ACP
AUTORIDAD DEL CANAL DE PANAMÁ

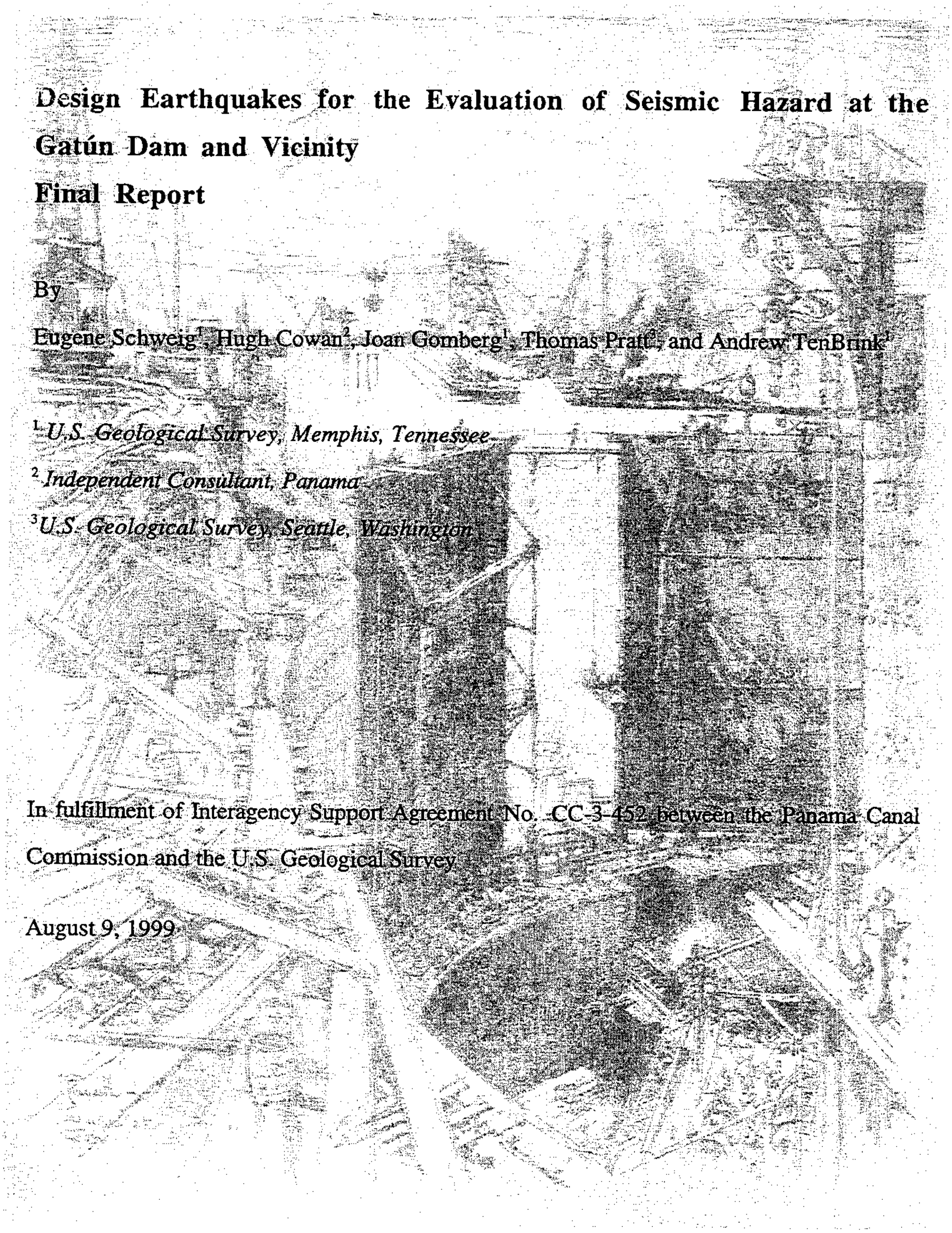
Design Earthquakes for the Evaluation of Seismic Hazard at the Gatun Dam and Vicinity

Diseños Sísmicos para la Evaluación de Peligros Sísmicos en la Represa de Gatún y Áreas Aledañas

Hugh Cowan

9 de agosto de 1999

Introducción y Recomendaciones
(No existe Resumen Ejecutivo)



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

By

Eugene Schweig[1], Hugh Cowan[2], Joan Gomberg[1], Thomas Pratt[3], and Andrew TenBrink[1]

[1] *U.S. Geological Survey, Memphis, Tennessee*

[2] *Independent Consultant, Panama*

[3] *U.S. Geological Survey, Seattle, Washington*

In fulfillment of Interagency Support Agreement No. CC-3-452 between the Panama Canal Commission and the U.S. Geological Survey

August 9, 1999

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

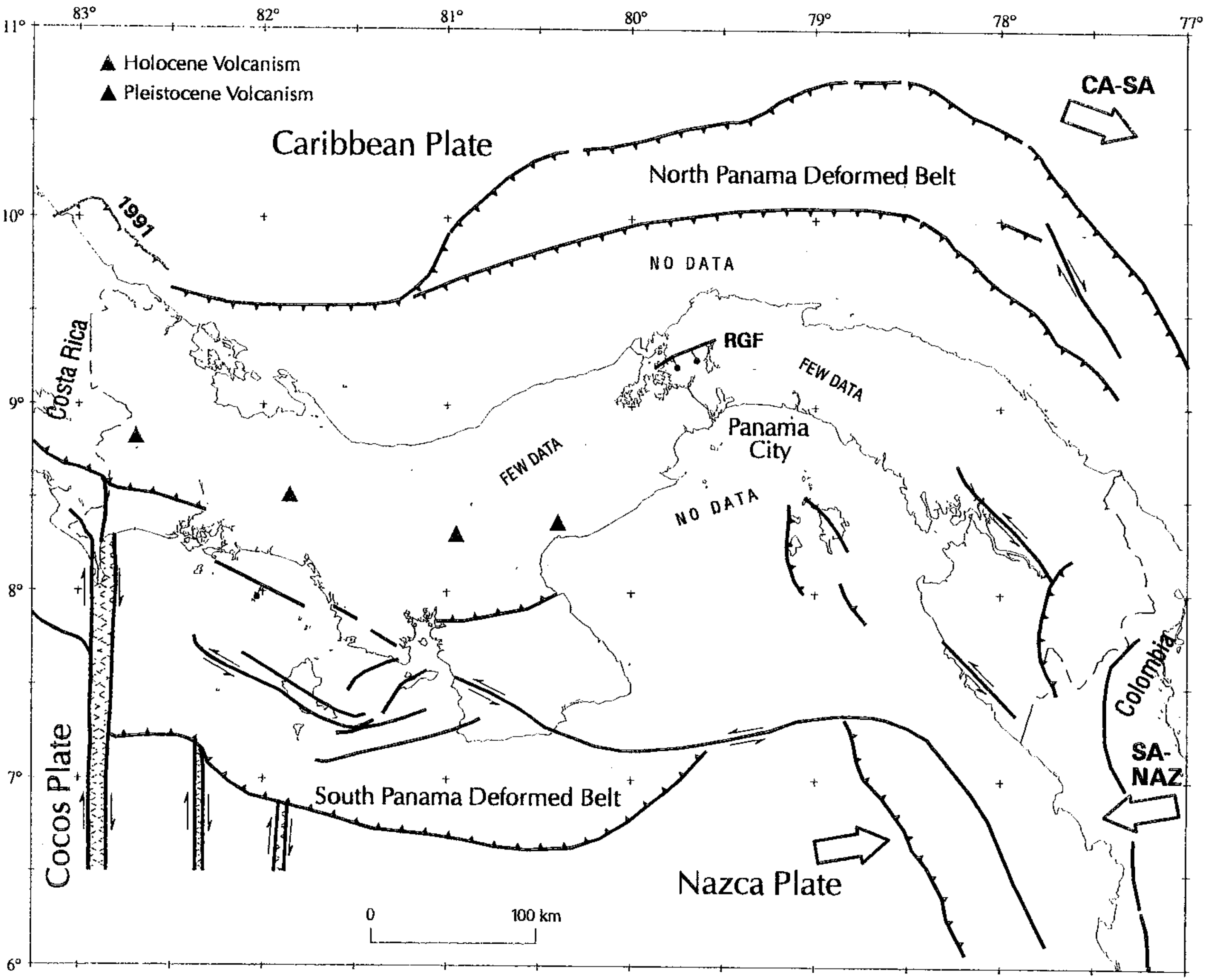


Figure 1.1: Major structural elements of the Panama Block and surroundings (after Cowan, 1998). Panama is located at the intersection of the Nazca, Cocos, Caribbean and South America plates, and is converging against South America across the northern Andes. The active boundaries of the Panama Block are 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)

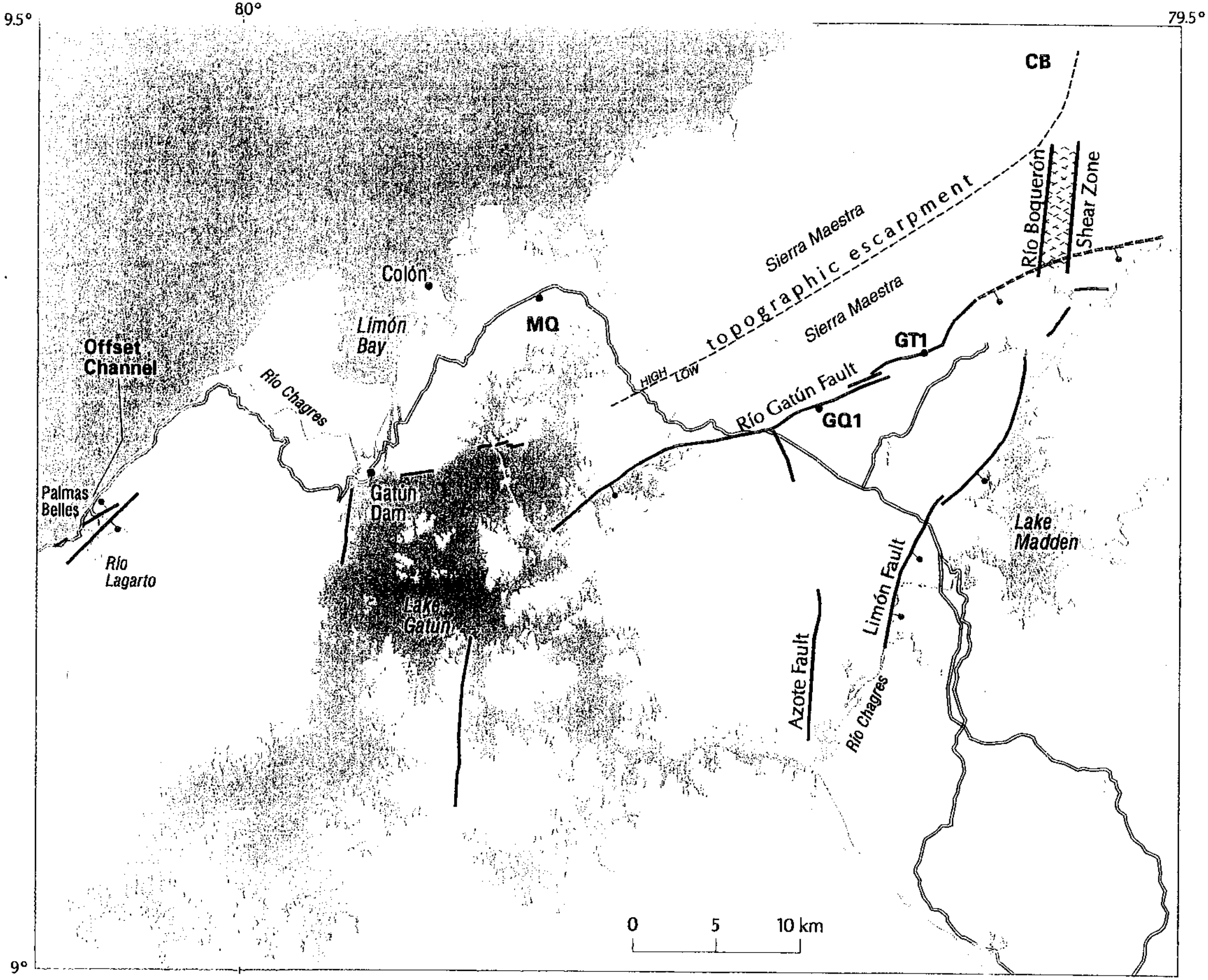


Figure 1.2: Structural features in the Lake Gatún area. MQ, Margarita Quarry; GQ1, quarry in Figures 4.3 and 4.4; GT1, site of two trenches across Río Gatún fault; CB, Cerro Bruja.

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.

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.