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Map and Database of Quaternary Faults and Folds in Panama and Its Offshore Regions

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INTRODUCTION

The U.S. Geological Survey (USGS) is assisting in the compilation of a series of digital maps of Quaternary faults and folds in Western Hemisphere countries as part of the International Lithosphere Program's (ILP) project for a “World Map of Major Active Faults.” The maps from this project show the locations, ages, and activity rates of major earthquake-related features such as faults and fault-related folds. They are accompanied by databases that describe these features and document current information on their activity in the Quaternary. The project is a key part of the Global Seismic Hazards Assessment Program (ILP Project II-0) for the International Decade for Natural Hazard Disaster Reduction.

The project is sponsored by the International Lithosphere Program and funded by the USGS’s National Earthquake Hazards Reduction Program. The primary elements of the project are general supervision and interpretation of geologic/tectonic information (Michael N. Machette, Project Chief), data compilation and entry for fault catalog (all personnel), database design and management (Kathleen M. Haller), and digitization and editing of fault and fold traces (Richard L. Dart) in [†]ARCINFO. For the compilation of data, we engaged experts in Quaternary faulting, neotectonics, paleoseismology, and seismology. These experts are the primary authors of this report, and questions about individual fault descriptions should be directed to them. Questions about the project, its status, and the GIS map should be directed to the USGS authors.

Prior to initiating this project, no modern or digital map of active or Quaternary faults existed for Panama or any other country within Central America, even though understanding the extent and character of active and older Quaternary faults are critical elements of seismic hazards analysis. Creation of this map and the accompanying database will help extend the relatively short record of instrumental and felt seismicity in Panama by creating a paleoseismic record of surface deformation associated with large (M>6.5) earthquakes.

Although basic fault data are available for most of the country, the degree of completeness varies greatly and often is a function of the degree of remoteness and vegetation cover. A few faults have been the subject of recent investigations involving modern paleoseismic techniques (see for example, Cowan and others, 1997). Other regions and faults have been studied in some detail, usually in association with concerns about hazards to urban areas or the safety of critical facilities such as lifelines, oil-and-gas pipelines, or power-generating facilities. Thus, considerable effort was required from the primary authors in order to compile information from a wide variety of sources and insure that the national product is up to date and provides fairly uniform coverage for the entire country. Nevertheless, the general state of knowledge for faulting in Panama is probably best described as being of a reconnaissance nature. Little is known in a collective sense about the overall rates of fault activity and fault chronology—information that is difficult to acquire but critical to seismic hazard assessments. Hopefully, additional paleoseismic studies will help augment this map and database.

STRATEGY AND PURPOSE

For the map of Panama, we relied on known, productive experts with strong local or regional knowledge of Panama who were willing to participate in this international project. Given the limited time to produce the map, the project was restricted to compilation of just those elements needed for ILP's Global Seismic Hazards Assessment Program (see database). We anticipate that the project will point out the shortcomings of past and current research on Quaternary faulting in Panama in terms of quantity, quality, scope, and regional coverage and should help promote new efforts to collect paleoseismological data in previously neglected or known critical areas.

In many cases, seismicity has been used to define some potentially active faults, especially along active plate margins. However, recent faulting events in the Western Hemisphere have shown that much of the faulting away from active plate margins occurs along faults with no significant level of seismicity and that only a fraction of active faults are characterized by ongoing seismicity. Thus, the information on Quaternary faulting included within this database should help extend the modern (past several hundred years) record of seismicity into prehistoric time, and allow better assessments of active and potentially active faults in Panama (Montero and others, 1998) and other Western Hemisphere countries.

TECTONIC SETTING

Panama comprises a zone of diffuse deformation, between the Caribbean plate to the north, the Cocos and Nazca plates to the west and south (respectively), and the South American plate to the east (for example, de Boer and others, 1988, 1995; Kellogg and Vega, 1995). The Provinces of Bocas del Toro and Chiriqui in the west, and San Blas and Darien to the east encompass the most seismically active regions of Panama. The southwestern Province of Los Santos, in the Azuero Peninsula, also borders the tectonically active southern margin of Panama. In

[†] Any use of trade names (such as this and others in the report) does not imply endorsement by the U.S. Geological Survey.

these areas, the steep topographic gradient of the highlands reflects the dynamic setting in a zone of active earth deformation and young volcanism. By contrast, central Panama is characterized by low topographic relief and a deeply weathered mantle of Miocene, or older, igneous and sedimentary rocks, which reflect a more stable, intraplate tectonic setting and much lower rates of tectonic deformation.

MAJOR STRUCTURAL ELEMENTS

Active subduction of the Cocos Plate occurs beneath the Pacific margin of the arc in southern Costa Rica, whereas the Nazca Plate is subducted obliquely, in a northeasterly direction, beneath the southwest margin of Panama. The Caribbean Plate is moving south with respect to Panama, underthrusting along the Caribbean margin of the isthmus. Westward relative motion of South America results in collision and shear deformation in the Darien Province, and underthrusting of the Nazca Plate in the Colombian subduction zone.

All major intervals of geological time since the mid-late Cretaceous (100 Ma) are represented in the rocks of Panama. However, the present configuration of the isthmus is the product of a major reorganization of regional tectonics that accompanied the collision of a volcanic arc with South America, between 25 and 7 Ma (for example, Weyl, 1980; Escalante, 1990). Most of the regions historical seismicity can be attributed to tectonic instability associated with relative movements between the neighboring plate boundary elements (for example, Wolters, 1986; Adamek and others, 1988) described as follows.

North Panama Deformed Belt (NPDB, PA-12)

The NPDB comprises an arcuate zone of distributed folding and thrust faulting that extends eastward from Costa Rica to the Gulf of Uraba, Colombia (Silver and others, 1990, 1995). The NPDB is drawn as a wide belt of deformation that contains thrusts and folds too numerous to show. 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. That event, located offshore northeast of Colon, occurred in 1882 with an estimated magnitude of 7.5-7.7. The earthquake produced widespread surface effects including liquefaction in northern Panama and a tsunami that drowned more than 60 persons in the Province of San Blas (Mendoza and Nishenko, 1989).

Cocos Ridge Collision and Subduction Zone

On the Cocos Plate, west of the Panama Fracture Zone (PA-04), a thickened area of oceanic crust (Cocos Ridge) is subducting beneath the southwest margin of the Caribbean Plate and the Panama Block. The rate of convergence is between 70 and 95 mm/year. The Cocos Ridge is buoyant and thicker than normal oceanic lithosphere, so the angle of subduction is shallow. Shortening and uplift of the overlying plates characterize the associated deformation. Some fraction of the thrust deformation is expressed as uplifted former coastlines and intertidal shore platforms, such as along the Osa and Nicoya Peninsulas on the Pacific margin and along the Limon coast on the Caribbean margin (Gardner and others, 1992; Plafker and Ward, 1992).

The subduction zone is defined by seismicity only to a depth of about 50-km beneath southern Costa Rica (Protti and others, 1995). The subduction interface has ruptured twice during large (M 7.5) earthquakes this century (1941 and 1983) in the southern Costa Rica sector (Adamek and others, 1987, 1988, Tajima and Kikuchi, 1995). On the Caribbean margin, the overthrusting of the Panama Block onto the Caribbean Plate reflects a lateral transmission of stress through the arc from the Cocos Ridge collision zone (Plafker and Ward, 1992). The depth distribution of seismicity is poorly constrained, but no events deeper than about 50 km have been reported.

Longitudinal Fault Zone (PA-01)

In western Panama and southern Costa Rica, an elongate, arc-parallel fore-arc basin contains several thousand meters of sediment that have been eroded from the volcanic arc during the past 60 Ma (Escalante, 1990). Numerous, arc-parallel (NW-trending) thrust faults and folds are known to offset the basin sediment, particularly in Costa Rica (see for example, Mora, 1979; Kolarsky and others, 1995). Significant shortening has been accommodated during the subduction of the Cocos Ridge, since Pliocene time.

The principal fault zone in this area is the Longitudinal fault zone, an oblique-reverse, structure that strikes east-southeast, parallel to the volcanic arc across southern Costa Rica (CR-48; see Montero and others, 1998) and the Chiriqui lowlands (PA-01) of western Panama (Montero, 1994). The Longitudinal fault zone juxtaposes early Tertiary (50 Ma) and late Quaternary (<1 Ma) rock and sedimentary units across a thrust contact in the Costa Rica-Panama region.

Panama Fracture Zone (PFZ, PA-04)

The Panama Fracture Zone (PFZ) separates the Cocos and Nazca Plates south of the Burica Peninsula, at the Pacific Coast frontier of Panama and Costa Rica. The PFZ accommodates major right-lateral strike-slip motion at an estimated rate of 50-70 mm/yr (DeMets and others, 1990; Kellogg and Vega, 1995). Two subparallel fracture zones—the Balboa and Coiba—splay off eastward from the PFZ and accommodate some of the right-lateral strike-slip motion (Lonsdale and Klitgord, 1978; Heil, 1988).

The PFZ intersects the Panama-Costa Rica mainland in the region of Burica Peninsula. The surface expression of the Cocos-Nazca plate boundary, landward of the PFZ, consists of narrow, dextral strike-slip fault zones (Medial fault zone, PA-03; Canoas fault zone, CR-49) that show evidence of rapid horizontal movement during the last 10,000 years (Corrigan and others, 1990; Kolarsky and others, 1995; Cowan and others, 1997). Rapid uplift of the Madre Vieja anticline (PA-03) may be associated with the northeastward expression of this dextral motion.

South Panama Deformed Belt (SPDB, PA-09)

East of the Panama Fracture Zone, the Nazca Plate is moving east-northeast, oblique to the southern margin of Panama, at a rate of about 35 mm/year. The PFZ and adjacent splays (Balboa and Coiba fracture zones) are being subducted obliquely beneath the southwest margin of Panama, and the associated deformation is accommodated by thrust faulting along the southern continental margin (MacKay and Moore, 1990; Moore and Sender, 1995). The South Panama Deformed Belt (SPDB) is drawn as a wide belt of deformation that contains thrusts and folds too numerous to show. Numerous earthquakes of moderate magnitude (5.5-6.0) have been recorded in the SPDB.

Azuero-Sona Fault Zone (PA-11) and South Panama Fault Zone (PA-21)

Although the South Panama Deformed Belt (PA-09) accommodates shortening between the Nazca Plate and Panama’s southern continental margin, several large strike-slip faults take up the shear along the margin and within the isthmus. The main structures include: 1) the Azuero-Sona fault zone (PA-11), which strikes northwest/southeast across the Azuero and Sona Peninsulas; and 2) the South Panama fault zone (PA-21), a left-lateral structure located offshore that extends eastward from the Azuero-Sona fault zone to the Colombian accretionary complex (PA-22) and associated Colombian (South American) subduction zone. The South Panama fault zone probably ruptured in 1904 and 1913, and another large (M>7) event occurred near the junction of the South Panama fault zone and the Colombian subduction zone in 1925.

PREPARATION OF MAP AND DATABASE

This compilation shows evidence for activity on Quaternary faults and folds in Panama and regions offshore of Panama. The data were compiled during 1996-98 from the available published literature (through 1998), recent geological investigations, and from interpretation of aerial photographs by Hugh Cowan. Michael Machette edited most of the text and map data and provided guidance for the project under the International Lithosphere Program's Task Group II-2 "Major Active Faults and Folds of the World," for which he is the Co-chairman (Western Hemisphere). The surface traces of the Quaternary faults and folds were compiled on topographic base maps at a scale of 1:200,000 by Hugh Cowan. Offshore traces are based primarily on marine geophysical studies and bathymetric maps; these traces are inherently less well defined and located, and should be considered approximate.

Richard Dart used GIS (Geographic Information System) technology to produce the fault and fold maps. The traces of Quaternary faults and fold were digitized, attributed for age, sense of slip, and line type (continuous, discontinuous, and concealed or inferred), and reprojected using a Mercator projection. The maps were prepared with ARC/INFO version 7.1.2 running under Solaris version 2.5.1 on a Unix workstation. The GIS data is scale independent but should not be used at scales greater (more detailed) than 1:200,000. Data for the fault endpoints, length, and average strike were generated from the ARC/INFO files.

The base-map information was taken from the Digital Chart of the World, which was created for use with ARC/INFO (copyright 1993 by the Environmental Systems Research Institute, Inc.). The Digital Chart of the World was compiled at a scale of 1:1,000,000, but is reasonably detailed at the printed scale of the map (1:750,000). It was originally developed for the United States Defense Mapping Agency (DMA) and is primarily derived from the DMA Operational Navigation Chart (ONC) Series.

MAP

The map of Quaternary faults and folds of Panama was compiled on and digitized from base maps at 1:200,000 scale (50-minutes of latitude by 1.5° of longitude). This scale allows output as a single-country map (1:500,000 to 1:750,000 scale) or provincial and regional maps (1:200,000 to 1:500,000 scale) while retaining all significant digital information. In addition to fault location and style, the map shows time of most recent movement and estimates of slip rate (as a proxy for fault activity). Although as many as five categories of Quaternary faults can be depicted on the Western Hemisphere maps, only three categories were used in Panama:

Historic (generally <200 years),
Holocene and latest Pleistocene (<15,000 years or <15 ka),
Quaternary (<1,600,000 years or <1.6 Ma).

Categories for differentiating late Quaternary (<130 ka) and late and middle Quaternary (<750 ka) ruptures were not used owing to the general lack of stratigraphic and chronological control needed to make these age differentiations. Nevertheless, this categorical time scheme allows some flexibility in reporting between countries owing to the differing levels of investigation and abilities to date prehistoric faulting.

Three ranges of slip rates depicted by differing lines are shown on the map in order to differentiate known rates of fault activity:

>5 mm/yr—Plate-boundary faults and subduction zones,
1-5 mm/yr—Lesser strike-slip and major extensional faults,
<1 mm/yr—Most extensional and intraplate faults.

Most faults in Panama with "unknown slip rates" are drawn with the <1-mm/yr line thickness.

DATABASE

The purpose of the database is to provide large quantities of fault data that can be readily accessed using a variety of search parameters. For this database, we anticipate that the user would want search-and-retrieve capabilities from a personal computer. The user may want to sort the data by such parameters as fault name, time of most recent movement (one of three categories), slip rate (one of three categories), sense of movement, or by multiple parameters.

The process of data compilation starts with data acquisition and synthesis. In the case of faults, the compiler must determine if the structure is a simple one, or if it qualifies as having sections (increasing complexity of geometry or fault history). Then using the appropriate form, the compiler tabulates information on the fault's parameters. The forms were built in Microsoft Word for the Macintosh.

After this report is released, we will incorporate suggested changes and additions; then import the data to the computer database. Each of the fields is a potential search object. The use of a computer database program allows us to custom format the reporting of data and to collapse unused fields or notes. The basic fields are restricted to 256 characters, but we use the note option for more explanatory information (shown under comments in this report).

The fault and fold data will be released in several forms. This open-file report constitutes a traditional hard-copy catalog (database and map) for Panama. The Panama data will eventually be part of a larger relational computer database for the Western Hemisphere that should be available on the World Wide Web (WWW). This interactive WWW product allows the user to browse, sort, and print the data. However, we do not anticipate allowing the database to be altered using only the run-time WWW version of the database program.

DEFINITION OF DATABASE TERMS

The following terms (in Spanish and English) provide data for specialized fields, most of which will be searchable when the computer database is released. In addition Specialized fields to the searchable fields, more detailed information is provided in the "Comments" section that follows some fields. If a field is empty or has been deleted, no pertinent information was found in the published literature. The following description provides definitions of fields (in alphabetic order) and indicates where various information, if known, can be found. Citations of references are in a traditional (USGS) format, although foreign language citations are as provided by the compilers.

Average dip General down-dip direction of the structure where known.

Average strike The length-weighted average strike of the trace of the structure is reported in the northwest and northeast quadrants of the compass (*i.e.*, N. 30° W., versus S. 30° E.). The error limits that follow the strike are standard deviations for all vectors contained with the trace of that particular fault or collection of faults. These values are included only to provide a general impression of the sinuosity or variability in strike of the mapped structure. Some fault zones include a number of faults with a wide variety of strikes, and thus the error limits are not meaningful values.

Compiler, affiliation and date of compilation The name and affiliation of the person(s) primarily responsible for compilation or update of data presented for the structure. Also shown is the date when data were compiled for this project (*e.g.*, January 1997).

Fault geometry This includes geographic information pertinent to the fault or fault being described. The data include length, average strike, average dip, and sense of movement.

Geomorphic expression General description of the structure's geomorphic expression including information on the the presence or absence of fault scarps, offset streams, monoclines, shutter ridges, associated landslides, etc.

Historical surface faulting When the timing of most recent movement is historic, then this field(s) describes evidence for surface faulting associated with historical earthquakes. Also included is seismological information for the historical earthquake.

Length This field specifies the end-to-end length of the Quaternary-age fault as measured from the most distal ends of the trace. The ends of overlapping or echelon traces are projected to a line defined by the average strike and the length is then determined from those projected end points. Also shown (in parentheses) is the cumulative length of all surface traces included in the fault, fault zone, or collection of faults.

Name (**Fault name** or **Section name**) The earliest referenced name for a structure, fault segment or fault section (where appropriate) generally is given preference, except in cases where a more commonly accepted name is widely used in the recent literature. "Comments" also contains other names and references in which they are used, the geographic limits of the structure, north to south or west to east, as shown in this compilation; various geographic limits that are different in other studies are also included. Minor changes in original name may have been made for reasons of clarity or consistency (such as segment to section) where appropriate. We have found no faults in Panama that justify using the term "segment", owing to a lack of precise timing information.

Number

Structure number The structure (fault or fold) is assigned a number that is preceded by a two character abbreviation (PA, Panama; CR, Costa Rica; etc.) that is unique to each of the countries in the Western Hemisphere. References to the same structure shown in other compilations, such as CR-50 and PA-12 are included in "Comments".

Section number An alpha character is assigned to the northernmost or westernmost section of a fault (*e.g.*, fault CR-50 has two sections: CR-50A and CR-50B).

Number of sections (only used for faults with sections) Numeric value for number of sections (*e.g.*, 4) defined in studies that do not meet the minimum requirements for segments established for this compilation. "Comments" include reference in which sections are discussed; if the term "segment" is used in the literature, an explanation of why "section" is used in the database is provided.

Recurrence interval Time interval in yr (based on historic data, calendric or calibrated radiocarbon dates), in ^{14}C yr (based on uncalibrated radiocarbon dates), or in k.y. (thousand years, based on less precise dating methods, stratigraphy, or geomorphology). Unknown is shown if there is no published recurrence interval value. Also included is the time interval (in parenthesis) for which this recurrence interval is valid. (*e.g*., 10-130 k.y.) Alternative published recurrence intervals, starting with that which applies to the most recent time interval, are included in "Comments. "

References A bibliographic citation (USGS style) is included for all references pertinent to each structure.

Section A geographic, geometric, structural portion of a fault or collection of faults that appear(s) to have a different character than adjacent portions of the fault (or fold). Typically, not enough information exists to show that this portion of the fault acts independently of adjacent portions, and thus does not qualify as a bona fide "segment" of a fault in a paleoseismic sense. There are no known faults with proven segments in Panama, although several faults are described as having sections. Further research is needed to document additional faults with sections or those with sections that may in fact be segments.

Section name (see **Name**)

Section number (see **Number**)

Sense of movement Includes thrust (T), less than 45° dip; reverse (R), greater than 45° dip; right-lateral strike slip (D, dextral); left-lateral strike slip (S, sinistral); or normal (N). For oblique slip, the principle sense of movement is followed by secondary sense (*i.e.*, DT). Ratios of the slip components are included, where known, in order to better characterize sense of movement (*i.e.*, DT 3:1).

Slip rate The primary field shows an actual value or one of several slip-rate categories used for the map part of this compilation: <0.2 mm/yr, 0.2-1 mm/yr, 1-5 mm/yr, or >5 mm/yr. "Unknown" precedes the suspected slip-rate or slip rate category if no published slip rate is known. "Comments" may include a synopsis of published slip rates and pertinent documentation. Generally speaking, there are two types of slip rates. The first type is termed a "Geologic slip rate" and is derived from the age and amount of offset of surficial geologic deposits. These rates are not precise, but allow one to place broad limits on possible slip rates, and hence characterize the fault in one of the above-mentioned categories. The second type of slip rate is termed a "Paleoseismic slip rate" and is derived from times of faulting events and amounts of offset of geologic datums or piercing point. This type of slip rate is more precise, but are rare owing to the extensive amount of work involved (*i.e.*, detailed paleoseismologic studies involving trenching and numeric dating).

Fault/fold name (see **Name)**

Fault/fold number (see **Number)**

Synopsis and geologic setting This field provides a short summary that describes the level of study, provides a snapshot of the scope of data that follows in the database and provides a generalized perspective of the fault in terms of its regional geologic setting, amount of total offset, and general age of offset strata

Timing of most recent event (faulting or folding event) The primary field shows one of the two prehistoric time categories: latest Quaternary (Holocene and latest Pleistocene, <15 ka) or Quaternary (<1.6 Ma). This field may document historic surface faulting, although details of the earthquake related to the faulting will follow.

Type of studies: This field briefly summarizes the types of studies conducted on the fault.

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PA-01, LONGITUDINAL FAULT ZONE

NUMERO DE LA FALLA/FAULT NUMBER: PA-01

NOMBRE DE LA FALLA/FAULT NAME: Longitudinal (zone)
Comentarios/Comments: In Costa Rica, the zone is referred to as the Rio Esquinas fault (Dengo, 1962), Esquinas fault (Berrange, 1989), Ballena-Celmira fault zone (Mann and Corrigan, 1990) and the Longitudinal fault system (CR-48) (Montero, 1994). In Panama, the preferred usage has been Falla Chiriqui (Direccion General Recursos Minerales de Panamá, 1976) or Ballena-Celmira fault zone (Mann and Corrigan, 1990); however, the term Longitudinal fault zone is preferred herein since the structure extends across two countries (thus superceding local names).

SINOPSIS Y AMBIENTE GEOLOGICO/SYNOPSIS AND GEOLOGIC SETTING: A WNW-ESE trending fault zone that has been inferred to extend from Azuero Peninsula, Panama in the southeast, to central Costa Rica in the west (e.g. Mann and Corrigan, 1990). West of the Panama-Costa Rica border this part of the fault is mapped as the Longitudinal fault (CR-48); it separates uplifted, thrust-bounded forearc basin sediments of early Tertiary to Quaternary age to the NE, from uplifted outerarc sediments and oceanic basement of Cretaceous to Quaternary age on the southwest. The sense of strike-slip motion on this zone is controversial. The fault zone may accommodate both arc-parallel strike-slip, and arc-normal shortening in this region of Costa Rica, since it lies arcward of the converging Cocos Ridge. Farther east in Panama, the Longitudinal fault is probably dominantly strike-slip. Recent unpublished work by Cowan in western Panama suggests that the fault may be traced eastward from the Panama-Costa Rica border to the region of David, where the trace of the fault appears to die out. Strain may be transferred to other faults located along the coast and offshore farther southeast (see PA-05a). The sense of movement is inferred to be left-lateral strike-slip in Panama based on regional kinematic modeling and limited seismicity data (e.g. Mann and Corrigan, 1990), but the Longitudinal (CR-48) and other associated faults in Costa Rica have been variously interpreted as being left-lateral strike-slip (e.g. Mann and Corrigan, 1990), dominantly SW-verging thrusts (Montero, 1994), and right-lateral strike-slip (Berrange, 1989; Kolarsky and others, 1995). The slip rate of the Longitudinal fault zone may be <1 mm/yr in Panama, and there is no evidence of Holocene movement east of the intersection with the Canoas fault zone (CR-49). West of this intersection (in Costa Rica), there is clear evidence of late Holocene rupture from radiocarbon dating of charcoal (Beta-117478, 2,580±60 yr B.P.) and pottery that are offset by the fault zone in a trench at Rio Abrojo (Cowan and others, 1997).

COMPILADOR, AFILIACION Y FECHA DE COMPILACION/COMPILER, AFFILIATION, & DATE OF COMPILATION: Hugh Cowan, Instituto de Geociencias, Universidad de Panamá, Panamá City, Panamá; Oct. 10, 1996.

TIPOS DE ESTUDIOS/TYPE OF STUDIES: Regional mapping, satellite and air-photo interpretation, a few localized studies, including recent mapping in western Panama (H. Cowan, unpubl. data, in prep.).

GEOMETRIA DE LA FALLA/FAULT GEOMETRY
LONGITUD/LENGTH: End-to-end 64.5 km (cumulative 69.4 km)
Comentarios/Comments: Length in Panama only. Continues westward into Costa Rica as the Longitudinal fault (CR-48) (see Costa Rican database; Montero and others, 1998).
RUMBO PROMEDIO/AVERAGE STRIKE: N. 78° W. ± 16°
Comentarios/Comments: Continues westward into Costa Rica as the Longitudinal fault (CR-48) (see Costa Rican database; Montero and others, 1998).

NUMERO DE SECCIONES/NUMBER OF SECTIONS: (2)
Comentarios/Comments: Two sections (A, B) on Panamanian territory, with a continuation into Costa Rica as the Longitudinal fault (CR-48, see Costa Rican database). Sections are defined solely on the basis of differences in the strike of cuestas that define the approximate location of the fault in Panama.

PA-01A, UNNAMED SECTION

NUMERO DE LA SECCION/SECTION NUMBER: PA-01A

NOMBRE DE LA SECCION/SECTION NAME: Unnamed (section of Longitudinal fault zone)

GEOMETRIA DE LA SECCION/SECTION GEOMETRY
LONGITUD/LENGTH: End-to-end 39.6 km (cumulative 40.8 km)
RUMBO PROMEDIO/AVERAGE STRIKE: N. 77° W. ± 20°
INCLINACION PROMEDIO/AVERAGE DIP: Unknown
SENTIDO DE MOVIMIENTO/SENSE OF MOVEMENT: Probably left-lateral strike-slip, with a component of extension; throw down to the southeast.
Comentarios/Comments: See comments under Synopsis (above).

EXPRESION GEOMORFOLOGICA/GEOMORPHIC EXPRESSION: Defined by relatively linear hills comprising uplifted inliers of Tertiary sediment, including prominent ridges of Eocene Limestone above the hanging-wall in the border region with Costa Rica. The transition from the Longitudinal fault in Costa Rica (CR-48) and this section (to the southeast) is somewhat arbitrary, but the Tertiary rocks that form linear outcrops along the supposed line of this fault section have a more north-trending strike. The transition from section a to section b is similarly based on a change in the strike of bedding and associated topography. Section b terminates in an area of upright open folds NE of the town of David. The precise location of the fault is weakly defined. There are no documented exposures of the fault, nor observations of Holocene or late Quaternary displacement in Panama.

INTERVALO DE RECURRENCIA/RECURRENCE INTERVAL: Unknown

TASA DE MOVIMIENTO/SLIP RATE: Unknown.

EDAD DEL ULTIMO MOVIMIENTO/TIME OF MOST RECENT OF MOVEMENT: Unknown, probably Quaternary (<1.6 m.y.)

PA-01B, UNNAMED SECTION

NUMERO DE LA SECCION/SECTION NUMBER: PA-01B

NOMBRE DE LA SECCION/SECTION NAME: Unnamed (section of Longitudinal fault zone)

GEOMETRIA DE LA SECCION/SECTION GEOMETRY
LONGITUD/LENGTH: End-to-end 28.4 km (cumulative 28.6 km)
Comentarios/Comments: Continues westward into Costa Rica as the Longitudinal fault (CR-48) (see Costa Rican database; Montero and others, 1998).
RUMBO PROMEDIO/AVERAGE STRIKE: N. 74° W. ± 9°
INCLINACION PROMEDIO/AVERAGE DIP: Unknown
SENTIDO DE MOVIMIENTO/SENSE OF MOVEMENT Probably left-lateral strike-slip, with a component of extension and throw down to the southeast. The dip direction has not been observed.
Comentarios/Comments: See comments under synopsis (above).

EXPRESION GEOMORFOLOGICA/GEOMORPHIC EXPRESSION: Defined by relatively linear hills comprising uplifted inliers of Tertiary sediment. Eocene limestone is the oldest unit exposed, but in this section it is only occasionally exposed as small outcrops that rarely project above the vegetation. The limestone generally dips more steeply (50-65° N) than other units inferred to be farther from the fault (20-45° N). The transition from section a to section b is similarly based on a change in the strike of bedding and associated topography. Section b terminates in an area of upright open folds NE of the town of David. The precise location of the fault is weakly defined. There are no documented exposures of the fault. The fault does not offset river terraces of Holocene or late Quaternary age in Panama.

INTERVALO DE RECURRENCIA/RECURRENCE INTERVAL: Unknown

TASA DE MOVIMIENTO/SLIP RATE Unknown

EDAD DEL ULTIMO MOVIMIENTO/TIME OF MOST RECENT OF MOVEMENT: Unknown, probably Quaternary (<1.6 m.y.)

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Dengo, G., 1962, Tectonic-igneous sequence in Costa Rica, *in* Engel, A.E.C., James, H. and Leonard, B., eds., Petrologic studies, Buddington Volume: Geological Society of America Monograph, p. 133-161.

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PA-02, MADRE VIEJA ANTICLINE

NUMERO DE PLIEGUE/FOLD NUMBER PA-02

NOMBRE DEL PLIEGUE/FOLD NAME: Madre Vieja Anticline

SINOPSIS Y AMBIENTE GEOLOGICO/SYNOPSIS AND GEOLOGIC SETTING: Forms a NW-SE trending (elongate) dome with about 10 m of relief of Holocene fluvial surface. Fold is located southeast of the southern termination of the surface trace of the Canoas fault (CR-49), 2 km west of the town of Esperanza, Panama. The dome was drilled (Corotu 1-B, Corotu 2) for hydrocarbons in the 1950s. The holes penetrated several hundred meters of Pleistocene sediment, but little more is known about the subsurface structure (Kolarsky and others, 1995).

COMPILADOR, AFILIACION Y FECHA DE COMPILACION/COMPILER, AFFILIATION, & DATE OF COMPILATION: Hugh Cowan, Instituto de Geociencias, Universidad de Panamá, Panamá City, Panamá; Oct. 10, 1998.

TIPO DE ESTUDIOS/TYPE OF STUDIES: Field mapping (Hugh Cowan, 1988, unpubl. commercial reports).

GEOMETRIA DEL PLIEGUE/FOLD GEOMETRY
LONGITUD DEL EJE/LENGTH OF FOLD AXIS: End-to-end 10.1 km (cumulative 10.2 km)
RUMBO PROMEDIO DEL EJE/AVERAGE STRIKE OF FOLD AXIS: N. 38° W. ±8°
INCLINACION DE LOS FLANCOS/DIP OF LIMBS: <2°
INCLINACION DEL EJE/PLUNGE: North and south

EXPRESION GEOMORFOLOGICA/GEOMORPHIC EXPRESSION: Doming of Holocene/Pleistocene sediment. Also, gentle warps Holocene terraces of Rio Chiriqui Viejo, west of Esperanza. Former channel of Rio Chiriqui Viejo crosses the dome axis as a series of tight meanders that are almost abandoned now. Drainage canals that cross the dome were engineered and constructed in the 1920s-1930s; now all are dry.

TASA DE LEVANTAMIENTO/UPLIFT RATE: Probably >1 mm/yr
Comentarios/Comments. Based on 10 m of surface relief that is believed to have occured in the Holocene (past 10,000 yrs).

EDAD DEL MOVIMIENTO MAS RECIENTE/TIME OF MOST RECENT MOVEMENT: Possibly Historic (1934), certainly Holocene or post glacial (<15 k.y.)
Comentarios/Comments. Young movement indicated by deformation of Holocene and Pleistocene sediment, and modification of young drainages.

FALLAMIENTO HISTORICO EN SUPERFICIE/HISTORICAL SURFACE FAULTING: Unknown

DEFORMACIONES HISTORICAS/HISTORICAL UPLIFT (SOLO SI CORRESPONDE): Possibly 1934
Comentarios/Comments. Drainage canals that cross the dome were engineered and constructed in the 1920s-1930s; now all are dry. Certainly movement in <15 k.y. for the anticline.

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PA-03, MEDIAL FAULT ZONE

NUMERO DE LA FALLA/FAULT NUMBER: PA-03 (same as CR-47)
Comentarios/Comments: Fault extends across Panama/Costa Rica boundaries.

NOMBRE DE LA FALLA/FAULT NAME: Medial (zone)
Comentarios/Comments: Named by orrigan and others (1990) who conducted a detailed investigation.

SINOPSIS Y AMBIENTE GEOLOGICO/SYNOPSIS AND GEOLOGIC SETTING: Fault zone is well defined in its general characteristics. It comes onshore on the Burica Peninsula of Costa Rica and Panama as the continental expression of the Panama fracture zone (PA-04), and extends north into Panama and northwest into Costa Rica. It is a high-angle, right-lateral strike-slip fault displaying 800-2,500 m of up-to-west vertical displacement. Offshore, the Panama fracture zone (PA-040 accommodates deflection of the Middle America Trench along the eastern edge of the subducted Cocos Ridge (Corrigan and others, 1990). Onshore, the Medial fault zone offsets Pleistocene and Pliocene rocks of the Charco Azul Formation and Late Cretaceous basement rocks of the Upper Nicoya Complex. Fault trace was transferred by inspection from the small-scale map of Corrigan and others (1990). Northern portion of the fault is based on photogeologic interpretation by Montero (unpubl. data). The northwestern limit of the fault is the headwaters of the Río Corotu, a small river located on the Burica Peninsula. To the south, the fault splays into several strands as it becomes the Panama fracture zone offshore, so its southern border it is not determined.

COMPILADOR, AFILIACION Y FECHA DE COMPILACION/COMPILER, AFFILIATION, & DATE OF COMPILATION: Walter Montero-Pohly, Central American School of Geology, University of Costa Rica; November 11, 1994.

TIPOS DE ESTUDIOS/TYPE OF STUDIES: Geologic mapping and photogeologic interpretation

GEOMETRIA DE LA FALLA/FAULT GEOMETRY
LONGITUD/LENGTH: End-to-end 35.8 km (cumulative 89.2 km)
Comentarios/Comments: Continues south as the Panama fracture zone, and probably merges to the northwest (in Costa Rica) with the Golfito fault (CR-45).
RUMBO PROMEDIO/AVERAGE STRIKE: N. 19° W. ± 23°
INCLINACION PROMEDIO/AVERAGE DIP: Unknown
Comentarios/Comments Poorly exposed fault zone without reported dip or trend measurements.
SENTIDO DE MOVIMIENTO/SENSE OF MOVEMENT: Dextral thrust
Comentarios/Comments: Magnitude of dextral-slip component is undetermined. Thrust component was defined by a left-stepping segment of the Medial fault zone near its northwest termination.

EXPRESION GEOMORFOLOGICA/GEOMORPHIC EXPRESSION: Fault forms a prominent 15-km-long and 600- to 1800-m-wide linear valley that strikes northward from the southwest coast of the Burica Peninsula to the headwaters of the Río Corotu. Near the headwaters of this river, the valley assumes a more northwestward trend and becomes poorly defined topographically (Corrigan and others, 1990).

INTERVALO DE RECURRENCIA/RECURRENCE INTERVAL: Unknown
Comentarios/Comments: More detailed studies are required to define individual paleoevents and thus recurrence intervals.

TASA DE MOVIMIENTO/SLIP RATE: Unknown, probably >10 mm/yr
Comentarios/Comments: High rate inferred because the fault zone must be a major element of the Cocos-Nazca plate boundary in this area. Plate motion predicts >50 mm/yr total across the zone, but considerably less on individual faults.

EDAD DEL ULTIMO MOVIMIENTO/TIME OF MOST RECENT OF MOVEMENT: Holocene or post glacial (<15 k.y.)
Comentarios/Comments: The fault offsets Pleistocene and Pliocene rocks of the Charco Azul Formation, but more detailed studies are required to define individual paleoevents or the timing of the most recent movement. Movement is likely Holocene or post glacial (<15 k.y.) owing to the high slip rate ascribed to the fault.

REFERENCIAS/REFERENCES

Corrigan, J., Mann, P., and Ingle, J.C., 1990, Forearc response to subduction of the Cocos Ridge, Panama-Costa Rica: Geological Society of America Bulletin, v. 102, p. 628-652.

PA-04, PANAMA FRACTURE ZONE (PFZ)

NUMERO DE LA FALLA/FAULT NUMBER: PA-04

NOMBRE DE LA FALLA/FAULT NAME: Panama fracture (zone)

SINOPSIS Y AMBIENTE GEOLOGICO/SYNOPSIS AND GEOLOGIC SETTING: The Panama fracture zone (PFZ) is a north-south-trending, right-lateral strike-slip oceanic transform that separates the Cocos and Nazca plates south of the Burica Peninsula of Panama/Costa Rica. The PFZ and associated splay faults (see PA-08, Balboa fracture zone) intersect the accretionary prism thrust-fault complex along the southern continental margin of Panama (see PA-09, South Panama Deformed Belt). The PFZ is mapped as a rather wide fracture zone offshore (for example, poor definition), but elements of the PFZ extend farther north onshore (Burica Peninsula) in Panama and Costa Rica as the Medial fault zone (PA-03, CR-47) and the Canoas Fault (CR-49).

COMPILADOR, AFILIACION Y FECHA DE COMPILACION/COMPILER, AFFILIATION, & DATE OF COMPILATION: Hugh Cowan, Instituto de Geociencias, Universidad de Panamá, Panamá City, Panamá; Oct. 10, 1996

TIPOS DE ESTUDIOS/TYPE OF STUDIES: Seismological studies, sea-floor magnetic anomaly studies, and GPS surveys have defined the kinematics of the fault zone. Seismic-reflection profiling and bathymetric mapping have defined the structure.

GEOMETRIA DE LA FALLA/FAULT GEOMETRY
LONGITUD/LENGTH: End-to-end >261 km; continues beyond map area (cumulative unknown)
Comentarios/Comments: Fracture zone is comprised of many subparallel faults across which a high rate of lateral slip is distributed.
RUMBO PROMEDIO/AVERAGE STRIKE: N. 0° W. ± 4°, continues beyond map area
INCLINACION PROMEDIO/AVERAGE DIP: Sub-vertical
SENTIDO DE MOVIMIENTO/SENSE OF MOVEMENT: Right-lateral strike-slip

EXPRESION GEOMORFOLOGICA/GEOMORPHIC EXPRESSION: Prominent ridge shown on bathymetric maps.

INTERVALO DE RECURRENCIA/RECURRENCE INTERVAL: Unknown
Comentarios/Comments: Although the recurrence is unknown, the PFZ is one of the most seismically active structures in Panama.

TASA DE MOVIMIENTO/SLIP RATE: Probably >50 mm/yr.
Comentarios/Comments: Relative plate motion (Cocos-Nazca) indicates 52 mm/yr offshore, south of the Burica Peninsula.

EDAD DEL ULTIMO MOVIMIENTO/TIME OF MOST RECENT OF MOVEMENT: Historic (1934)
Comentarios/Comments: Although the Puerto Armuelles earthquake is on this zone, the entire structure is shown as Holocene or post glacial (<15 k.y.) owing to the high slip rate ascribed to the fault. Inferred to be the (general) source of 1934 Puerto Armuelles earthquake. Mainshock was reputedly offshore in the Gulf of Chiriqui, but wide pattern of aftershocks (radius at least 50 km) makes it difficult to discriminate among several possible fault sources (see also PA-03, CR-49).

FALLAMIENTO HISTORICO EN SUPERFICIE/HISTORICAL SURFACE FAULTING: Unknown

NOMBRE DEL TERREMOTO/NAME OF EARTHQUAKE: Puerto Armuelles (southwestern Panama)

COMENTARIOS/COMMENTS: See comments under PA-03 and CR-49.

FECHA/DATE: 0136 hrs UT, July 18, 1934.

MAGNITUD O INTENSIDAD/MAGNITUDE OR INTENSITY: Ms 7.6 and Modified Mercalli Intensity IX at Puerto Armuelles.
Comentarios/Comments: An aftershock of Ms 6.75 at 1039 hrs UT, July 21, 1934, produced similar levels of shaking and more damage than the mainshock at Puerto Armuelles. Review of felt effects is from unpublished data.

MOMENT MAGNITUDE: Unknown

LONGITUD DE RUPTURA/LENGTH OF SURFACE RUPTURE: Unknown

DESPLAZAMIENTO MAXIMO/MAXIMUM SLIP AT SURFACE: Unknown

SENTIDO DE MOVIMIENTO/SENSE OF MOVEMENT: Right-lateral strike-slip on NNW-trending fault plane constrained by first-motion data. Reasonable azimuthal distribution of stations for mechanism (see Camacho, 1991).

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Geological and Geodetic Studies:

Corrigan, J., 1986, Geology of the Burica Peninsula, Panama-Costa Rica—Neotectonic implications for the southern Middle America convergent margin: Austin, University of Texas, unpubl. M.S. thesis, 152 pp.

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