Design Earthquakes for the Southeast Area of the Canal Basin, Panamá.

By

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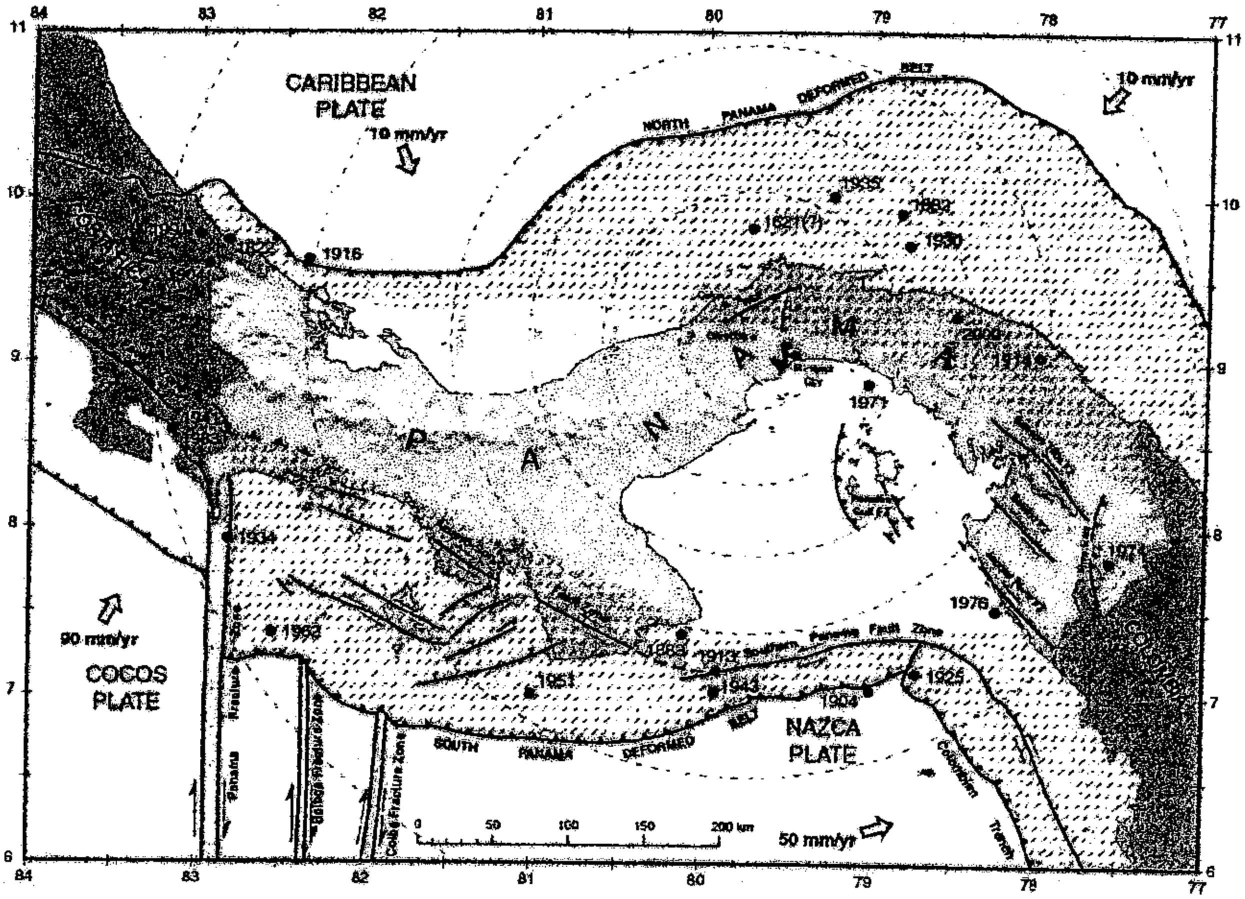

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1.0 Executive Summary

This report describes the major active geological fault zones and large historical earthquakes of Panamá and adjoining offshore regions, for the purpose of reviewing the selection of design earthquakes in the southeast of the Panamá Canal Basin.

Particular emphasis is placed on earthquake sources of the Pacific margin of Panamá, to determine whether or not additional design earthquakes to those of Schweig et al. (1999) are required for engineering design. The locations considered for the design earthquakes of this study include the Pacific Locks area (Miraflores and Pedro Miguel), and the Madden dam on the upper Río Chagres.

Data for the review of fault sources and seismicity were compiled from published reports, recent conference proceedings and international data archives, supplemented by unpublished data on the regional tectonics of Panamá, collected by the author during the previous five years. On the basis of this review and consideration of other requirements for estimating ground motions in the Panamá Canal Basin, the following conclusions are presented:

- There are major active faults associated with the Pacific margin of Panamá, but all are located at greater distances relative to sites of engineering interest than those selected for design earthquakes by Schweig et al. (1999).
- The largest seismic source of engineering interest in the Canal Basin remains the North Panama Deformed Belt, and the interface of the subducted Caribbean plate beneath the Panamá Block.
- The Río Gatún fault remains the principal, shallow crustal fault for hazard modelling in the Canal Basin.
- Based on the conclusions listed above, the design earthquakes of Schweig et al. (1999), are adopted with minor adaptation as follows:
  - Source 1: A moment magnitude (M) 7.7 thrust earthquake located at the Caribbean plate-Panamá Block interface:

    50km from Madden Dam
    70 km from the Pacific Locks
  - Source 2: A M6.8 earthquake on the Río Gatún fault

    12km from Madden Dam
    40km from the Pacific Locks

The Source 1 earthquake will continue to dominate the hazard assessment, but uncertainties about the source and path effects associated with this event emphasize the need for caution in the selection of ground motion attenuation models or time histories. The attenuation model of Dahle et. al. (1995) derived from Central American and Mexican strong motion data provides a useful basis for comparison with other attenuation relationships. Sensitivity analysis with attention to the effect of extreme data values for different attenuation models should provide a guide to the appropriate level of conservatism for engineering design in the Canal Basin.

2.0 Introduction

2.1 Background

Between 1996 and 1998 the United States Geological Survey (USGS) was contracted by the Geotechnical Branch of the Panamá Canal Commission[1], to characterize potential seismic sources most likely to affect the Gatún Dam. The primary objective of this work was to advise the Commission on appropriate design earthquakes for evaluation of seismic hazard at Gatún Dam.

The range of tasks included geological and geophysical surveys in the Panamá Canal Basin (PCB) and vicinity to identify and evaluate potential active faults and seismicity patterns (Schweig et al., 1999). Based on the data analysed, three design earthquakes were recommended:

- Source 1 - a moment magnitude (M) 7.7 thrust earthquake, located on the interface between the Caribbean Plate and the Panamá block at a distance of 35 km;
- Source 2 - a M 6.8 earthquake on the Río Gatún fault at a distance of 13 km;
- Source 3 - a M 5.0, or M 6.0, earthquake on a crustal fault at a distance of 2 km.

Design ground motions corresponding to the recommended earthquakes were proposed, based in particular on comparison of the Source 1 earthquake with historical data from similar settings elsewhere (Joyner, 1999).

2.2 Scope of Work

The aim of this study is to determine whether or not new earthquakes are required for engineering design in other parts of the Canal Basin, particularly at localities farther to the east and south. The locations considered for this study therefore include the Pacific locks area of Miraflores-Pedro Miguel, and the Madden dam on the upper Río Chagres. The study has been conducted as a desk-top review of existing knowledge, describing the principal active geological fault zones and large historical earthquakes of Panamá in an up-to-date scientific context. Particular emphasis is placed on identifying major earthquake sources of the Pacific region of Panamá, which were not reviewed in the earlier studies by the USGS.

Data for this study were compiled from a review of technical reports, published scientific articles, recent conference proceedings and international data archives, supplemented by data collected by the author during the previous five years and in preparation for publication.

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[1] Interagency Support Agreement CC-3-452

2.3 Data

Studies of regional tectonic structure have been conducted using seismicity recorded on distant seismographs (e.g. Wolters, 1986; Vergara, 1988; Adamek et al., 1988). Those studies, together with similar work in Costa Rica (Montero and Morales, 1990) have defined the principal structures, but not in sufficient detail for local seismic hazard assessment.

Cowan et al., (1995) used portable seismographs to record more than 140 local earthquakes in Chiriquí and Bocas del Toro. The spacing of stations in that study was too wide to constrain the locations of most small earthquakes in Bocas del Toro, but previously unrecognized seismic activity, together with fault style and stress information was obtained in Chiriquí. A similar study on the Azuero Peninsula has indicated the presence of a dipping seismic zone, consistent with subduction of the Nazca plate (Camacho et al., 1996).

Geological studies have confirmed the existence of highly active faults in the border region of Panamá and Costa Rica (Cowan, 1996; Cowan et al., 1997). However, with the exception of detailed studies in the Canal Basin by Schweig et al (1999), such work is yet to be done in other parts of the republic. Currently, the most comprehensive source of information on active faulting and potential seismic hazard at a regional scale in Panamá is Cowan et al. (1998).

3.0 Tectonic Framework

3.1 Panamá Block

The Republic of Panamá is situated on a relatively rigid geological block (Panamá Block) at the southern end of the Central American volcanic arc (Kellogg and Vega, 1995). The volcanic arc initiated in the late Cretaceous or Early Tertiary period, 70-50 Ma ago[2]. Its present configuration is the product of a major reorganization of regional tectonics that accompanied the collision of the arc with South America, between 25 and 7 Ma ago (e.g. Weyl, 1980; Escalante, 1990).

Westward relative motion of South America results in continuing deformation around the eastern margin of the Panamá Block in the Darién region, and under-thrusting of the Nazca plate along the Colómbian trench (Kellogg and Vega, 1995; Taboada et al., 2000). Cocos plate is subducted beneath the Pacific margin of the arc in southern Costa Rica, and Nazca plate is subducted obliquely in a northeast direction beneath the southwest margin of Panamá. Thrusting of the Caribbean plate beneath the north margin of the Panamá Block has produced some of the largest historical earthquakes in the Republic (Adamek et al., 1988; Mendoza and Nishenko, 1989; Camacho and Viquez, 1993) (Figure 1).

The provinces and adjoining offshore regions of Bocas del Toro, Chiriquí and Los Santos in the west and south, and San Blas and Darién in the east are the most

[2] Ma = million years

seismically active regions of Panamá, corresponding to the margins of the Panamá Block. Most of the historical seismicity within a 400km radius of the Canal Basin can be attributed to collision and shear deformation at the neighboring plate boundaries (Figure 1).

3.2 Slab Window Beneath Panamá

In contrast to the margins described above, the interior of the Panamá Block is characterized by low rates of internal deformation (Kellogg and Vega, 1995) and low rates of seismicity even at very small magnitudes (Cowan et. al., 1995; Schweig et. al., 1999) (Figure 2). The occurrence of recently active volcanoes at several localities along the Cordillera Central (El Baru, La Yeguada and El Valle), implies that oceanic lithosphere has been subducted recently beneath the isthmus (de Boer et. al., 1991; Drummond et. al., 1995). However, whereas seismological evidence for subducted lithosphere has been documented beneath the western parts of Chiriquí province and Azuero Peninsula (Cowan et al., in preparation), no such evidence has been documented beneath central Panamá.

The explanation lies in the composition of selected volcanic rocks in Panamá and in southern Costa Rica. Lavas with distinctive (and unusual) geochemical and isotopic compositions have been discovered, leading to speculation that an oceanic spreading ridge probably has been subducted beneath the Panamá Block leading to the creation of a "slab window" (Johnston and Thorkelson, 1997). A slab window is a slab-free region beneath the convergent margin of an overriding plate. The window develops during subduction of a "ridge" in which two oceanic plates are diverging[3].

One of the predicted consequences of a slab window beneath Panamá is a high heat flow and ductile deformation at depths that would normally be characterized by brittle fracture and seismicity, if a subducted slab were present. The evidence for a slab window beneath Panamá comes from the volcanic rocks whose chemistry reflects the influence of a deeper mantle source of magma relative to those normally derived from melting of a descending slab (Abratis et al, in press).

A slab window constrains the dimensions and potential rupture surface area of the adjoining subducted plate (slab), so there are implications for seismic hazard assessment. Johnston and Thorkelson (1997) proposed the concept of a slab window beneath Panamá on the basis of geochemical evidence and considerations of regional plate motions. The concept can also be reconciled with patterns of seismicity and faulting documented in Panamá and an integrated tectonic model is now being proposed to clarify the regional structure and relative importance of different fault zones (Figure 3) (Cowan et al., in preparation).

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[3] Spreading ridges are associated with the accretion of new oceanic crust at zones of mantle upwelling. It is inferred that a segment of spreading ridge beneath Panama would have adjoined the northern end of the Panama Fracture Zone and originated by strike-slip faulting from the Galapagos spreading ridge c. 1000 km farther south.

4.0 Major Fault Zones[4]

4.1 *Introduction*

This review includes the known major faults in the Panamá Canal Basin and the principal tectonic regions of Panamá. The tectonic regions define the boundaries of the Panamá Block and include:

- Panamá Block-Caribbean plate boundary
- Panamá Block-Nazca plate boundary
- Eastern Panamá-Colómbia collision zone
- Panamá Block-Cocos plate boundary

The tectonic regions and respective fault zones illustrated in Figure 1 and Table 1 were compiled using the criteria and nomenclature of Cowan et. al. (1998), supplemented by seismological data that help to define the subsurface geometry of the subducted Caribbean and Nazca slabs beneath the Panamá Block (Schweig et. al.,1999; Cowan et. al., in preparation).

4.2 *Canal Basin Crustal Faults*

4.2.1 Río Gatún Fault

The Río Gatún Fault (RGF) bounds the northwest margin of the Madden Basin and the slopes of the Sierra Maestra in the Canal Basin. The RGF strikes east northeast and separates middle/late Tertiary sediments of Madden Basin from older (probably Cretaceous-Paleocene) sedimentary and igneous rocks. The RGF has been mapped between Lago Gatún and Río Boqueron at the north end of the Madden Basin.

Mann and Corrigan (1990) postulated left-lateral strike-slip along the RGF based on regional kinematic considerations. Available field evidence indicates predominantly dip-slip displacement and no late Quaternary offsets have been documented on alluvial terraces or fans (Schweig et.al., 1999).

Seismicity is weakly correlated with the RGF, and the geomorphic expression of the fault zone (faceted spurs) is consistent with late Quaternary activity. However, observations of the fault zone in basement rocks indicate partial annealing of the crushed zone. Schweig et al., concluded that there has been no surface movement on the Río Gatún fault for at least 10,000 years.

4.2.2 Undifferentiated Faults, Canal Basin and Madden Basin

A system of north-south trending, predominantly east-facing normal faults (Azote and Limón faults), located west and south of the western termination of the Río Gatún fault, have been mapped previously (Stewart et. al., 1980; TenBrink, 1999). One of

[4] See Figures 1 and 3 and Table 1

these structures (Limón fault) passes within 3.5 km of the west abutment of the Madden Dam.

These faults have been attributed to localized extension at the western termination of the Río Gatún fault (Mann and Corrigan, 1990) and to 'flexing' of the Panamá Block in response to shortening across the North Panamá Deformed Belt (TenBrink, 1999). No evidence for recent movement on these faults has been documented in previous studies and it is reasonable to infer activity rates that are comparable to, or lower than, the Río Gatún fault, which remains the largest documented shallow crustal fault in the Canal Basin.

4.2.3 The "Canal Discontinuity"

The Canal Discontinuity is a hypothetical fault zone proposed by Case (1974) to explain the distribution of gravity anomalies in central Panamá. The gravity data originally presented in support of the discontinuity do not require the presence of such a structure, but numerous references to the Canal Discontinuity have appeared subsequently in the geological literature, including synoptic maps of geological structure in Panamá. The structure is commonly aligned with the Panamá Canal on a northwest trend (e.g. Maury et al., 1995).

No direct geological or geophysical evidence for the discontinuity has been documented. Marine geophysical and geological studies in the Gulf of Panamá have shown that the discontinuity, if it exists, must be older than about 3-5 million years because sediments of this age and younger show no evidence of deformation.

However, there is no evidence of a structure with the proposed orientation accommodating movement across the Panamá isthmus today, so the Canal Discontinuity is not identified as a major seismic source in this study. A definitive answer to the existence and significance of the Canal Discontinuity will require further study of the deeper crustal structure as proposed by Schweig et al. (1999).

4.3 Panamá Block-Caribbean Plate Boundary

4.3.1 North Panamá Deformed Belt

The North Panamá Deformed Belt (NPDB) comprises an arcuate zone of distributed folding and thrust faulting that extends eastward from Costa Rica to the Gulf of Uraba, Colómbia (Silver et al., 1990, 1995). In the west, the NPDB reflects the lateral transmission of stress through the arc from the Cocos Ridge collision zone and over-thrusting of the Panamá Block onto the Caribbean plate, most recently during the 1991 Limón, Costa Rica earthquake (Plafker and Ward, 1992).

The NPDB has been the source of several large earthquakes during the historical period (Mendoza and Nishenko, 1989; Camacho and Viquez, 1993; Boschini and Montero, 1994), including the largest recorded earthquake in southern Central America in 1882 AD. That event had a magnitude of 7.5-7.7, and was located in the eastern part of the zone, northeast of Colón. The widespread surface effects, included liquefaction in northern Panamá, and a tsunami that drowned more than 60 persons in the province of San Blas (Mendoza and Nishenko, 1989).

Other earthquakes during the instrumental recording period (see below) have been located at greater depths beneath northeastern Panamá and attributed to subduction of Caribbean plate beneath eastern Panama (Adamek et al., 1988) (Figure 2). Schweig et al. (1999) described a dipping zone of seismicity extending from depths of 30 to 60km consistent with the presence of subducted Caribbean plate beneath the Canal Basin and vicinity (Figure 1, Figure 3).

4.4 *Panamá Block-Nazca Plate boundary*

4.4.1 South Panamá Deformed Belt

Seismicity and geological data from western Panamá indicate recent subduction of oceanic plate to depths of 100-120 km beneath the Cordillera Central. This is inferred to represent one or more 'slice' of Cocos oceanic lithosphere, cut off between the Coiba, Balboa and Panamá Fracture zones due to local migration of the Cocos-Nazca plate boundary (Cowan et al., in preparation) (Figure 3).

East of the Panama Fracture Zone (PFZ) the Nazca plate is moving east-northeast, oblique to the southern margin of Panamá. The PFZ and adjacent splays are being subducted obliquely beneath the southwest margin of Panamá. The associated deformation is accommodated by thrust faulting along the continental margin and oblique normal faulting within the over-riding Panamá Block, west of Azuero Peninsula and Coiba Island ((MacKay and Moore, 1990; Moore and Sender, 1995; Kolarsky and Mann, 1995). Numerous earthquakes of moderate magnitude (4.0-6.0) have been recorded in this region (Figure 2).

4.4.2 Azuero-Soná Fault Zone

The Azuero-Soná fault zone (ASFZ) is a large strike-slip fault that accommodates left-lateral shear along the margin and within the Panamá Block (Mann and Corrigan, 1990; Westbrook et. al., 1995). The ASFZ strikes northwest to southeast and defines a linear valley across the Azuero and Soná peninsulas and Gulf of Montíjo. The ASFZ extends offshore to the southeast and merges with the Southern Panamá fault zone (Figure 1 and Figure 3). Numerous, moderate to large historical earthquakes have occurred in this region (see below). A recent study of seismicity beneath the Azuero Peninsula in 1996 associated shallow earthquakes with the ASFZ and its junction with adjoining structures offshore (Camacho et al., 1996; Cowan et al., in preparation).

4.4.3 Southern Panamá Fault Zone

The Southern Panamá fault zone (SPFZ) forms the left lateral, strike slip margin of the Nazca Plate, offshore Azuero Peninsula and farther east across the Gulf of Panamá. The SPFZ strikes east northeast, accommodating relative motion between the Nazca plate and Panamá, extending from the South Panamá Deformed Belt at 80.5 W. Long, eastward to 78.5 W. Long, then southeast parallel to the Colómbia Trench offshore northern Colómbia. The SPFZ is well expressed in the bathymetry offshore Azuero Peninsula (Westbrook et. al., 1995) and associated with several large historical earthquakes (see below).

4.5 Eastern Panamá-Colómbia Collision Zone

4.5.1 Gulf of Panamá and Pearl Islands

Nine northwest-striking, west-verging thrust faults offset rocks of Oligocene (~30 Ma) to Plio-Pleistocene age (2-3 Ma), and at some localities deforms the seafloor, in the eastern Gulf of Panamá. The longest and westernmost of these faults is located beneath the western margin of the Pearl Islands, which form the emergent part of an associated hanging-wall anticline. The faulting history has been inferred from analysis of multi-channel seismic surveys tied to two exploration wells, and integrated with geological outcrop data from the Pearl Islands and mainland Panamá (Mann and Kolarsky, 1995 and references therein). Arching of the seafloor is evident southeast of the Pearl Islands so the faults are inferred to be active.

4.5.2 Sanson Hills Fault Zone

Left-lateral, strike-slip faults of the Sanson Hills fault zone (SHFZ) juxtapose a sedimentary sequence of upper Cretaceous-to-upper Miocene age (~70-10 Ma) in the Bayano-Chucunaque basin on the northeast, from an upper Cretaceous, oceanic igneous and sedimentary sequence to the southwest (Mann and Corrigan, 1990; Mann and Kolarsky, 1995) (Figure 1).

The SHFZ fault zone is well defined by a series of seven, en echelon, doubly plunging anticlines along its northeastern flank (Wilcox et al., 1973; Mann and Corrigan, 1990). To the northwest the Sanson Hills fault terminates in a half-graben, developed at an inferred releasing bend in the fault. To the southeast the fault terminates against north-trending highlands (Serranía de Pirre) bounded by the Pirre Hills Fault Zone (see below). The fault is inferred to be active based on its geomorphic expression, but no data are available to constrain the time of most recent movement.

4.5.3 Pirre Hills Fault Zone

Also known as "Falla del Río Balsas", a north northeast-striking and northwest verging, reverse or thrust fault bounds the northwestern flank of the Serranía de Pirre, south of the town of Yaviza, Darién. The Pirre Hills fault accommodates locally northwest directed shortening across the Colómbia-Panamá border region, and sharply truncates, the Sanson Hills fault zone. The Pirre Hills fault zone is defined by a topographically prominent highland block developed in the hanging wall of the fault, and bounded to the east in the border region of Colómbia by the sinuous, west-dipping Unguia fault (MacDonald, 1969; Mann and Kolarsky, 1995). The most recent movement possibly occurred on July 12, 1974 associated with a M 7.3 earthquake centered in this area.

4.5.4 Sambú fault zone

Northwest striking inferred left-lateral strike-slip fault that bounds the southeast margin of the Sambú Basin, Darién (Lowrie et. al., 1982; Mann and Kolarsky, 1995). The Sambú Fault bounds the southwest flank of the Serranía de Bagre and the onshore extension of the Sambú Basin, along the linear Río Sambú valley (MacDonald, 1969;

Mann and Kolarsky, 1995). The fault is inferred to be active but no data are available to constrain the time of most recent movement.

4.5.5 Jaqué River Fault Zone

Northwest striking inferred left-lateral strike-slip fault that bounds the southwest margin of the Serranía de Sapo, Darién (Mann and Corrigan, 1990; Mann and Kolarsky, 1995). The Jaqué River Fault bounds the southwest flank of the Serranía de Sapo and Serranía de Jungurudo, along the landward margin of a narrow coastal plain, possibly extending into Colómbia (MacDonald, 1969; Mann and Kolarsky, 1995). The fault is inferred to be active but no data are available to constrain the time of most recent movement.

4.5.6 Colómbian Trench

A zone of westward and eastward verging, folded thrust slices define the near-surface deformation associated with Nazca plate collision and subduction beneath South America, between 78W and 79W Longitude. The trench axis and deformation structures are well expressed in the bathymetry offshore the border region of Panamá and Colómbia (Westbrook et.al. 1995) and constitute the northern part of the Colómbia-Ecuador subduction zone. The locations of all but the most recent events in the Panamá sector are poorly constrained due to sparse instrumentation, but this zone has been the source of several large historical earthquakes.

The Colómbia-Ecuador subduction zone farther south produced the third-largest earthquake of the 20th century (M 8.7, 1906). Li and Toksöz (1993) have noted that the seismic moment released in the northern part of the zone during the past several decades is a small fraction of the total potential seismic moment, suggesting that a great (M >8.0) may occur here in future.

4.6 Panamá Block-Cocos Plate Boundary

4.6.1 Panamá and Balboa Fracture Zones

The Panamá Fracture Zone (PFZ) separates the Cocos and Nazca plates south of the Panamá-Costa Rica border. The PFZ accommodates right-lateral strike-slip motion at a rate of 50-70 mm per year (DeMets et al., 1990; Kellogg and Vega, 1995). Two sub-parallel fracture zones – the Balboa and Coiba – splay off from the PFZ to the north-northeast (Lonsdale and Klitgord, 1978; Heil, 1988).

The Panamá Fracture Zone is being subducted beneath the Panamá Block adjacent to the Cocos Ridge (Figure 3) The fracture zone retains a strong surface expression for tens of kilometers farther north in the form of strike-slip faults that cut up through the overriding Panama Block. These include the Medial fault zone (Corrigan et al., 1990) and the Canoas fault zone, which shows evidence of rapid horizontal movement during the last 10,000 years (Cowan et al., 1997 a, b). The Panamá Fracture Zone (and possibly the Balboa Fracture Zone) ruptured during the 1934 Ms 7.6 earthquake and associated aftershocks (Camacho, 1991; Cowan et al., 1997a, b).

4.6.2 Cocos Ridge Collision and Subduction

On the Cocos plate, west of the PFZ, a thickened area of oceanic crust (Cocos Ridge) is being subducted beneath the southwest margin of the Caribbean plate and the Panamá Block. The rate of convergence is approximately 90 mm/year. The Cocos Ridge is buoyant and thicker than normal oceanic lithosphere, so the angle of subduction is shallow. The deformation is characterised by shortening and uplift of the overlying plates (Figure 3). The subduction interface ruptured twice in this sector during large (M 7.5) 20th century earthquakes (1941 and 1983: Adamek et al., 1987, 1988, Tajima and Kikuchi, 1995) (Figure 1). The Cocos Ridge is defined by seismicity to a depth of about 50km, but not more, beneath southern Costa Rica (Protti et. al., 1995).

4.6.3 Longitudinal Fault Zone

The Longitudinal fault zone is an oblique-reverse structure that strikes east-southeast, parallel to the volcanic arc across southern Costa Rica and the Chiriquí lowlands of western Panamá (Cowan et al., 1998) (Figure 1). The fault zone juxtaposes early Tertiary (50 Ma) and late Quaternary (<1 Ma) rock units across a thrust contact in the Costa Rica-Panamá region. Recent studies have shown that the fault has ruptured in the Costa Rica sector during the last 2500 years, but in Panamá the zone shows no evidence of movement during the last 10,000 years (Cowan, 1996; Cowan et al., 1997).

5.0 Seismicity

5.1 Earthquake Catalog Completeness

The historical record of earthquakes in Panamá dates back to the 16th century but the record is sparse prior to about 1900 AD due to the uneven distribution of population and literate observers. The historical record of earthquakes for central Panamá and the surrounding areas is probably complete for events larger than magnitude 7.0 since A.D. 1800, and larger than about magnitude 5.7 since 1910 (Kirkpatrick, 1921; Gutenberg and Richter, 1954; Jorgenson, 1966; Leeds, 1978; Viquez and Toral, 1987; Camacho et al., 1997). However, the epicentral locations and depths of those earthquakes may have uncertainties of 50 km or more. The uncertainties in the locations of pre-1900 events are likely to be even larger, especially for events located offshore.

Long-period seismographs were first installed at the Panamá Canal, Ancon Observatory in 1908 and later replaced by short-period instruments in 1932. In 1962, a WWSSN (Worldwide Standard Seismograph Network) instrument was installed at Balboa Heights in the Panamá Canal Zone, and operated until 1976. From 1976 through 1983, the Balboa Heights station was non-operational so the local catalog is incomplete below about magnitude 4.7 during that period.

Until the early 1990's, there were no seismographs located in western or eastern Panamá, but larger earthquakes (M >5.0) throughout the Republic and offshore have been recorded on seismographs in neighboring countries and are archived in international catalogs (Figure 2). Since 1992, a Norwegian-Swedish collaborative project with the University of Panamá has resulted in the deployment of a sparse short-period seismograph network throughout the republic. The recent expansion of the Panamá seismograph network is beginning to provide new opportunities to evaluate local seismicity, but the depth distribution and geological significance of seismicity remains poorly constrained due to the wide spacing of the stations.

Except for the 1882 San Blas earthquake, which has been studied in detail, little is known of the relationship between seismicity and individual geological structures central and eastern Panamá. The correlation of earthquakes and local geological structure remains uncertain because permanent seismographs are widely spaced, but Schweig et al. (1999) demonstrated that most of the earthquakes recorded beneath the Canal Basin and vicinity during a six month long study were associated with deeper structures. The largest surface faults were virtually devoid of seismic activity, consistent with the geomorphic and geological evidence of long quiescence.

The largest historical earthquakes within a 400km radius of the Canal Basin are clearly associated with offshore (or deeper) fault structures. These are described briefly based on documented historical reports.

5.2 *Significant Historical Earthquakes*[5]

5.2.1 1621, May 2 Epicenter unknown, M > 7.0

The earliest documented earthquake in Panamá described by don Juan Requejo Salcedo (1640) a priest of Panamá la Vieja. Viquez and Camacho (1994) assign this event a magnitude of 5.6-6.0 and suggest that it originated as an intraplate earthquake associated with the "Canal Discontinuity". There is uncertainty whether or not this earthquake generated a tsunami along the Pacific coast and therefore to which side of the isthmus the epicenter should be assigned. Salcedo describes how the "inhabitants with Peruvian experience fled to higher ground to avoid the anticipated sea-waves (tsunami), but these did not arrive", suggesting a source perhaps on the Caribbean side of the isthmus. However, there is also reference to waves flooding or threatening "la calle de la Carrera", which would imply a Pacific source, possibly the Gulf of Panamá or Azuero peninsula (Nishenko, 1991; Molina, 1997).

The true source of this earthquake is likely to remain uncertain. The reported damage to masonry structures in Panamá City and similar effects described from Veraguas province, nearly 200 km farther west, together with the long duration reported, imply a larger magnitude than that suggested by Viquez and Camacho (1994).

5.2.2 1822, May 7 North Panama Deformed Belt (Bocas) M 7.5

Montero (1986 a, b, 1989) and Nishenko (1991) assign this event to a source on the Pacific coast of Costa Rica with a magnitude of M 7.5. Detailed revision of archival sources, however, indicates a more probable epicenter on the Caribbean coast, in the Limón-Bocas area (Gonzalez and Montero, 1990; Boschini and Montero, 1993; Camacho and Viquez, 1993)

[5] Within a site radius of approximately 350 km or MMI intensity V or greater at Balboa Heights

The event comprised three violent shocks during a 24hour period. Surface effects, consistent with lateral spreading, liquefaction and tsunami inundation were documented along the Caribbean coastline as far north as Nicaragua (Roberts, 1827; Montessus de Ballore, 1888; Gonzalez Viquez, 1910). Camacho and Viquez (1993) infer strong shaking in the Bocas area and coastal uplift at the Costa Rica-Panamá border.

5.2.3 1882, Sept. 7 North Panamá Deformed Belt (San Blas) M7.7-8.0

The largest earthquake recorded in Panamá since European settlement in the 16th century. Mendoza and Nishenko (1989) and Camacho and Viquez (1993) have described the effects of this earthquake, which is also reviewed by Schweig et al. (1999). Widespread liquefaction along the coastal plains and river valleys and a tsunami that killed 68 persons in the San Blas islands. Numerous masonry buildings in Panamá City and Colón were destroyed or badly damaged.

5.2.4 1883, Feb. 5 Azuero-Soná Fault Zone or offshore M ~7.0

Damaging effects were greatest in Los Santos where part of the church tower collapsed and walls were cracked in Las Tablas. "Panic" but little damage reported from Penonomé and Panamá City.

5.2.5 1904, Jan. 20 Southern Panamá Fault Zone M >7.4

A large earthquake located south of Panama (7.0 Lat., 79W Long.) reported by Gutenberg and Richter (1954) but no reports of damage from Panamá sources.

5.2.6 1904, Dec. 20 North Panama Deformed Belt (Bocas) M 7.5

For many years this event was assigned to a source on the Pacific coast of southern Costa Rica (Gutenberg and Richter, 1954; Miyamura, 1980; Montero 1986a; Nishenko, 1991). Review of the felt effects and reinterpretation of teleseismic recordings indicates that the event was probably located in the Limón and Bocas del Toro area (Camacho and Viquez, 1993; Ambraseys, 1995).

The reported effects indicate strong shaking in the Changuinola area (Camacho and Viquez, 1993). Various estimates of magnitude have been inferred from M 7-7.5. Damage at Bocas del Toro may have been lessened because much of the town had been destroyed by fire in March 1904 and was under reconstruction at the time of the earthquake (Camacho and Viquez, 1993).

5.2.7 1913, Oct. 1 Azuero-Soná Fault Zone or offshore M ~7.0

Damage to buildings was severe in Los Santos. There was extensive liquefaction in the valleys and landsliding in the mountains (MacDonald and Johnson, 1913). The international telegraph cable offshore from the southeast coast of Azuero Peninsula broke, probably due to submarine landsliding.

Viquez and Camacho (1993) give M 6.5 for this event; Ambraseys and Adams (1996) assign magnitude 6.7. These may be underestimates because the earthquake was followed by aftershocks that persisted for several months, of which 10 were reportedly felt throughout the isthmus (Leeds, 1978).

There are three potential sources for this event: 1) the Azuero-Soná fault zone; 2) the Southern Panamá fault zone; and 3) slip on the Nazca plate, Panamá Block interface beneath the Azuero Peninsula. The available data are insufficient to discriminate between these sources, but all three sources are capable of generating earthquakes larger than M 7.

5.2.8 1914, May 27 North Panamá Deformed Belt (San Blas) M ~6.5-7.2

This earthquake was centered ~70 km beneath Serranía de San Blas and associated with the subducted Caribbean plate. The event was strongly felt in Panamá City and Colón where people fled into the streets. Only minor damage reported. No damage reported from Los Santos province.

5.2.9 1916, Apr. 25 North Panama Deformed Belt (Bocas) M ~7.0

The event was strongly felt in Panamá and Costa Rica, and was particularly severe in Almirante and Bocas town, where people had difficulty standing and the contents of shops and houses were thrown down. More than 80 houses were shifted from their foundations and many windows were broken. Water tanks were thrown down, and railroad lines were twisted. Debris and canoes were washed 200 meters inland at Bocas town. Several other localities were inundated temporarily. The reported effects of this event indicate strong shaking in the Bocas-Almirante area (Acres International, 1982). The locally severe effects and moderate magnitude together suggest that the earthquake was located within a few kilometers of Bocas del Toro.

5.2.10 1925, Mar. 29 Eastern Panamá-Colómbia Collision Zone M >7.0

A large earthquake located in the Southern Panama fault zone or possibly the subducted Nazca plate in the near-shore region of Darién. No reports of damage from Panamá

5.2.11 1930, Mar. 7 North Panamá Deformed Belt (San Blas) M ~6-6.5

Strongly felt in Panamá City and Colón where people fled into the streets. Minor cracking of walls at the Canal Administration building

5.2.12 1935, Nov. 21, North Panamá Deformed Belt (San Blas) M ~6.5

Strongly felt in the Canal Zone and hundreds of people ran into the streets at Balboa. Furniture was shifted. Minor non-structural damage to masonry buildings.

5.2.13 1943, May 2, Southern Panamá Fault Zone M >7.0

Strongly felt in Panamá City. Plaster shaken down in offices of the Adminstration Building and similar reports from concrete buildings throughout the Canal Zone. Wooden buildings pitched on their foundations.

5.2.14 1951, Jan. 4 and 6, Southern Panamá Fault Zone M 6.7 , M ~7.0

The first event is inferred to be a foreshock of the January 6 earthquake. No material damage occurred in the first event, but moderate damage to masonry structures and widespread panic was reported for the second event in towns between Veraguas and Panamá City. Strongly felt in the Canal Zone and Panamá City, where many walls were cracked. The lake level recorder on Gatún Lake apparently was damaged.

5.2.15 1962, Jul. 26 South Panama Deformed Belt M 6.7-7.0

An event strongly felt in the Canal Zone and Panamá City, but no reports of damage.

5.2.16 1971, Jan. 19 North Panamá Deformed Belt (Panamá) M 5.5-6.5

The International Seismological Center (ISC) assigns M 5.5-5.6 but reported damage suggests this could be higher, perhaps M ~6.0-6.5. This event was described in Panamá City as the strongest earthquake in nearly 90 years. Walls were cracked and windows shattered. Water pipes broke and power was disrupted. The Adminstration Building at Balboa Heights was cracked again. Many people remained outside for several hours. Leeds (1978) reports an epicenter at the northwest margin of Gatún Lake (near Escobál), but NOAA and the ISC place the event east of Panamá City. Probably associated with the subducted Caribbean plate, but a shallow crustal source cannot be ruled out.

5.2.17 1974, Jul. 12 Eastern Panamá-Colómbia Collision Zone M ~7.3

A large shallow earthquake (<15 km deep) possibly located on the Pirre Hills fault zone. Liquefaction was reported at Jaqué and strong shaking and damage was reported from settlements between El Real and Yaviza (Viquez and Toral, 1987). 11 persons were killed and others injured.

5.2.18 1976, Jul. 11 Eastern Panamá-Colómbia Collision Zone M 6.8, 7.0

Two strong earthquakes within the space of four hours, located beneath the Colómbian Trench, Darién. Landslides were triggered and several persons were injured at Jaqué on the Pacific coast of Darién. Strongly felt in Panamá City but no serious damage.

5.2.19 1991, Apr. 22 North Panama Deformed Belt (Bocas) M 7.5

The Limón earthquake affected an area of 8,000 km^2 in the border region of Panamá and Costa Rica. Structural losses in Costa Rica, where the highest shaking intensities were experienced, included 80 km of roading, the collapse of five bridges and severe damage to a further six. Lateral spreading, settlements and liquefaction affected 92 km of railroad alignment, and tectonic uplift reduced the draft (water depth) in the Port of Limón. Severe damage to water pipelines in the Limón area resulted in acute water shortages for a period of three months. The total economic losses in Costa Rica were estimated at US$188 million, amounting to more than 4% of GNP (Sauter, 1994; Morales, 1994).

The Limón earthquake ruptured the North Panamá Deformed Belt, which dips landward at an angle of 30° (e.g. Plafker and Ward, 1992; Montero et al., 1994; Protti and Schwartz, 1994; Tajima and Kikuchi, 1995). Acceleration time histories revealed a complex rupture involving several sub-events, and after-shock studies defined a rupture area of approximately 85 x 45 km^2. Geological reconnaissance in the epicentral region later revealed secondary faulting, and 0.5-1.5 meters of co-seismic uplift of inter-tidal reefs, along an 80 km stretch of coastline, southeast from Limón, Costa Rica (Plafker and Ward, 1992; Denyer et al., 1994).

5.2.20 2000, Feb. 26 North Panamá Deformed Belt (San Blas) M 6.1

An event located 110 km northeast of Panamá City and ~60 km beneath Serranía de San Blas in the subducted Caribbean plate. Strongly felt in Panamá City. Numerous persons fled into the streets. Minor non-structural damage to buildings in San Blas.

6.0 Slip Rates and Recurrence Intervals

Current knowledge of the regional fault sources provides a reasonable basis for the selection of design earthquakes in Panamá, but there are few historical or geological data available to characterize the behavior of individual active faults. For this reason the earthquake potential of local faults must be evaluated from other parameters that can be related to earthquake magnitude and rate of slip. A number of empirical relationships have been developed relating earthquake source parameters and regional plate motion rates, from which estimates of magnitude, slip-per-event and recurrence interval may be estimated (Wells and Coppersmith, 1994). These formed the basis for evaluating fault activity rates for the Gatún Dam study of Schweig et al., (1999). The same methodology is applied in this study, with indicative slip rates and recurrence intervals for rupture assigned to faults in Table 1, based on local relative plate motion rates, historical seismicity and assumptions about the partitioning of plate motion. The inferred rates should be interpreted only as a guide to relative differences in the activity rates for the respective fault zones.

These estimates represent a first approximation and it is reasonable to use these values only as a basis for deriving *indicative* recurrence intervals for fault rupture. The term indicative is emphasized to discourage the assumption of a constant rate of strain accumulation and release. There are different models of fault behavior and abundant data are usually required to adequately define the behavior model (e.g. Sieh et al., 1989; Kagan and Jackson, 1995; Cowan et al., 2000).

7.0 Design Earthquakes and Ground Motion

7.1 Southeast Area of the Canal Basin

This review demonstrates that there are major active faults associated with the Pacific margin of Panamá, but all are located at greater distances relative to sites of engineering interest than those identified by Schweig et al. (1999).

The largest seismic source of engineering interest in the Canal Basin remains the North Panama Deformed Belt and its extension at depth across the interface of the subducted Caribbean plate and Panamá Block. Seismicity attributable to the slab-interface by Schweig et al (1999) is within approximately 50km and 70km, respectively, of localities such as Madden Dam and the Miraflores-Pedro Miguel locks area in the southeast of the Canal Basin.

There is only one shallow (crustal) fault located closer to the Madden Dam than those faults identified by Schweig et al., (1999) for the Gatún Dam. The Limón fault passes within 3.5 km of the west abutment of Madden Dam, but no data are available regarding its slip rate or time of last movement. The length of the Limón fault is only half that of the Río Gatún fault (Table 1), which remains the principal shallow crustal fault for hazard modelling in the Canal Basin.

Based on the conclusions listed above the design earthquakes for the Canal Basin (south east) follow those recommended by Schweig et al. (1999), with minor adaptation as follows:

- Source 1: A moment magnitude (M) 7.7 thrust earthquake located at the Caribbean plate-Panamá Block interface:

  50km from Madden Dam
  70 km from the Pacific Locks

- Source 2: A M6.8 earthquake on the Río Gatún fault

  12km from Madden Dam
  40km from the Pacific Locks

7.2 *Attenuation Models*

Seismic hazard assessment for engineering design requires assumptions to be made about the magnitude distribution of earthquakes in space and time. Ground shaking is the most pervasive of seismic hazards and the one most difficult to anticipate due to many factors that influence the propagation and attenuation of seismic waves. The parameters that must be defined in order to estimate ground motions are earthquake magnitude, type of faulting, distance, and local site conditions.

The source-to-site distances for the Source 1 earthquake, at localities in the south and east of the Canal Basin, are in a range for which more data are available to constrain ground motion attenuation models. Considerable progress has been made in developing attenuation expressions for response spectra appropriate to Central America. Climent et al. (1994) conducted the first comprehensive analysis of combined Central American and Mexican strong motion data, comprising 280 recordings of 72 different earthquakes from about 100 different recording stations[6].

The study combined shallow crustal and subduction zone earthquakes, with most events recorded at distances less than 100km. Data from the Guerrero, Mexico strong motion network were included for events larger than M_w 6.5 and up to magnitude 8.

[6] Country and (no. of records): Costa Rica (157); Nicaragua (34); El Salvador (27); Mexico (62)

These data, comprising ~22% of the total, provide important high magnitude observations at a range of distances greater than 10 km[7].

Minor revision of the Climent et al. model has led to better smoothing of the near-field ground motions (Dahle et al., 1995), and was followed by modeling of a significantly updated Costa Rican strong motion database (Schmidt et al., 1997). The derived peak acceleration (PGA) values for the whole data set were found to be close to those of Dahle et al. (1995), while the PGA curves for shallow crustal earthquakes were close to recent Californian estimates (Boore et al., 1997). There was insufficient distance coverage to model the subduction zone earthquakes separately.

The Dahle et al. (1995) attenuation curve for Central American/Mexico is shown in comparison to other global models in Figure 4 for the Source 1 earthquake of Schweig et al. (1999). The spread among global models arises from the subdivision of data from different tectonic settings, faulting types and the use of different magnitude scales[8]. Surprisingly, the relationship derived for subduction zone earthquakes indicates lower ground motions than most other models. The Dahle et al., (1995) curve predicts ground motions in the middle of the global range, whereas the Joyner (1999) model, based only on the 1985 Valparaiso, Chile earthquake is the most conservative.

One of the difficulties deciding an appropriate level of conservatism for design ground motions in the Canal Basin is that little is known about the degree of seismic coupling between the Caribbean plate and the Panamá Block, relative to other regions. Factors that will control the down-dip width of the coupled (seismogenic) zone[9] on the Caribbean plate interface thrust fault, include the:

- thickness of the Panama Block crust;
- dip profile of the subduction thrust fault, and;
- thermal regime that controls the transition from brittle to ductile deformation

None of these parameters is well constrained by available data, so it is difficult to judge whether the conservatism of the Joyner (1999) model, for example, is appropriate for design purposes.

7.3 Near-field Source Effects and Site Response

Factors that influence the pattern of ground shaking for a given earthquake may include the earthquake source mechanism, direction of rupture propagation, and geometric complexities that affect the velocity and arrest of a rupture. Wave scattering induced by subsurface and surface topography, and resonance effects at certain frequencies within soil layers or sedimentary basins may also influence the dynamic interaction between the soil and an engineered structure.

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[7] Moment magnitudes were established for the Central American data either directly from Harvard moment tensor solutions where available or by regression equations developed by Rojas et al. (1993). Ordaz and Singh (1992) determined the moment magnitudes for the Guerrero, Mexico data.

[8] For example, the relation of Fukushima and Tanaka (1990) was developed for surface wave magnitude, not moment magnitude; and the Youngs et al. (1997) model has standard deviations that are much larger than other models.

[9] (Hyndman et al., 1997).

Large discrepancies between the "averaged" PGA values of an attenuation model and the recorded motions of an individual earthquake may be attributed to near-field source effects, such as fault rupture directivity or amplified soil response (Somerville, 2000). These factors may significantly affect the earthquake motion at the top of a soil deposit. Many of these effects are frequency dependent and some depend on the geometry and size of a structure as well as its distance from the earthquake. Current empirical and analytical techniques for evaluating source, source-to-site and site effects do not yet offer integrated solutions to these uncertainties.

The selection of ground motion time histories is beyond the scope of this study, but the caution advised by Joyner (1999) is reiterated, regarding bias that may be introduced due to local site or path directivity effects. For example, during the M 7.5, 1991 Costa Rica earthquake at the Siquirres dam site, 70km northwest of Limón, the shaking exceeded 0.70g at the surface, but deconvolution of the record indicated about 0.44g at the bedrock-soil interface several meters below the surface (Laporte, 1994). The Siquirres locality is one of the closest to the Canal Basin for which high-magnitude strong motion data are available, but the recording of the 1991 earthquake is highly anomalous, suggesting the influence of local topographic or directivity effects.

8.0 Conclusions

On the basis of this literature review of the active faults and historical seismicity, and consideration of the requirements for estimating ground motions in the Panamá Canal Basin, we conclude:

- There are major active faults associated with the Pacific margin of Panamá, but all are located at greater distances relative to sites of engineering interest than those selected for design earthquakes by Schweig et al. (1999).
- The largest seismic source of engineering interest in the Canal Basin remains the North Panama Deformed Belt, and the interface of the subducted Caribbean plate beneath the Panamá Block.
- The Río Gatún fault remains the principal, shallow crustal fault for hazard modelling in the Canal Basin.
- Based on the conclusions listed above, the design earthquakes of Schweig et al. (1999), are adopted with minor adaptation as follows:
    - Source 1: A moment magnitude (M) 7.7 thrust earthquake located at the Caribbean plate-Panamá Block interface:

      50km from Madden Dam
      70 km from the Pacific Locks
    - Source 2: A M6.8 earthquake on the Río Gatún fault

      12km from Madden Dam
      40km from the Pacific Locks

The Source 1 earthquake will continue to dominate the hazard assessment, but uncertainties about the source and path effects associated with this event emphasize the need for caution in the selection of ground motion attenuation models or time histories. The attenuation model of Dahle et. al. (1995) derived from Central American and Mexican strong motion data provides a useful basis for comparison with other attenuation relationships. Sensitivity analysis with attention to the effect of extreme data values for different attenuation models should provide a guide to the appropriate level of conservatism for engineering design in the Canal Basin.

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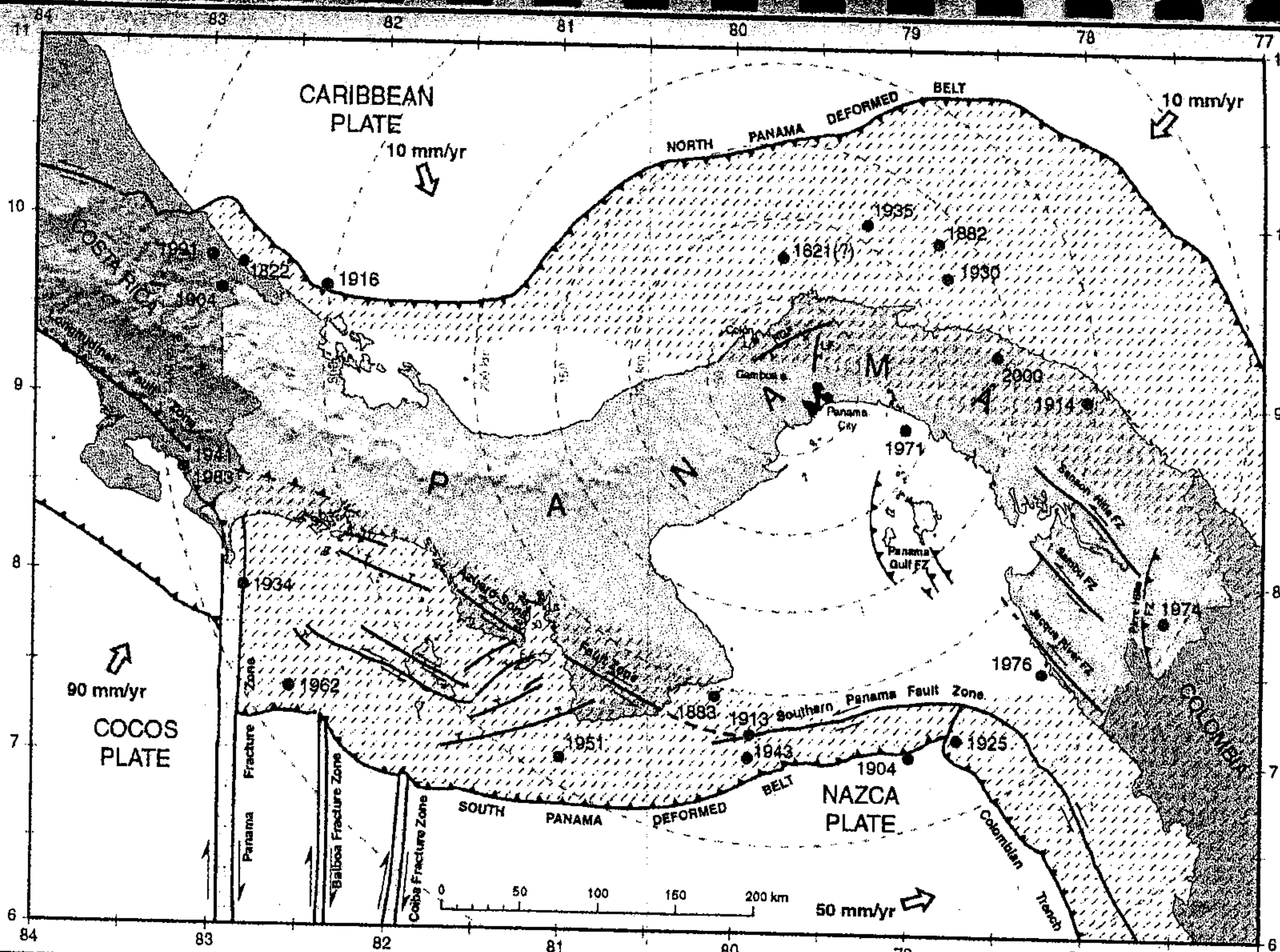
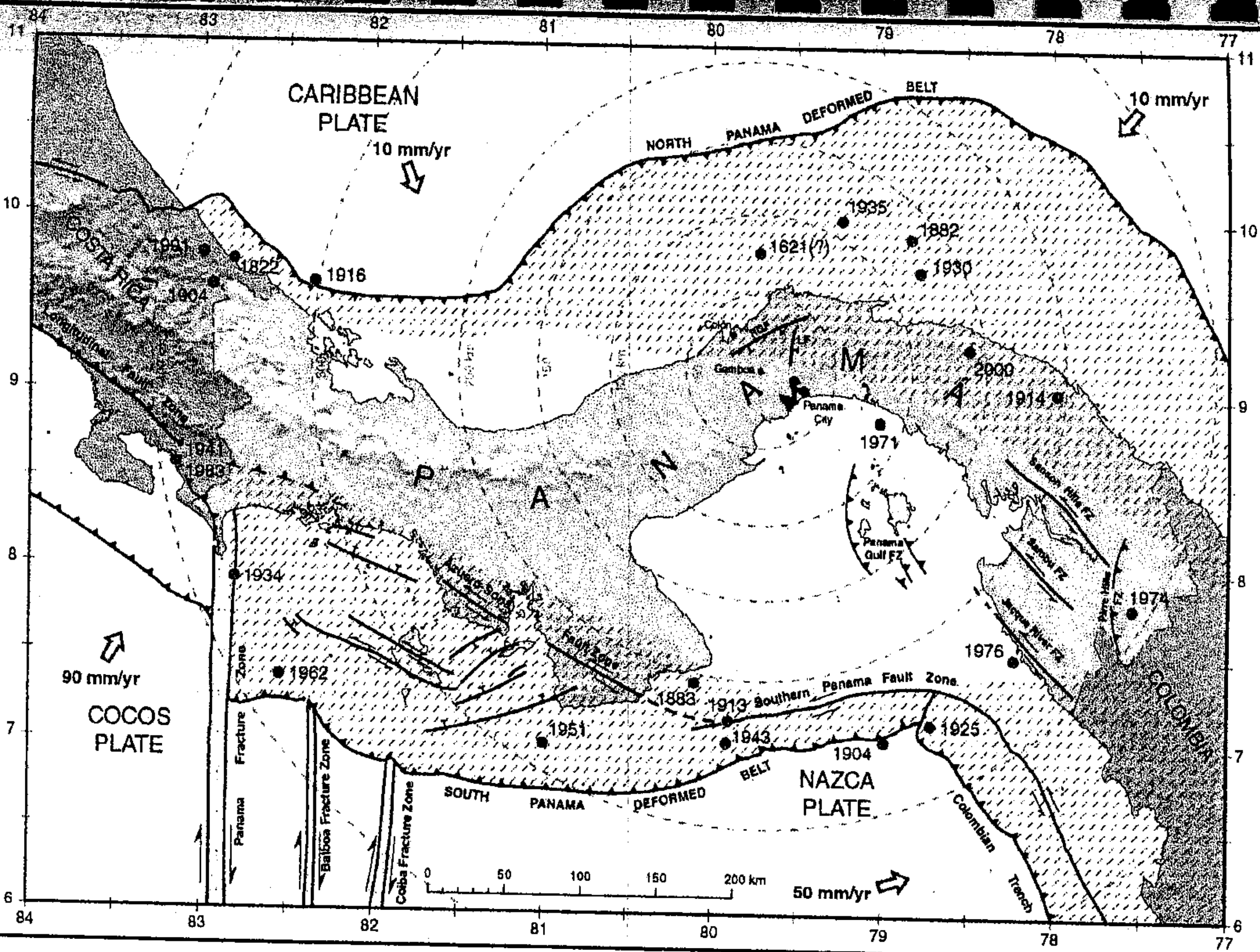


Design Earthquakes for the Southeast Area of the Canal Basin, Panamá	Report No. HC-ACP-01	Fig. No. 1
ɪr historical earthquakes (year and epicenter) and fault zones of Panamá and adjoining regions within a radial nce of 400km from Gamboa, approximate geographic center of the Canal Basin. The hatch tone represents the red extent of subducted lithosphere beneath the margins of the Panamá Block (adapted from Cowan et al., 1998).	Prepared by HC	Date February 2001

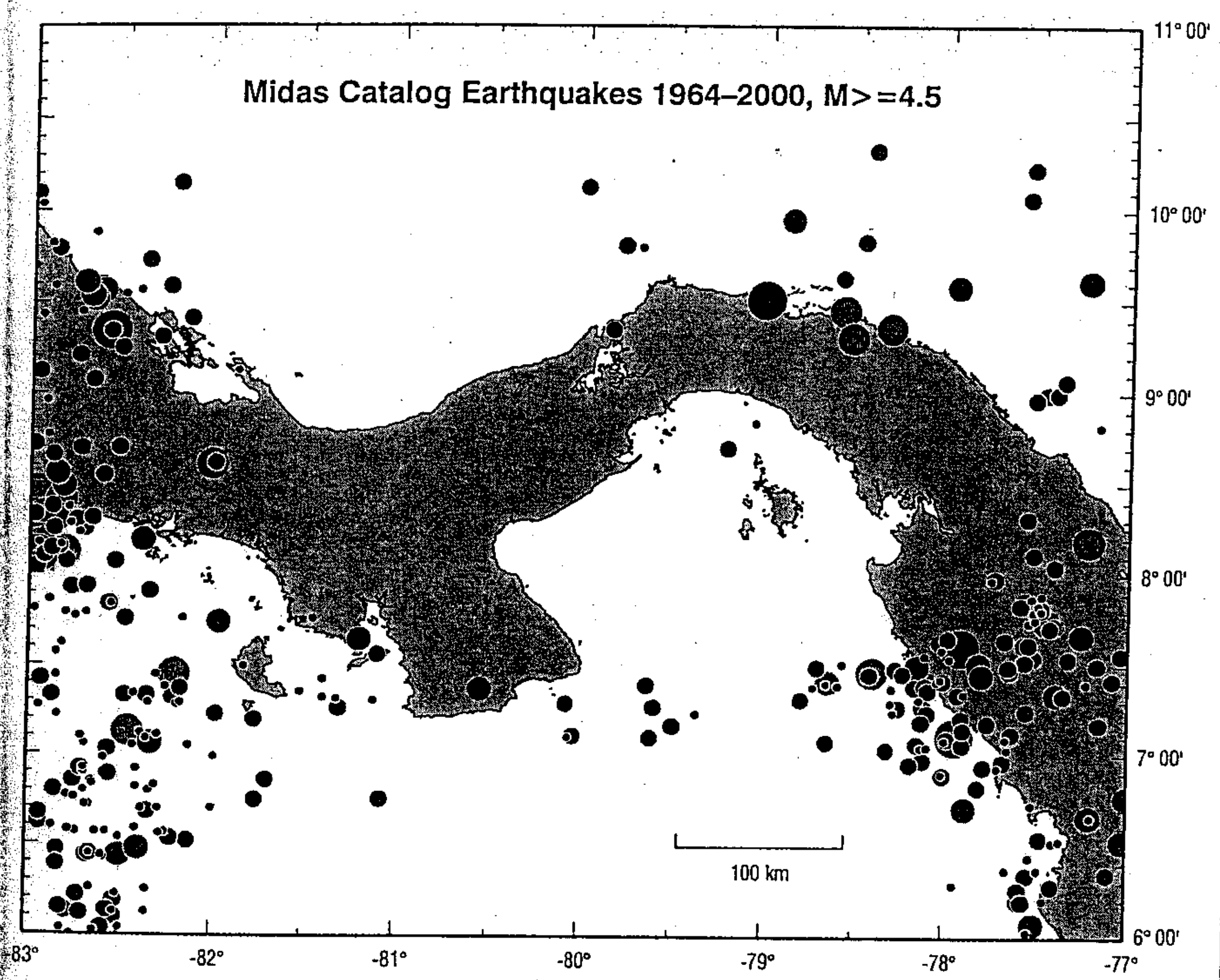
Tectonic Region	Fault Zone and Type	Cumulative Length[1] (km)	Average Slip Rate (m/kyr)	Recurrence (years) and slip per event [m]	Max M	Site Distance[2]	
						Madden	Miraflores
Panamá Block Canal Basin Faults	*Rio Gatún fault zone* - oblique normal	~40 km	<1	10,000 – 20,000 [0.8]	6.8	12	37
	Limón fault – oblique normal	~23 km	<1	10,000 – 20,000 [0.5]	6.5	3.5	23
Panamá Block-Caribbean Plate Boundary	*North Panamá Deformed Belt* thrust and normal	>900 km	~10	330-1000 [3.3]	7.7	~50	~70
Panamá Block-Nazca Plate Boundary	*Southern Panamá Fault Zone* – strike-slip	~130 km	>10	<500 [2-3]	7.3	220	196
	Azuero-Sona Fault Zone -strike slip	~180 km	<5	<1000 [2-3]	7.3	235	212
	South Panamá Deformed Belt – thrust and normal	~550 km	>5	500-1000 [2-3]	7.3	220	195
Eastern Panamá-Colómbia Collision Zone	*Gulf of Panamá Faults* thrust	~50 km	<5	>1000 [probably ~1.0]	7.0	105	85
	Sanson Hills fault zone - strike slip	~90 km	<5	>1000 [probably ~1.0]	7.2	165	155
	Pirre Hills fault zone – thrust	~40 km	<5	>1000 [probably ~1.0]	7.0	250	235
	Jaqué River fault zone – strike slip	~60 km	<5	>1000 [probably ~1.0]	7.0	225	200
	Colómbian Trench – thrust and normal	>250 km	>10	<500 [3-4]	7.7	257	235
Panamá Block-Cocos Plate Boundary	*Balboa and Coiba Fracture Zones* – strike slip	>130 km	>10	<500 [2-3]	7.6	386	370
	Panamá Fracture Zone – strike slip	>260 km	>50	<500 [2-3]	7.6	379	370

[1] After Cowan et al. (1998) and Schweig et al (1999)
[2] Shortest slant distance from potential rupture edge to site. The NPDB distance is determined from the seismicity data of Schweig et al. (1999); all other faults from Cowan et al. (1998)

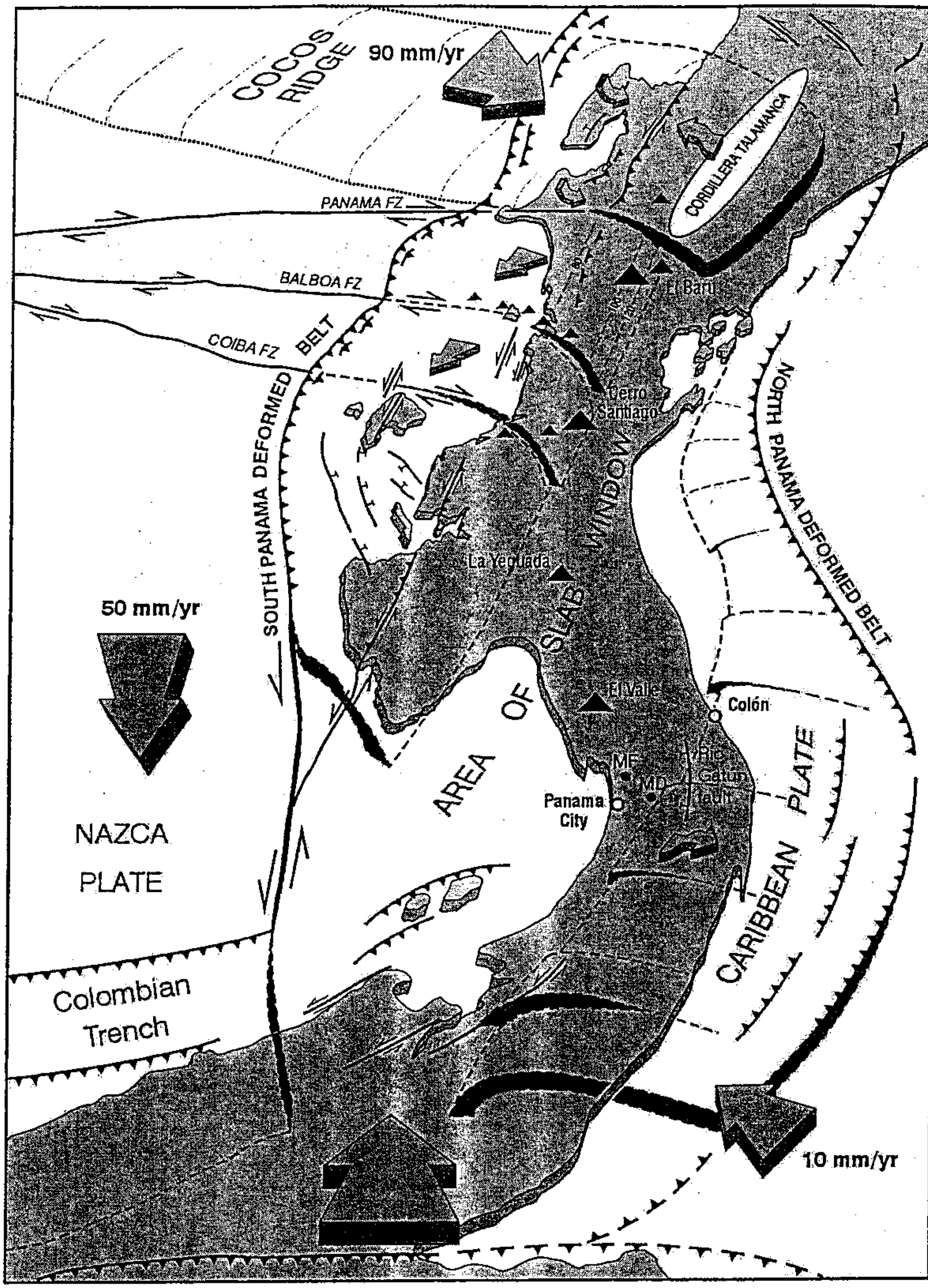
Table 1. Major active faults in Panamá and vicinity and their distance from Madden Dam and the Pacific Locks area



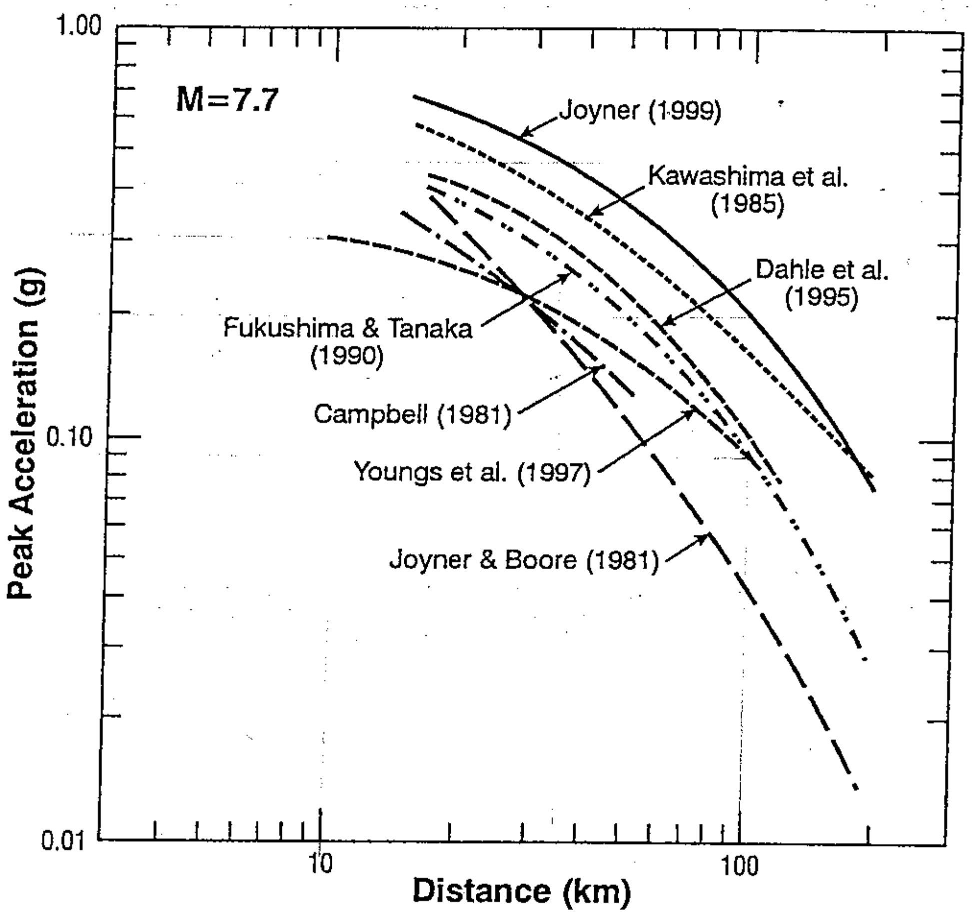
Design Earthquakes for the Southeast Area of the Canal Basin, Panamá	Report No. HC-ACP-01	Fig. No. 1
or historical earthquakes (year and epicenter) and fault zones of Panamá and adjoining regions within a radial nce of 400km from Gamboa, approximate geographic center of the Canal Basin. The hatch tone represents the red extent of subducted lithosphere beneath the margins of the Panamá Block (adapted from Cowan et al., 1998).	Prepared by HC	Date February 2001



Design Earthquakes for the Southeast Area of the Canal Basin, Panamá	Report No. HC-ACP-01	**Fig. No.** 2
Earthquakes greater than magnitude 4.5 in Panamá and vicinity between 1964 and 2000. Events are plotted in depth increments of 20km with darkest symbols corresponding to shallow crustal earthquakes. The distribution of earthquakes and seismically quiet areas match the known geological faults and the inferred presence of a slab window beneath the center of the Panamá Block. Earthquake data courtesy of the Middle America Seismograph Consortium, MIDAS.	Prepared By HC	Date February 2001



Design Earthquakes for the Southeast Area of the Canal Basin, Panamá	Report No. HC-ACP-01	**Fig. No.** **3**
Perspective diagram of the structure and tectonic forces in Panamá and vicinity based on recorded seismicity and geological data. Major structural elements include subduction thrust faults beneath the Pacific and Caribbean margins of the Panamá Block. Lateral curvature of the Caribbean plate may be accommodated by vertical faults in the slab. The lateral extension of this structure beneath Colombia is omitted for clarity of illustration. Black	Prepared by HC	Date February 2001



Design Earthquakes for the Southeast Area of the Canal Basin, Panamá	Report No. HC-ACP-01	**Fig. No.** **4**
The attenuation of peak ground acceleration (PGA) for subduction zone earthquakes (Kawashima et al., 1985; Fukishima and Tanaka, 1990; Youngs et al.1997; Joyner, 1999), and shallow crustal earthquakes (Campbell, 1981, Joyner and Boore, 1981), compared to a model derived from subduction zone and crustal earthquakes in Central America and Mexico (Dahle et al., 1995). The curves shown are for rock sites and the Source 1 design earthquake of Schweig et al. (1999).	Prepared By HC	Date February 2001

Documentation Page

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NEW SPECTRAL STRONG MOTION ATTENUATION MODELS FOR CENTRAL AMERICA

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Abstract: Cooperation between six Central American countries (Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica and Panama) and Norway, within the frame of the CEPREDENAC organization, has made it possible to collect, collate and analyze a data base of 280 sets of three-component strong motion recordings from Central America, including some recordings from the Guerrero array in Mexico in order to obtain a better coverage in magnitude and distance. Response spectral attenuation relations are developed.

1 Data background

The data selected for analysis are based on strong-motion records from a Central American data base established during the project "Reduction of Natural Disasters in Central America, Earthquake Preparedness and Hazard Mitigation", sponsored by The Norwegian Agency for Development Cooperation (NORAD). The data base is documented in more detail by Taylor (1992), Taylor et al. (1994), Santos (1992), and Segura et al. (1994).

In order to strengthen the magnitude-distance distribution of the data at larger magnitudes, some records for earthquakes above M_w 6.5 from Guerrero, Mexico have been included in the analysis.

The number of records contributing to the analysis by country and agency providing the data are given in table 1. The data used in the regression amounts to 280 records from 72 different earthquakes recorded at around one hundred different stations. The earthquakes are classified as subduction zone or shallow crustal events.

The recordings are classified as being rock (92) or soil (188), and this is an active parameter used in the regression analysis. The distribution of the records with respect to magnitude and epicentral distance is shown in fig. 1. The correlation coefficient of the distribution is 0.45, representing a moderate dependence between magnitude and distance. As a first approximation in this initial analysis, therefore, a simple one-step regression was applied (for a more detailed discussion of one-step vs. two-step approaches, see Dahle et al., 1991).

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**** Centro de Investigaciones Geotechnicas (CIG), San Salvador, El Salvador.
***** Instituto Nicaragüence de Estudios Territoriales (INETER), Managua, Nicaragua.

No. rec.	Country	Institution providing the data
102	Costa Rica	Laboratorio de Ingenieria Sismica (LIS), University of Costa Rica, San Jose
62	Mexico	National University of Mexico (UNAM), Mexico City
55	Costa Rica	Instituto Costarricense de Electricidad (ICE), San Jose
34	Nicaragua	Instituto Nicaragüense de Estudios Territoriales (INETER), Managua
19	El Salvador	Centro de Investigaciones Geotecnicas (CIG), San Salvador
8	Nicaragua, El Salvador	United States Geological Survey (USGS), Boulder, Colorado

Table 1 : Number of strong motion records contributing to the analysis by country and by agency providing the data.

The location of epicenters and recording sites for the strong motion data are shown in fig. 2. It should be emphasized that the Guerrero (Mexico) data comprise 62 of 280 records, amounting to around 22% of the data, and mainly stemming from large magnitude earthquakes at large distances.

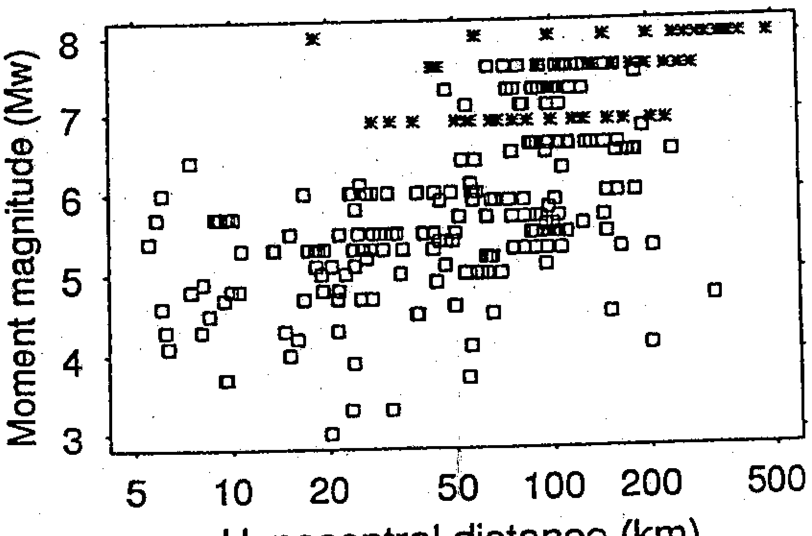

Fig. 1 : Magnitude-distance distribution of strong motion records used in the present study. The open squares represent Central American recordings, while the stars represent recordings from Guerrero strong motion array in Mexico.

Throughout this analysis only the largest horizontal component of ground motion has been used, selected from a data base of 280 three-component recordings. For recordings from the Guerrero, Mexico array, only data above magnitude 6.5 were used.

The magnitude-distance distribution (fig. 1) shows that magnitudes around 5-6 and 7-8 are well represented, with the important high magnitude coverage obtained by the inclusion of the Guerrero (Mexico) data. For more details concerning the determination of source parameters for the selected events we refer to Taylor et. al. (1994) and Segura et al. (1994).

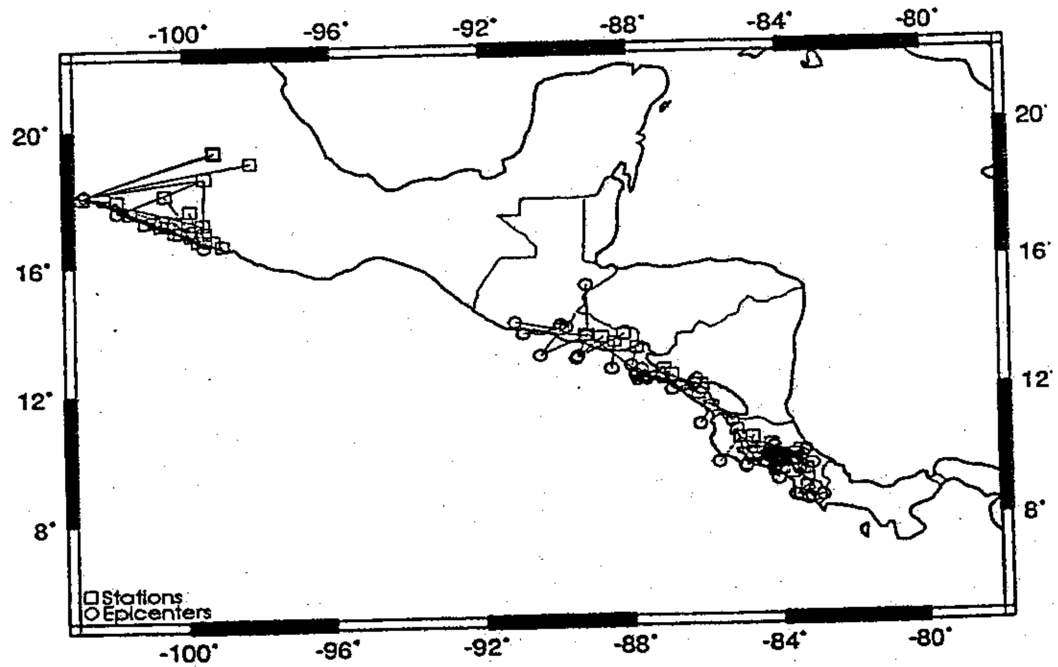

Fig. 2 : Epicenters, stations and wave paths for the data set analyzed.

Moment magnitudes were established for the Central American data either directly from Harvard moment tensor solutions whenever available, or by regression equations developed by Rojas et al. (1993b), see alsoLindholm et al. (this issue), for different magnitude types versus M_w. The order of priority of the magnitudes used for conversion to M_w, were M_S (surface wave), m_b (body wave), M_D(local), respectively. For the Guerrero (Mexico) data the moment magnitudes were taken from Ordaz and Singh (1992).

The work by Rojas et al. (1993a) contains several alternative locations and magnitudes for particular earthquakes. A special catalogue linking the preferred location and magnitude to the strong motion data was established and entered into the headers of the strong motion data files before we commenced the processing and analysis.

2 Data analysis

The analysis of the strong motion data in this study is based on a simple one-step procedure incorporating a term that accounts for soil amplification. This procedure requires a classification of recording sites (rock or soil), which was performed as a part of the data base establishment (Taylor et. al., 1994).

2.1 MODEL FORMULATION

The initial analytical approach taken to develop prediction equations for earthquake ground motion was based on the general linearized simple form of the ground motion amplitude formula:

$$\ln A = c_1 + c_2 M_w + c_3 \ln R + c_4 R + c_5 S + \ln \varepsilon \quad (1)$$

where M_w is moment magnitude and $R = \sqrt{r^2 + r_h^2}$, where r is hypocentral distance in km and r_h is an adaptive, fictitious depth parameter in km introduced to ensure constant ground motion in the very near field. S is zero for rock sites and 1 for soil sites and $\ln\varepsilon$ is a normally distributed error term with zero mean and standard deviation σ i.e. $\ln\varepsilon = N(0, \sigma)$.

One of the basic problems in the estimation of prediction equations for earthquake ground motion by ordinary least squares procedures, is that the resulting coefficients are inconsistent with the physics of wave propagation. In particular, those physical effects which are dependent on distance (geometrical spreading, anelastic attenuation and dispersion) may be difficult to resolve in terms of physically meaningful, predictive coefficients.

However, the fact that seismological problems may be described by physical theory presents some important a priori expectations to the coefficients that represent different physical properties of the wave-field. Also, earlier empirical and analytical results pertaining to the same problems, contribute directly to a better understanding of the distribution of the coefficient values in equation 1. Bayesian analysis (Broemling, 1985) combines information contained in the above mentioned background sources with the actual empirical data being analyzed, resulting in predictive equations that are more in accordance with the a priori expectations, and avoiding physically unrealistic coefficient values.

Following the requirements of the procedure (and computer code) of Ordaz et al. (1994), we have assessed the 90% confidence interval for each of the parameters c_1-c_5 and determined mean values and the standard deviations of their a priori distributions.

2.2 RESULTS

Regression coefficients and standard errors obtained by the Bayesian least squares procedure using equation 1 are given in table 2 for response spectral pseudo-relative velocity (PSV) in m/s and for peak ground acceleration (PGA) in m/s^2. The relations are shown for PSV at 1.0 Hz (near top of spectrum) and for PGA (high frequency asymptote) in fig. 3.

f(Hz)	c_1	c_2	c_3	c_4	c_5	r_h	σ_{bay}	σ_{ls}
0.25	-7.324	1.009	-0.629	-0.00038	0.496	6	0.73	0.67
0.50	-7.205	1.131	-0.762	-0.00051	0.536	6	0.79	0.75
1.00	-6.595	1.084	-0.792	-0.00075	0.588	6	0.82	0.79
2.00	-5.717	0.920	-0.761	-0.00106	0.566	6	0.83	0.81
5.00	-4.746	0.645	-0.674	-0.00155	0.470	6	0.82	0.80
10.00	-4.608	0.486	-0.609	-0.00198	0.381	6	0.81	0.79
20.00	-5.375	0.449	-0.575	-0.00246	0.308	6	0.78	0.76
40.00	-7.106	0.554	-0.560	-0.00302	0.326	6	0.75	0.73
PGA	-1.579	0.554	-0.560	-0.00302	0.326	6	0.75	0.73

Table 2 : Regression coefficients according to equation 1 for response spectral PSV in m/s (PGA in m/s^2) for the largest horizontal component of ground motion at 5% damping. The sigma values are given for the Bayesian (bay) and the least squares (ls) regressions, for comparison.

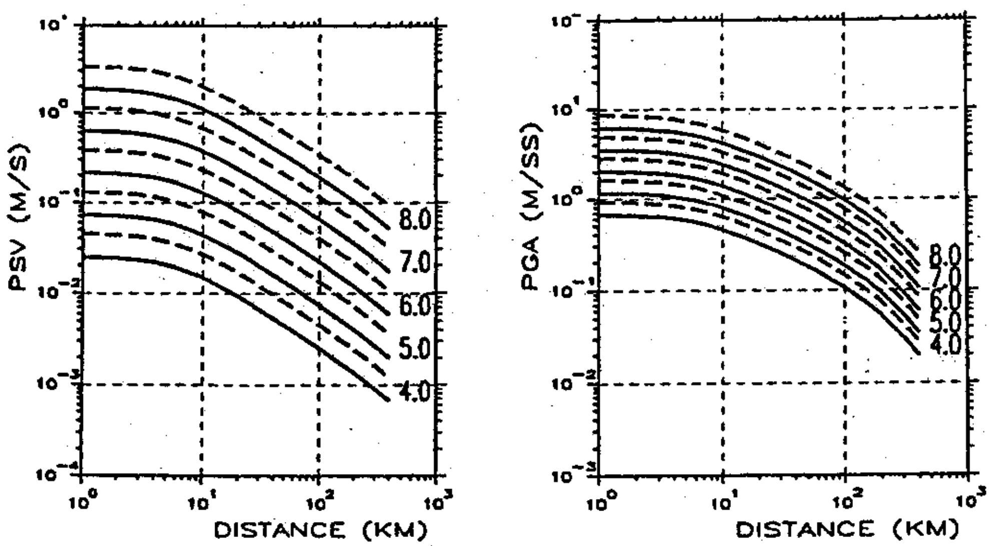

Fig. 3 : Derived attenuation relations shown for M_w 4-8 for PGA (left) and for PSV at 1 Hz (right), for rock (solid) and soil (dashed).

The coefficients in table 2 are smoothed values except for the 0.25 Hz and 40 Hz (PGA) values. The smoothing was done on the basis of nearly twice the number of points in frequency as those shown in table 2, using a conventional third order polynomial fit. Predicted spectra for a few combinations of magnitudes, distances and site conditions are shown in fig. 4.

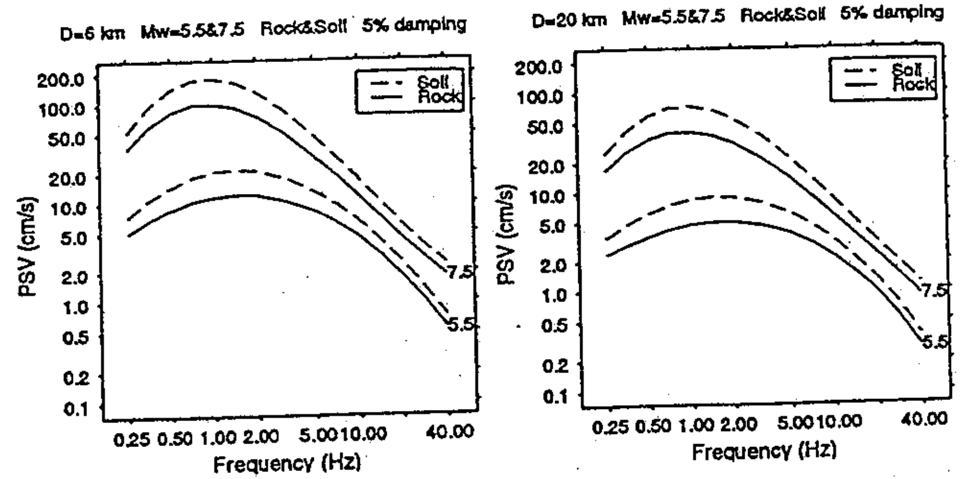

Fig. 4 : Predicted spectra for soil and rock site conditions at 6 and 20 km distance for magnitudes 5.5 and 7.5.

3 Discussion and conclusions

One of the main concerns in merging Guerrero (Mexico) data with the Central American data to strengthen the coverage at high magnitudes is the possible difference of the two data sets. This has been studied by plotting observed PSV simultaneously for both data sets, corrected to the nearest magnitude using the c_2 coefficient of table 2.

Fig. 5 shows comparative plots for soil and rock site observations around magnitude 8. Based on this and similar plots at other magnitudes, it may be concluded that no significant difference is clearly visible in the data, neither for soil nor for rock conditions.

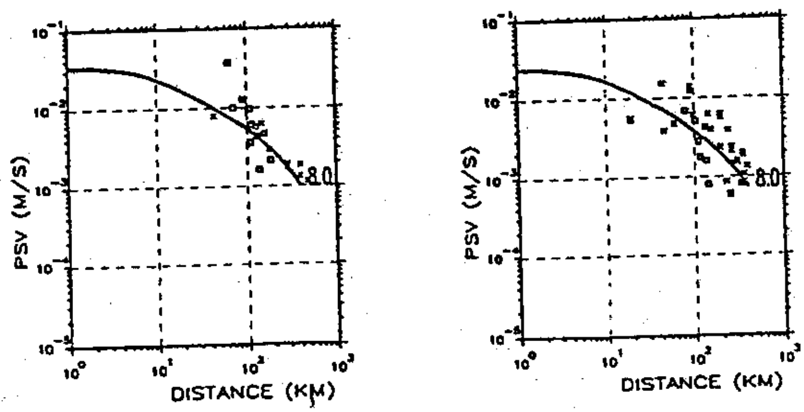

Fig. 5 : Soil (left) and rock site (right) observations of PSV at 40 Hz corrected to M_w 8. Open squares represent Central American observations while crosses represent Mexican data. The derived relation is shown for magnitude 8.

The data base of strong motion data (Taylor et al., 1994) classifies strong motion records according to their inferred origin as shallow crustal or subduction zone events. Fig. 6 shows subduction and shallow crustal event observations plotted against the regression results for PSV at 40Hz and 1 Hz PSV, respectively. It is seen, as confirmed also from similar plots at other magnitudes, that no clear difference exists between the populations. The distinction between shallow crustal and subduction zone events was therefore disregarded in the final analysis.

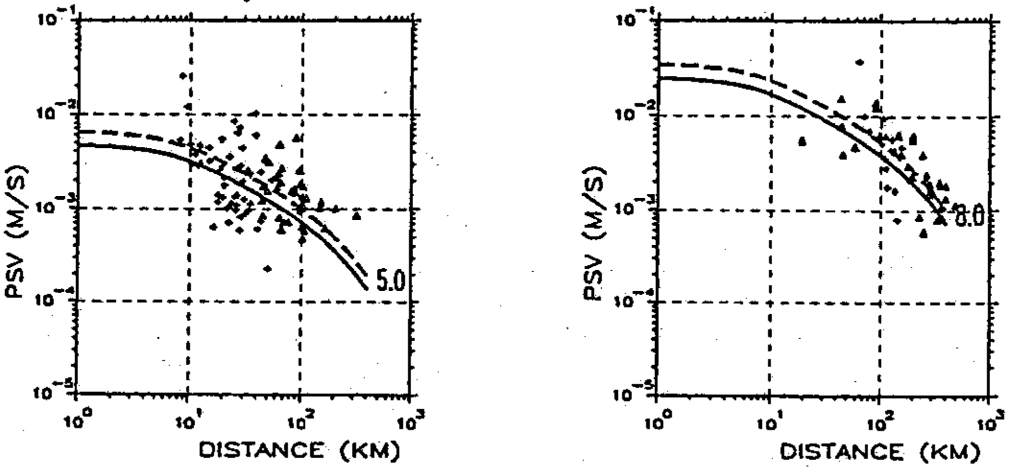

Fig. 6 : Observations of PSV at 40 Hz for Central American and Guerrero (Mexico) data for moment magnitudes 5 and 8. Subduction events (delta) and shallow crustal events (plus). The derived relations for the two magnitudes are shown for both rock and soil site conditions.

Very few strong motion attenuation relations from tectonically similar environments exist for comparison. We have chosen here to compare our results, as shown in fig. 7, with the PGA relationship developed for Japan by Fukushima and Tanaka (1990).

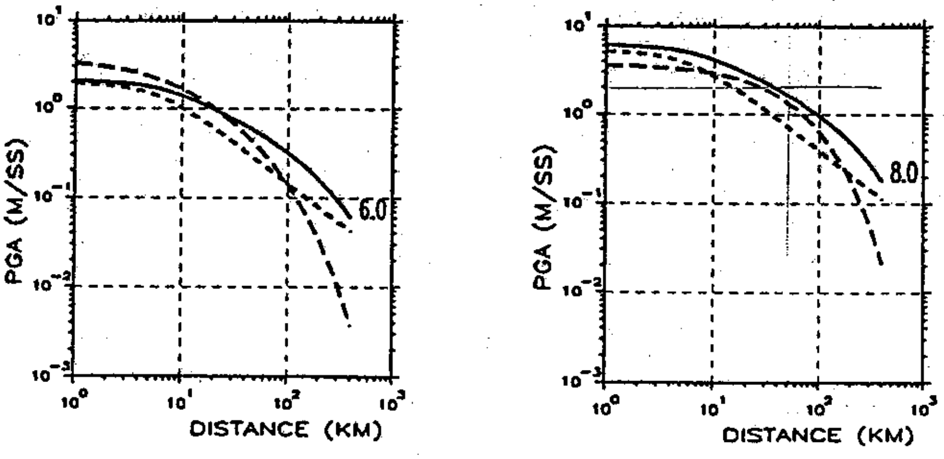

Fig. 7 : PGA relations for magnitude 6 (left) and 8 (right) for this study (solid line) and those obtained by Fukushima and Tanaka (1990) (dashed) and Boore et al. (1993) (dotted).

Also, even though the tectonic similarity is poor, we have chosen to compare with the recently developed relation by Boore et al. (1993) for California. A direct comparison is problematic here, however, also because the Californian study is using the closest distance to fault rupture as a measure of distance, while the Japanese study uses M_S magnitude. However, the comparisons, as shown in fig. 7, do serve as a general indication of levels and trends.

In conclusion, as a first approximation, the inversion by a simple one step Bayesian linear regression procedure presents an adequate estimate of response spectral PSV and PGA for rock and soil conditions applicable for Central America. The attenuation of response spectral ground motion is characterized by geometrical spreading closer in form to cylindrical than spherical spreading in this environment. The average soil amplification is in the range 40-80%, highest around the frequency of 1 Hz.

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