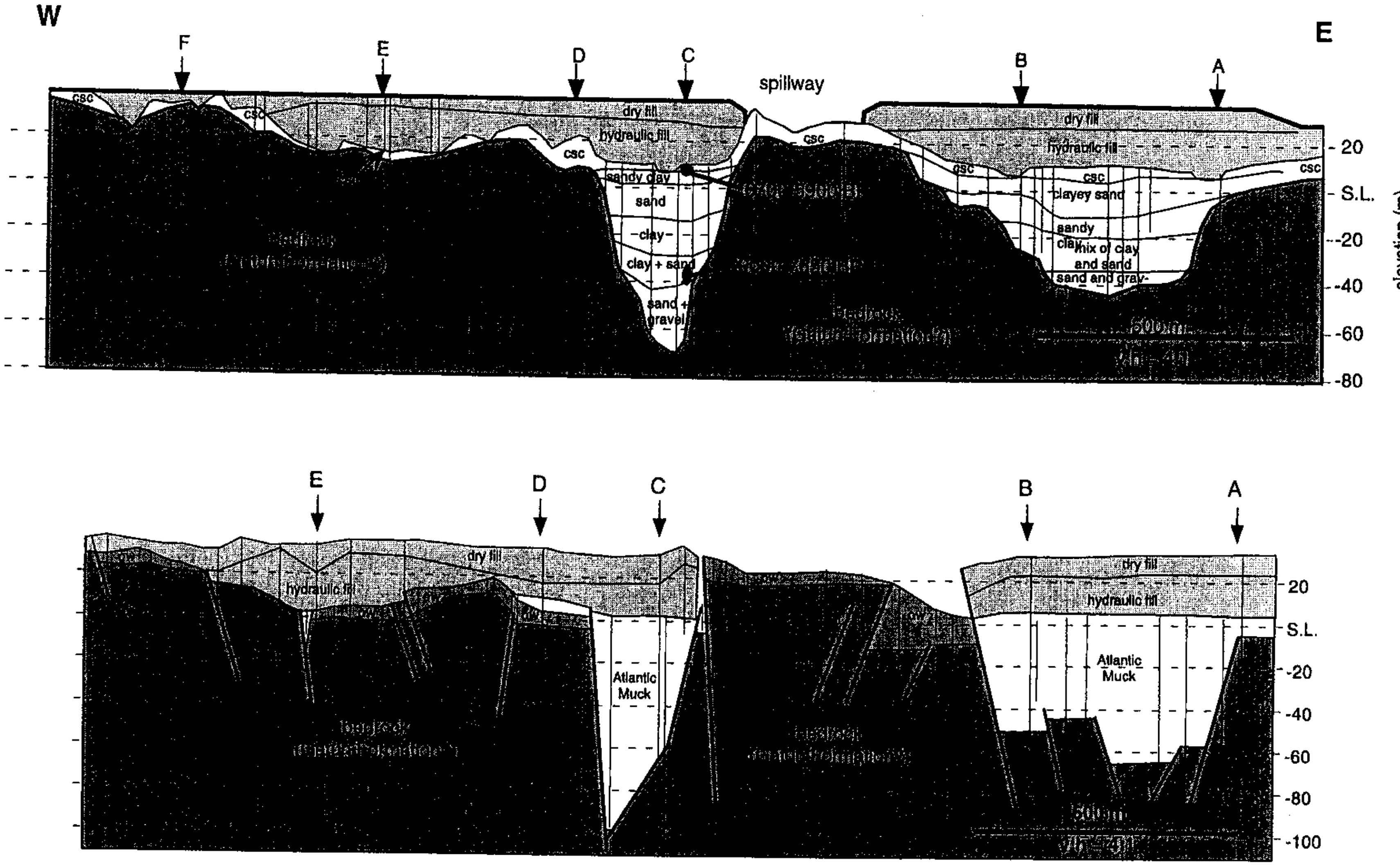

Figure 5.2: Cross sections along the crest of Gatún Dam made from borehole logs, with two contrasting interpretations. The section on top, created for this strudy, assumes no faulting - all changes in depth to bedrock (Gatún Formation?) are interpreted to be caused by erosion. Cross section on the bottom (P. Franceschi, PCC) assumes that many of the changes in depth to bedrock are caused by faults (heavy lines). The letters at the top are the locations of perpendicular cross sections (figure 5.3) and the light vertical lines are the locations of boreholes used to construct the profile. The shaded ovals beneath the 'C' in the top profile are the approximate locations of samples with the range of carbon-14 age dates shown. csc=clay, sandy clay; ow=overburden and weathered rock. The locations of the two cross-sections are not identical, nor are the boreholes used. Vertical scale is elevation in meters.

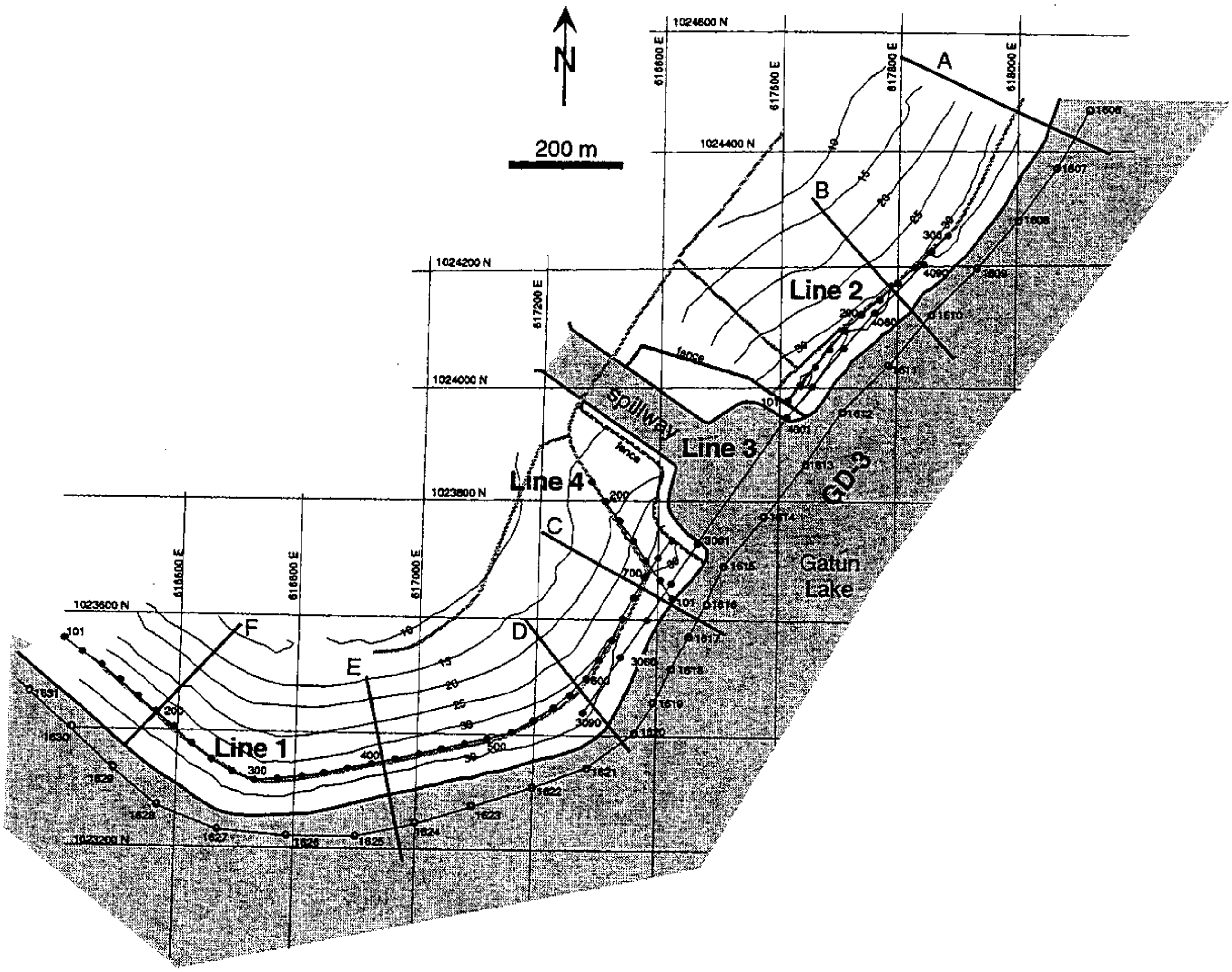

Figure 5.3: Map of Gatún Dam showing the locations of the seismic reflection profiles. The marine profile (GD-3) is the best of the 1996 and 1997 profiles. For the marine profile the dots show the location of the boat at 5 minute intervals; for the land profiles the dots show station locations (every 20th station) with station number marked. The lines with the letters next to them are the locations of borehole profiles; the borehole profile along the length of the dam is located near seismic lines 1 and 2. Shaded lines are roads; shaded region is water.

The old bedrock surface may be faulted near the west end of profile GD-3; about 200 m west of Gatún Dam. The three reflectors appear to be displaced by about 3 to 5 m, with the layers on the east lower than those to the west. A valley in the bedrock surface or diffractions are not present. We cannot prove this apparent displacement is due to faulting rather than just being a steep topographic surface, but a fault is certainly a reasonable interpretation. If it is a fault, it displaces the bedrock surface beneath the Atlantic muck and motion must be about 6000 years old or younger. Aside from this one fault, profile GD-3 does not show any compelling evidence for faults beneath the dam west of the spillway. Continuous layers preclude faulting with a vertical component of displacement beneath the western 400 m the dam and across about 200 m of the deep channel just west of the spillway.

Borehole information indicates that the prominent fault we interpreted earlier just west of the spillway (Pratt and others, 1996) is *not* present: there appear to be two different reflectors rather than a single reflector that has been faulted.

Profile GD-3 provides little information on faulting beneath the east part of Gatún Dam between the spillway and Gatún locks. Energy penetration beneath the east part of the dam was too weak to image any layers.

5.3.4 Profiles along Gatún Dam

To further investigate the subsurface beneath Gatún Dam we acquired a profile along the crest of the dam for most of its length (lines 1, 2, and 3), and we acquired a perpendicular profile (line 4) near borehole cross section 'C' (above the deep channel - Figure 5.2).

The profiles along the dam allow us to preclude faults along the western 500 m of the dam, but across most of the rest of the dam the profiles were inconclusive for several reasons. First, imaging through Gatún Dam proved difficult, with little energy getting below the bedrock surface and even the bedrock not being evident in places. The profiles show only weak reflections from within Gatún Dam. Reflections from layers within the Atlantic muck are visible only from the deepest channels. The top of the bedrock surface was well imaged beneath much of the dam, but reflectors within the bedrock are visible for only short distances at a few locations. Second, the bedrock surface is rough. There are numerous, abrupt changes in depth to the bedrock surface that could be formed by either erosion or faulting. Vertical displacement of the top of bedrock is thus not necessarily indicative of faulting, and other evidence must be found.

Our profiles along Gatún Dam west of the spillway thus indicate a possible, young fault about 200 m west of the dam, preclude faulting beneath the western 500 m of the dam, but are inconclusive for the 600 m just west of the spillway. It is encouraging, however, that the profiles across Gatún Dam just west of the spillway, above the deepest channel, do not show any obvious faulting.

A part of the imaging process, we measure the speed of sound through the materials we are imaging. The accuracy of these measurements is about 10% to 15% of the speed. Our profiling indicates the dry and hydraulic fill within Gatún Dam has an acoustic velocity of about 800 to 1000 m/sec, the Atlantic muck has a velocity of about 1500 m/sec, and the bedrock (Gatún Formation) below the dam has a velocity of about 2000 to 2200 m/sec.

5.3.5 East of the spillway

Line 2, east of the spillway, shows that there are no large (20 m), fault-bounded steps in the bedrock surface as depicted in the lower cross section in Figure 5.2. Rather, the bedrock surface slopes gently downward with relatively minor variations in depth. Unfortunately, the bedrock surface is too rough for us to determine whether some of the variations in depth to bedrock are due to erosion or faulting. There are several places where the Atlantic muck reflectors show disruptions that could be due to faulting, but we caution that these are in old channel deposits in which the river could cause truncations.

One line of evidence does suggest that faults are likely present only beneath the deepest channel on profile 2. Almost all of the faults visible in the Limón Bay profiles lie below depressions in the bedrock surface probably caused by erosion of the fractured rocks in the fault zone. The depressions are generally 50 to 100 m in width and 5 to 10 m in depth. There are two locations where such depressions might lie beneath profile 2. Thus, we see no direct evidence that faults are present, but we cannot eliminate the possibility that active faults underlie the east side of the dam.

5.4 Conclusions.

On the basis of seismic reflection profiling is southern Limón Bay and near Gatún Dam we conclude:

1. Numerous, northeast-trending faults are pervasive beneath the channel from Gatún locks to Limón Bay and beneath Limón Bay 2 to 8 km north of Gatún Dam. The 8 to 13 km length of one of these faults indicate they are probably capable of generating M5.0 to M6.0 earthquakes. The faults we imaged have had Miocene (8 to 11 million years old) motion, but we cannot constrain the age of most recent motion on many of these faults. The relatively low seismicity rate in this part of Panama, the lack of definitive evidence of recent fault motion, and the lack of geologic evidence for recent faulting suggests earthquakes are relatively infrequent near the dam.

2. Although we can preclude the presence of active faults beneath the western 500 m of Gatún Dam, a young (6000 years or less) fault may be present about 200 m west of the dam. Our data are inconclusive about faulting beneath much of the rest of the dam because the bedrock surface has many variations in depth that could be due to either erosion or faulting. We did not find any direct evidence of active faults beneath the dam, but we cannot eliminate that possibility.

3. Despite the lack of direct evidence for or against faulting beneath the dam, the approximately 250 m average distance between faults in southern Limón Bay and 2 to 3 km north of Gatún locks, is strong indirect evidence that there are likely faults directly below the 2.2 km expanse of Gatún Dam.

6. RECOMMENDATIONS

In this section we highlight some of the most significant uncertainties still remaining with respect to earthquake hazards to the Gatún Dam and other critical Canal facilities. We recommend various future investigations that would reduce these uncertainties, and in some cases provide brief descriptions of the time and effort required to carry them out. These recommendations begin with uncertainties pertaining to earthquake effects, followed by those relevant to earthquake source characterization. Both types of uncertainties impact the accuracy of seismic hazard evaluations.

6.1 Earthquake Effects

Is amplification of earthquake ground motion at the Dam and other critical facilities likely? If so, at what frequencies and thus for what earthquake sources, will it be most significant?

We recommend both a short-duration field study and modification of the strong motion instruments currently installed on Gatún Dam. Both of these should provide 'ground truthing' of modeled site response. While such modeling is appropriate, it cannot account for potentially significant 3-dimensional effects (e.g., focusing due to topographic or basin structure) or for true non-linearities. We recommend a short-term field study to constrain the former. Such a study utilizes measurements of microtremor (noise) and earthquake ground motions made in the vicinity of the Dam. Such measurements may be analyzed using a variety of standard and well understood techniques. A few test measurements were made in April, 1998. Preliminary analyses of these data illustrate that a significant amount of site response data can be gathered with minimal effort (e.g., the measurements at seven sites were made in a single day).

Accurate quantification of non-linear effects really requires in situ measurement of strong ground motions. However, 'strong' may be a complex function of source distance and rupture characteristics, coupled with the site response. To improve the likelihood of defining the thresholds at which non-linearities become significant we recommend reducing the triggering threshold of strong ground motion instruments currently operating on Gatún Dam.

What is the tsunami and seiche potential?

The 1882 earthquake in the NPDB produced a tsunami that drowned 60 people in the archipelago of San Blas. Several other historical earthquakes in the western part of the NPDB have also generated tsunamis: in 1798, 1822, 1916 and 1991 (Acres International, 1982; Camacho and Viquez, 1993; Camacho 1994). The event of 1822 was reportedly associated with liquefaction and tsunami inundation as far north as the Mosquito coast of Nicaragua (Roberts, 1827; Gonzalez Viquez, 1910). The potential for a tsunami caused by a shallow earthquake in the northern Panama Deformed Belt must be regarded as high. The potential impact of a tsunami (or seiche in Lago Gatún) at the Canal installations is unknown and would require detailed hydraulic modeling. A historical database of tsunamis along the Caribbean coast has been recently been published and may be used as a guide to assess the probability of tsunami-generating earthquakes and to define their characteristics. This information, and offshore bathymetry maps, may be used as inputs to a number of computer modeling programs. Thus, such a study requires no fieldwork, utilizing existing data and analysis tools.

6.2 Earthquake Sources

Is the spatial seismicity pattern observed, and thus are the seismogenic processes inferred, temporally stationary?

The regional geology and the distribution of earthquakes recorded in this study are generally consistent. In particular, the paucity of earthquakes at any depth within the Isthmus west of Lake Madden and the Sierra Maestra corroborates the low deformation rates inferred from the geologic structure. However, while the cluster of deeper earthquakes to the east is probably related to subduction of the Caribbean plate beneath the Isthmus, an explanation for the sharp shut-off of this activity to the southwest remains a mystery. The simplest explanation is that the spatial clustering of seismicity reflects only temporal clustering, and would become less so with time. However, all previous reports of intermediate-depth seismicity are restricted similarly to the region of San Blas and eastern Panama, east of the Canal Zone (Adamek et al., 1988; Toral, 1998). This question can only be resolved by accurate monitoring of the local seismicity over a longer time period.

We recommend augmenting the UPA network of permanent seismographs as the most efficient means of lengthening the seismicity record. The present distribution and number of UPA stations in central Panama is insufficient to resolve accurate hypocenters in the Canal Zone area and its surroundings. As explained in Schweig et al. (1998), the accuracy of earthquake locations and mechanisms is a function of the spatial density of recording stations and their azimuthal distribution. We therefore recommend the deployment of at least six new, permanent seismographs in the area covered by our network. This would significantly improve the quality of information about seismic activity in this region.

Is the inferred spatial distribution of deformation consistent with how stress is accumulating?

Additional, structural and neotectonic mapping could establish the detailed geometry and kinematics of long-term deformation. The rates and location of contemporary deformation accommodated by the geological structures could be quantified using Global Positioning System (GPS) geodesy. GPS is a satellite-based positioning system that allows centimeter-scale geodesy to be performed with low-cost portable receivers. Strain anomalies could delineate individual structures undergoing deformation and could thereby help guide future paleoseismological studies. Repeated geodetic measurements with GPS provide direct measurements of displacements due to Earth deformation on a time-scale of a few years. GPS measurements have been made to determine plate motions and regional crustal deformation in Central America and northern South America. Those studies have shown that Panama behaves essentially like a rigid block, moving northward relative to the Caribbean plate and eastward relative to the northern Andes. The spacing between observations, however, is very wide (>500 km) so shorter-wavelength strain anomalies that may exist due to local faulting are not resolved.

We recommend installation of a GPS geodetic array, spanning the Panama isthmus and extending west to the Azuero Peninsula, east to the Bayano region of eastern Panama province, and south to the Pearl Islands. This array would be of sufficient extent and density to monitor both the rate and distribution of tectonic strain across the isthmus. GPS measurements would provide a powerful tool for studying the relationship between the earthquake cycle and large-scale plate motion across the isthmus. This is because the time window imaged by the GPS measurements is intermediate between the individual earthquakes recorded by seismic networks, and the geological displacements that accumulate over hundreds or thousands of years.

How is subduction accomplished and how does this process vary spatially? What is the precise geometry and dimensions of structures associated with subduction of the Caribbean beneath Panama?

Despite significant advances in knowledge of the major plate boundaries around Panama during the last 5-10 years, we still know very little about the 3-dimensional deep structure and how this contributes to seismic hazard. Limited seismological evidence of subduction of the Caribbean plate has been documented from the eastern provinces of

Panama and San Blas, and of the Nazca plate beneath Chiriquí and the Azuero Peninsula. There are large areas intervening, including much of central Panama, for which few data are available to illuminate the deep structure. Previous studies of volcanic rocks indicate that large slices of oceanic crust have been thrust beneath the Caribbean and Pacific margins of the Panama isthmus, and our seismic network data have revealed for the first time, the presence of probable subducted Caribbean plate beneath the Canal Zone. What is lacking is a unifying model to explain how the known plate boundary structures, e.g. the North and South Panama Deformed Belts, interact and terminate at depth. These questions are relevant to the characterization of seismic sources because sharp changes in the geometry of structural elements are commonly associated with stress concentrations and the nucleation of large earthquakes.

We recommend a study of the deep structure of Central Panama, utilizing marine seismic reflection techniques and imaging between depths of 30-70 km extending from 100 km south of the Pacific entrance of the Canal, to about 120 km north of the Caribbean entrance. The 30-70 km depth is enough to image the subducted Caribbean plate, thus providing insight into what happens to faults deep in the crust, and which faults may be most active. Additional profiles could be acquired parallel to the Pacific and Caribbean coasts, to construct a 3-D model and test further for the existence of the Canal Discontinuity. Thus far, we find no evidence to support the existence of a Canal Discontinuity.

What is the dominant sense of motion on crustal faults, particularly those most evident in the geologic record, east of the Canal?

Our work has shown that there is much greater structural complexity to this region than previously reported. A better knowledge of the existing faults, their ages and kinematics, and an understanding of the regional stratigraphy and structural geology would improve our ability to estimate seismic hazard in the region. This would require structural and neotectonic mapping of the area north and east of the Canal, incorporating existing published and unpublished data collected during recent years by Canal Commission staff and others. Such work may be of considerable importance for the interpretation of crustal seismicity during future seismic network deployments, and for the understanding of the fault data collected during the seismic reflection surveys.

We know that the area east of the Canal (Sierra Maestra) was uplifted and eroded to a deeper level than adjoining areas to the west, during the last 1-3 million years. The major faults that accommodated this uplift include the Río Gatún fault and those north of the Madden Basin. Our geological investigations of the Río Gatún fault zone have revealed evidence of dominantly normal faulting (extensional strain), and a low rate of slip during the last 10-20,000 years. Both the fault kinematics and the apparent slip rate were unexpected results, based on previous interpretations, and indicate that the Río Gatún fault was more active in the past than it is today.

The pattern of faulting and associated paleostress indicators in this area should provide insight into the evolution of crustal structure and help to define its seismic potential, by constraining the fault sizes and fault orientations within the modern stress field. Although this type of analysis is relatively standard it has not been attempted in central Panama, because the area in question has never been adequately mapped. We therefore recommend that systematic structural mapping of the basement rocks be conducted to acquire the basic data needed to understand the recent structural history of the area. We also emphasize that the interpretation of geophysical studies of crustal structure and seismicity will be greatly enhanced by a structural framework of geological observations.

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APPENDIX A

Design Ground Motions for Seismic Evaluation of the Gatún Dam

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A.1 Introduction

Schweig et al. (1998) proposed three design earthquakes for seismic evaluation of the Gatún Dam, (1) a moment magnitude M 7.7 thrust earthquake located on the interface between the Caribbean Plate and the Panama block at a distance of 35 km, (2) a M 6.8 earthquake on the Rio Gatún fault at a distance of 13 km, and (3) a M 5.0 or M 6.0 earthquake on a crustal fault at a distance of 2 km. The purpose of this report is to provide design ground motions corresponding to the three earthquakes.

A.2 EARTHQUAKE ON THE INTERFACE BETWEEN THE CARIBBEAN PLATE AND THE PANAMA BLOCK

The first question that must be addressed in choosing design motions for this earthquake is whether to consider it a subduction earthquake or a shallow crustal earthquake. The answer has a large impact on the size of the motions. The International Workshop on Strong Motion Data held in Menlo Park, California, in December, 1993, concluded that there are clear differences in ground motion from different types of earthquakes. Three types were recognized: (1) subduction earthquakes, (2) shallow earthquakes in tectonically active regions, and (3) shallow earthquakes in stable regions (Iai, 1993). The first and second types are obviously the only ones to be considered for the interface between the Caribbean Plate and the Panama Block. Of these two types, subduction earthquakes give significantly larger ground motions for a specified magnitude and distance, as is shown in Figure A.1. It is true that the largest recorded ground motions have been from shallow crustal earthquakes, but those motions were recorded at distances much smaller than the smallest distances at which subduction earthquakes have ever been recorded. The North Panama Deformed Belt, which is at the boundary between the Caribbean Plate and the Panama Block, may not be a typical subduction zone, but it should be considered as such for the purpose of choosing ground motions so that the motions chosen will not be too small. The seismicity data reported by Schweig et al. (1998) support this choice. Almost all the seismicity (80-90 percent) seemed to occur below the upper plate (at crustal depths), loosely defining a dipping subduction zone.

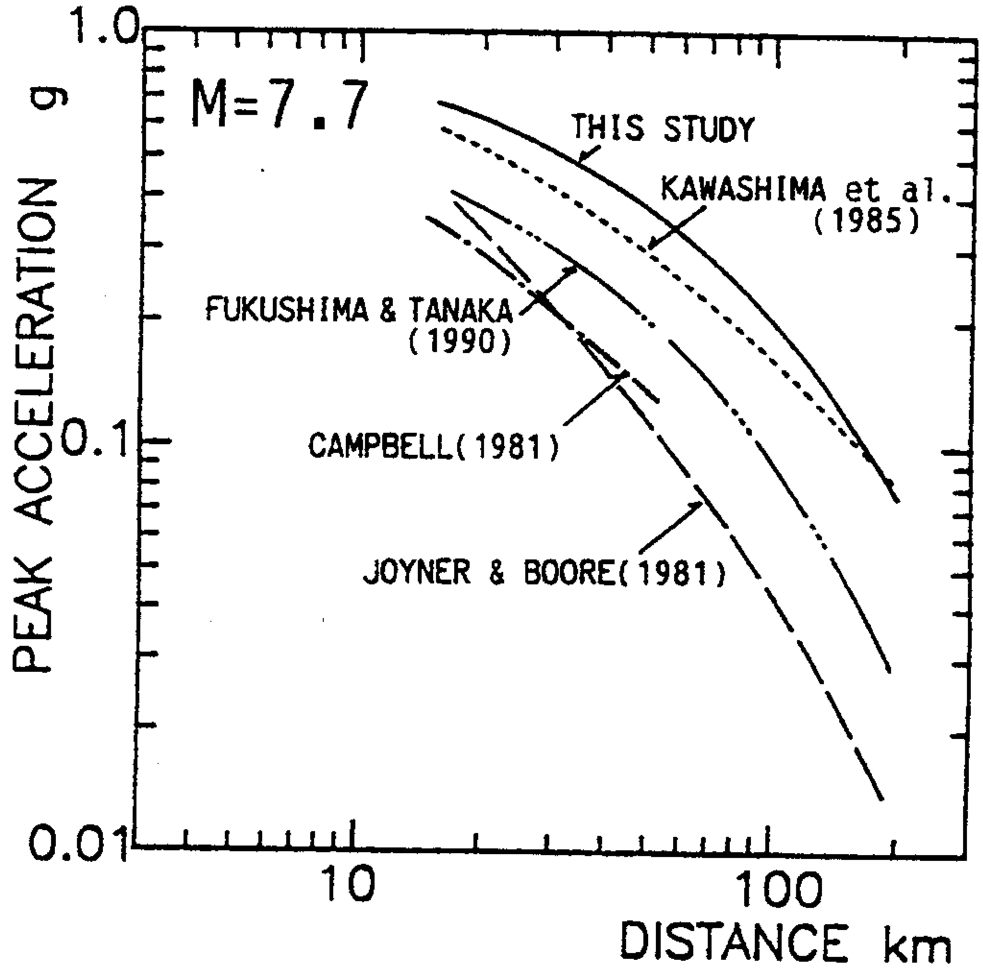

Figure A.1: Comparison of attenuation curves for subduction earthquakes (from Midorikawa, 1991). The curves marked FUKISHAMA AND TANAKA (1990), KAWASHIMA ET AL. (1985) and THIS STUDY were derived from subduction zone earthquakes; the curves marked CAMPBELL (1981) and JOYNER & BOORE (1981) were derived from shallow crustal earthquakes.

The obvious way to estimate peak ground-motion values for the earthquake at the interface of the Caribbean Plate and the Panama Block is to use one of the many attenuation relationships that have been developed for subduction earthquakes. That way is not the best way, however, because, of the dozens of earthquakes used in developing those relationships, only two with moment magnitude greater than 7.0 have multiple recordings in the distance range of interest, the 1985 Michoacan, Mexico, earthquake and the 1985 Valparaiso, Chile, earthquake. It makes sense to focus in on the data in the same magnitude and distance range as the postulated design earthquake. The 1985 Mexico and Chile earthquakes, however, have very different ground motions, as is shown in Figure

A.2. The higher values for the Chile earthquake in Figure 2 may be due in small part to the larger number of soil sites in the Chile data set compared to the Mexico data set, but only in small part. The basic reason for the difference is not clear. The best simple alternative is to chose the design ground motions on the basis of the Chile data. That choice is somewhat conservative, but to base the motions on some equal weighting of the Mexico and Chile data would be unacceptably unconservative.

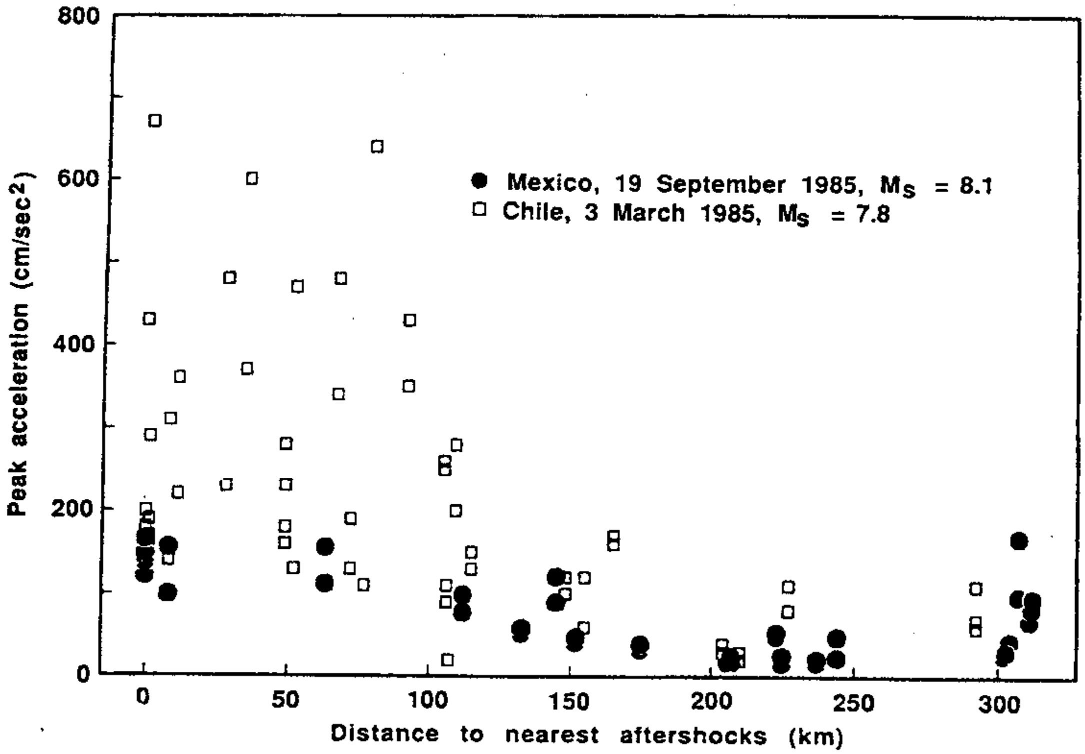

Figure A.2: Comparison of peak horizontal accelerations between the 1985 Mexico and Chile earthquakes (from Anderson et al., 1986). The distance to the nearest aftershocks is an approximation of the horizontal component of the distance to the rupture. Since the two ruptures occurred over about the same range in depth, that distance is a fair basis for comparison.

Consideration of a number of attenuation relationships for subduction earthquakes confirms that the 1985 Chile data are a better basis for choosing the design motions. Relationships by Crouse (1991) and Iai et al. (1993) cannot be used because they do not distinguish rock and soil sites. The relationship by Kawashima et al. (1986) does not have a separate category for rock sites, though it does have three site categories. There are other reasons, however, for not using the Kawashima et al. (1986) relationship. The data set upon which it is based contains only three data points within 60 km for magnitude greater than or equal to 7.0. Those three points represent a magnitude of 7.0 at distances greater than 40 km. The Kawashima et al. (1986) relationship, moreover, was developed using ordinary least squares, a procedure Fukushima and Tanaka (1990) have shown can lead to serious error. The relationship by Molas and Yamazaki (1995) is based on a data set that contains no data within 60 km for magnitude greater than 7.0. The relationship by Fukushima and Tanaka (1990) is based on a data set that includes a significant number of data points from shallow earthquakes not in subduction zones and therefore is not representative of subduction earthquakes. The relationship by Youngs et al. (1997) is based on a data set that includes 28 records from the 1985 Michoacan, Mexico, mainshock and 23 records from the 1985 Valparaiso, Chile, mainshock. That relationship will therefore give ground-motion values at the magnitude and distance of interest that are essentially an equally weighted average of the 1985 Mexico and Chile data, an outcome that Figure A.2 suggests is not appropriate.

Data from the 1985 Chile mainshock are the best basis for choosing design ground motions for the earthquake at the interface between the Caribbean Plate and the Panama Block. Midorikawa (1991) has developed an attenuation relationship based only on data from the 1985 Chile earthquake. Midorikawa's equations are

$$\log A = 1.33 + 0.26d + 0.21s - \log(x + 50) - 0.0020x \quad (1)$$

$$\log V = 3.03 + 0.17d + 0.31s - \log(x + 30) - 0.0018x, \quad (2)$$

where A is peak horizontal acceleration in g, V is peak horizontal velocity in cm/s, d takes on a value of zero at rupture-backward sites as defined in Figure A.3 and a value of one at other sites, s takes on a value of zero at rock sites and a value of one at soil sites, and x is the closest distance to the rupture in km. The values of A and V represent the larger of the values for the two horizontal components. The standard deviation of the residuals of $\log A$ is 0.15 and of $\log V$ is 0.18.

The original plan was to use Midorikawa's (1991) equations to obtain the design ground motions. Examination of the ground-motion data set in the possession of the U.S. Geological Survey (USGS) (Celebi, 1988; Campbell et al., 1989), however, disclosed significant discrepancies at two stations between the values used by Midorikawa (1991) and the values in the USGS data set. In order to increase confidence in the design ground motions, Midorikawa's analysis was repeated using the USGS data set. The coordinates of all the stations were checked and the distances to the rupture surface given by Barrientos (1988) were recomputed. All the records were examined and 4 records were excluded because of strong resonances suggestive of instrumental or emplacement problems. One record was excluded because it was located at essentially the same site as another record already in the data set. Records in the USGS data set that were not in the Midorikawa data

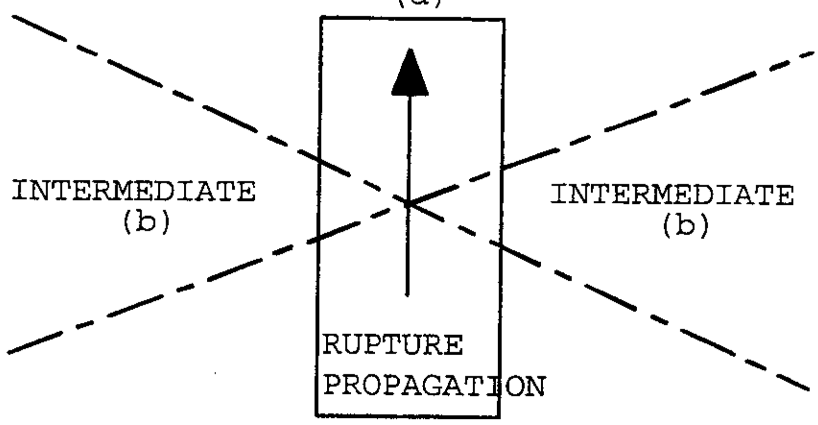

Figure A.3: Definition of rupture towards and rupture backward sites (from Midorikawa, 1991).

set were included only if their distance did not exceed the maximum distance of the records in the Midorikawa data set. Table A.1 lists the records in the USGS data set that were excluded from the analysis. Table A.2 gives the data upon which the analysis is based. The resulting equations are

$$\log A = 1.16 + 0.19d + 0.28s - \log(x + 31) - 0.0010x \quad (3)$$
$$\log V = 2.89 + 0.20d + 0.25s - \log(x + 26), \quad (4)$$

where the symbols are as defined above for equations (1) and (2). The standard deviation of the residuals of $\log A$ is 0.24 and of $\log V$ is 0.25. The coefficients of the two sets of equations appear to differ significantly, but, because of tradeoffs between the coefficients, the predicted values do not differ greatly, as shown in Table A.3, which compares predictions of the two sets of equations for the median and 84th percentile values of A and V for d=1 and d=0 at rock sites at x=35 km, the distance corresponding to the desired ground motions.

The values in the right-hand column of Table A.3 are recommended to represent the design ground motions for the earthquake at the interface between the Caribbean Plate and the Panama Block. The horizontal components of the records listed in Table A.4, scaled by the values in the right-hand column of Table A.3, can be used as time series for the seismic evaluations of structures. Records for which d=1 should be scaled only by A and V corresponding to d=1 and likewise for d=0. Both the cases d=1 and d=0 need to be considered. Probably the d=1 case will be controlling, but this needs to be checked, particularly in the case of nonlinear response, because duration should be greater in the case

d=0. Both mean and 84th percentile values are given. It would not be suitable for this report to recommend which values to use, because the choice depends more on engineering, economic, and political considerations than on seismological considerations. For important structures like the Panama Canal, 84th percentile values are commonly used for design. New design is a different issue from retrofit, however. Some degree of conservatism, moreover, has been introduced into the ground-motion values of equations (3) and (4) by two factors. One of these factors is the choice of the 1985 Chile earthquake data rather than some combination of the 1985 Mexico and Chile earthquake data to develop the equations. The other factor is the moment magnitude of 7.86 for the 1985 Chile earthquake from long-period body waves (Christensen and Ruff, 1986) compared to the moment magnitude of 7.7 recommended by Schweig et al. (1998) for the design earthquake.

Table A.1. Records in the USGS data set excluded from the analysis

Name	S. Lat.	W. Long.	Reason
Papudo	32.51	71.45	Severe 3 Hz resonance
Iloca	34.92	72.22	Severe 3 Hz resonance
Ventanas	32.75	71.49	Severe 1 Hz resonance
San Isidro	32.90	71.27	Severe 3 Hz resonance
Chillan Institute	36.60	72.10	Distance greater than 155 km*
Cauquenes	36.00	72.22	Distance greater than155 km*
Colbun	35.72	71.43	Distance greater than 155 km*

*Most distant station in Midorikawa's (1991) data set

As noted in Table A.4 Midorikawa classified station Llolleo as a soil site, whereas the station description given by Çelebi et al. (1988) unambiguously indicates that it is a rock site. This discrepancy should be kept in mind when using the Llolleo record for seismic evaluation. Reclassifying the Llolleo record would reduce the values in the right-hand column of Table A.3 by 10 to 20 percent.

A.3 OTHER EARTHQUAKES

The earthquake at the interface between the Caribbean Plate and the Panama Block will probably dominate the seismic evaluation. For the other earthquakes the equations of Abrahamson and Silva (1997) are recommended for determining peak horizontal acceleration and five-percent-damped horizontal response spectral values. If time series are needed, the method of Boore (1996) can be used to generate simulated time series, and these can be scaled, if desired, by the values from the equations of Abrahamson and Silva (1997).

Table A.2 Data used in developing equations (3) and (4)

Name	S. Lat.	W. Long.	Dist (km)	s	d	Peak A (g)	Peak V (cm/s)
Illapel	31.63	71.17	147	1	0	0.117	5.4
La Ligua	32.50	71.10	70	1	0	.177	7.7
Llay Llay	32.83	70.98	66	1	0	.475	41.8
Llolleo	33.68	71.60	26	0	1	.713	40.3
San Felipe	32.75	70.73	88	1	1	.434	17.8
Univ. Santa Maria	33.08	71.63	30	0	0	.176	14.6
Talca	35.43	71.67	154	1	1	.171	11.9
Vina del Mar	33.03	71.58	32	1	0	.363	30.7
Constitucion	35.30	72.32	154	0	1	.131	17.8
Santiago	33.45	70.67	81	1	1	.127	14.1
Hualane	34.97	71.82	105	1	1	.171	11.4
Los Vilos	31.92	71.50	111	0	0	.035	2.9
Melipilla	33.68	71.22	41	1	1	.687	40.3
Pichilemu	34.38	72.02	56	0	1	.259	12.5
Quintay	33.20	71.68	27	0	1	.260	19.3
Rapel	34.03	71.58	25	0	1	.224	10.4
San Fernando	34.60	71.00	80	1	1	.340	24.5
Zapallar	32.57	71.47	50	0	0	.305	13.5

Table A.3 Comparison of ground motion values between Midorikawa's (1991) equations and those of this report for rock sites at 35 km

	Midorikawa	This Report
median A d = 1	0.390 g	0.313 g
median A d = 0	0.214	0.202
84^{th} pctl A d = 1	0.550	0.544
84^{th} pctl A d = 0	0.302	0.351
median V d = 1	21.1cm/s	20.2 cm/s
median V d = 0	14.3	12.7
84^{th} pctl V d = 1	31.9	35.9
84^{th} pctl V d = 0	21.6	22.6

Table A.4 Records to be used as input in seismic evaluation

Name	Dist (km)	d
Llolleo*	26	1
Pichilemu	56	1
Quintay	27	1
Rapel	25	1
Valparaiso (Santa Maria Univ.	30	0
Zapallar	50	0

*Classified as a soil site by Midorikawa