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THE PUERTO ARMUELLES EARTHQUAKE (SOUTHWESTERN PANAMA) OF JULY 18, 1934

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ABSTRACT: The Puerto Armuelles Earthquake of July 18, 1934 and its six main aftershocks nave been relocated using a new version of Dewey´s Joint Hypocenter Determination program: JHD89. The main event focal mechanism has been determinated from historical seismograms first arrivals. The results of this study suggest that the active Panama, Balboa and possibly the Mykland fracture zones extent through the southwestern Panama continental shelf up to connect with faults inland as proposed by BERRANGE & THORPE (1988). The Burica Peninsula medial fault zone, stratigraphically infered by CORRIGAN (1986) also seems to be active. This group of parallel northwest trending right lateral strike-slip faults interact, at least for large events. The focal mechanism solution of the 1934 Puerto Armuelles Earthquake indicates a right lateral strike slip solution with a normal component.

RESUMEN: En este trabajo se ha relocalizado el sismo de Puerto Armuelles del 18 de julio de 1934 y sus seis réplicas principales utilizando una nueva versión del programa de Dewey para la determinación grupal de hipocentros: JHD89. El mecanismo focal del evento principal se ha determinado a partir de los primeros arrivos de sismogramas históricos. Los resultados de este estudio sugieren que las activas zonas de fracturas de Panamá, Balboa y Mykland se extienden a través de la plataforma continental del suroeste de Panamá hasta conectar con fallas en tierra como ha sido propuesto por BERRANGE & THORPE (1988). La zona de falla media de Burica, la cual fue inferida estratigráficamente por CORRIGAN (1986) también parece estar activa. Este grupo de fallas paralelas transcurrentes diestras interactúan al menos, para eventos grandes. El mecanismo focal para el evento principal indica una solución transcurrente diestra con una componente normal.

INTRODUCTION

The Pacific coast of Panama and Costa Rica is characterized by numerous peninsulas and promontories formed by obducted ophiolitic segments of oceanic crust of Cretaceous to Early Tertiary age (DENGO, 1985).

Unlike the rest of Central America and northwestern South America most of the Pacific continental margin of the Isthmus of Panama presents a wide continental shelf. In this region does not exist a conclusive evidence that an active subduction process is still taking place.

Around the coast of the Gulf of Chiriquí live near one third of the total population of the Republic of Panama. This is a region of great industrial and agricultural wealth, where many important infrastructures have been built. Among them we have the transisthmian oil-pipeline, which transports the Alaskan crude oil through the isthmus on its way to the east coast of the United States, and the hydroelectric dams that provide seventy percent of the electric power consumed by the whole country.

Even though this region has been shaken by several destructive earthquakes, at least during the last four hundred years (VIQUEZ & TORAL, 1987), the absence of a local seismic network impedes a better knowledge of the seismotectonics of this zone.

Because in this gulf events larger than Ms = 6.0 do not occur very often the study of historical earthquakes is of great importance to improve the understanding of the seismotectonic and seismic hazard of southwestern Panama.

The study of historical events is greatly improved by using historical seismograms (those recorded before 1962). The use of historical seismograms presents several problems: there is a small number of valuable and "readable" records, the instrument response are not well known and their polarity calibration sometimes is not too reliable. Unfortunately these historical seismograms constitute the only source of instrumental information, principally for regions without seismic networks, of some of their more important earthquakes. Furthermore seismic events do not repeat exactly in the same way, and consequently the study of historical seismograms is very important for a thorough understanding of the earthquakes phenomenon (KANAMORI, 1988). It is also crucial to distinguish the type of focal mechanism of the events for a better evaluation of seismic gaps (McCANN, et al., 1984).

In this research we have studied the Puerto Armuelles earthquake of July 18, 1934. This is the largest event, Ms = 7.6 (ABE, 1981), of the Gulf of Chiriqui region to have been instrumentaly recorded. We relocated the hypocenters of the main event and its large aftershocks using a joint hypocenter determination computer program (JHD89). Because the historical records of the aftershocks are scarce or are very deteriorated, we were just able to determine the focal mechanism of the main event form first motion analysis. This is so, because most of the afterschocks were not strong enough to be recorded teleseismically by the low gain instruments of those years, and also because many of the few available records are very deteriorated.

TECTONIC SETTING

The Gulf of Chiriqui in the southwestern continental margin of the Isthmus of Panama forms part of the Middle America Forearc Ridge (CASE, 1984). Here the crust is 17 to 25 km thick and is overlain by a primitive magmatic arc complex, including thick pelagic and turbiditic components. This gulf is considered to be a modern pull apart basin (BERRANGE & THORPE, 1988; BERRANGE, 1989).

Analysing seismic sections from the Gulf of Chiriqui, near the west of Coiba island (81.9° W), OKAYA & BEN-AVRAHAM (1987) discovered four major active submarine normal faults (see Fig. 1), with a WNW-ESE trend. One of these faults, the Coiba fault, could be an extension of the Puerto Armuelles-Esquina fault, which lies to the north of the city of Puerto Armuelles, in the northern side of the Burica Peninsula (LUQUE, personal comm., 1989). OKAYA & BEN AVRAHAM (1987) have also proposed that these faults probably bound a large northwest-southeast graben or pull apart basin, that extends for approximately 100 km, from a bathymetric depression in the northwest through Coiba island to the sharp bend of the continental slope al 81.5° W.

The Panama-Coiba Fracture Zone extends from the Costa Rica rift zone, around 3.0° N (GRIMM, 1970), up to 6.0° N, and between 83.0° and 82.0° W, as a belt which exhibits a vigorous shallow focus seismicity (WEYL, 1980; ADAMEK, 1986). It has been shown by several researchers (MOLNAR & SYKES, 1969; LOWRIE, et al., 1979; PENNINGTON, 1981; WOLTERS, 1986; ADAMEK, 1986), that this oceanic transform fault, which forms the boundary between the Cocos and Nazca plates, displays a right lateral strike slip motion (see Fig. 1).

Approximately north of 6.00° N the Panama-Coiba Fracture Zone splays in a series of parallel, north trending dextral strike slip faults. The most prominent of these faults are: the Panama, Balboa, Mykland and Coiba fracture zones (LOWRIE, et al., 1979).

There are two models to explain the tectonics of the northern terminus of the splayed Panama-Coiba Fracture Zone. One states that the north

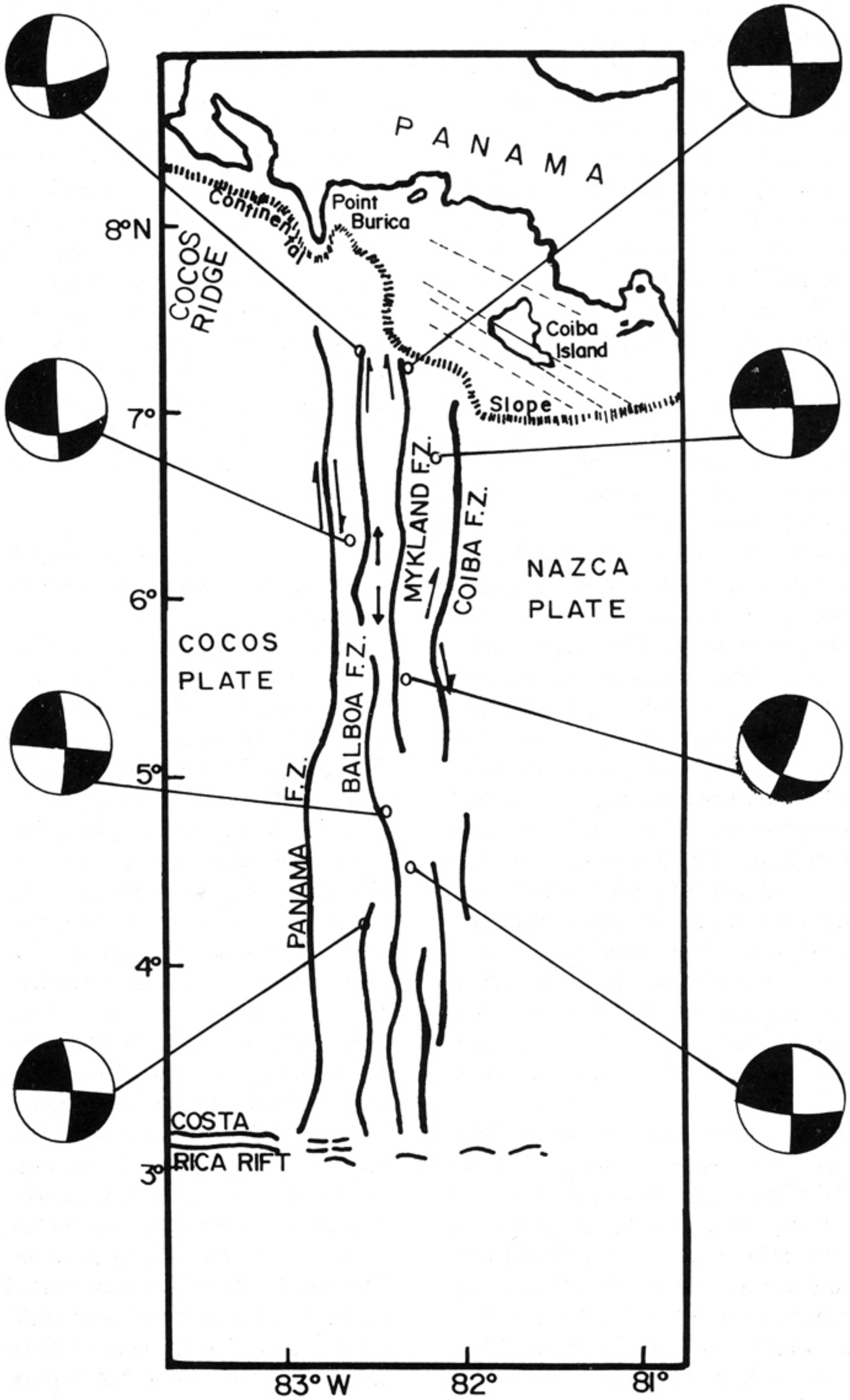

Fig. 1: Map depicting the southwestern Panama continental margin and the Panama-Coiba Fracture Zone with some of its characteristic focal mechanisms.

trending right-lateral strike slip faults subduct obliquely in the southwestern Panama continental margin into a NNW-SSE trend (MOORE, et al., 1985; HEIL & SILVER, 1987). Subduction of the fracture zone apparently produces the uplift of the adjacent contiental slope; e.g. The Panama Fracture Zone aligns with the Burica Peninsula, the Balboa Fracture Zone with an anomalous bathymetric high on the continental slope and the Coiba Fracture Zone with Coiba and Jicaron islands (HEIL et al., 1986; SILVER et al., 1990). The other model proposes that the right lateral fracture zones extend through the continental shelf up to intersect the coast in the vicinity of the Osa and Burica Peninsulas, in the Panama-Costa Rica border region, where they bend to the northwest to form a series of braided coast parallel dextral trench faults (BARRIT & BERRANGE, 1987; BERRANGE & THORPE, 1988). Further northwest these NW-SW trending faults transform into thrust and reverse faults which parallel the Mid America Trench (CORRIGAN, 1986).

The seismotectonic pattern around the Burica Peninsula, at the northwestern margin of the gulf, could be affected by the subduction of the Panama Fracture Zone and the Cocos Ridge, located to the southwest of the peninsula, beneath the South Central American Arc (VERGARA, 1988). Its long term uplift rate of 1.25 mm/year, as well as the Neogene fault pattern show that the Cocos Ridge subducts beneath the Burica Peninsula (CORRIGAN, 1986). This also seems to be confirmed by normal focal mechanism of the July 9, 1963, event, and the July 1, 1979 event. The eastward-dipping nodal plane of this last event is consistent with uplift of this peninsula (ADAMEK, 1987).

North of the Burica Peninsula the Coto Colorado-Chiriqui basin contains 2500 m of sediment (SPRECHMANN, 1984). This is part of a series of basins which prolong from the Gulf of Nicoya, in northwestern Costa Rica, to the Gulf of Chiriqui in southwestern Panama (FISCHER, 1980). It has been suggested by BARRIT & BERRANGE (1987), and BERRANGE & THORPE (1988), that these are pull apart and tipped wedge basins filled with sediments derived locally from adjacent mini horst blocks of uplifted ophiolitic Nicoya Complex, and developed as result of the strong N-S horizontal stress field generated by the Colon spreading ridge in the Tertiary.

Close to the western shore of the Gulf of Chiriqui the bathymetry changes abruptly. Very close to the coast runs a V shaped submarine valley which parallels the Burica Peninsula for more than 5 km and can be traced some 16 km farther south to the 1800 m line (TERRY, 1941).

It has been pointed out by MORALES (1986), that the absence of focal mechanisms from the continental margin of southwestern Panama makes difficult to confirm if there is an active subduction process taking place or just the continuation of the fracture zones inland. The rupture zone of the July 18, 1934 Puerto Armuelles Earthquake characterizes the extension of this zone (MORALES, 1985).

THE PUERTO ARMUELLES EARTHQUAKE OF JULY 18, 1934.

On July 18, 1934 at 01h36m29s UTC, a very strong earthquake (Ms = 7.6) hit the Gulf of Chiriqui region. The epicenter reported by the 1934 ISC Bulletin is 8.2° N, 82.6° W. GUTENBERG & RICHTER (1958) report an epicenter with coordinates 8.0° N, 82.5° W.

This event caused very local damage mainly in the southwestern Panama region (VIQUEZ & TORAL, 1987). It was strong enough to trigger a Wenner accelerograph, on firm ground at Balboa Heights Panama (BHP) in the Panama Canal Zone, 340 km away, that recorded a maximun horizontal acceleration of 7 cm/s^2 at 0.6 s (NEWMANN, 1936). This earthquake was also felt in Panama City and in San Jose, Costa Rica at 350 and 300 km from the epicenter, respectively with a M.M. intensity of V. It has been suggested that the Panama Fracture Zone works as an elastic wave buffer zone so that earthquakes to the west of it cause more destruction in Costa Rica and those to the east produce most of the damage in Panama (GUENDEL, written comm., 1989). This phenomenon could possibly be explained by the findings by DETRICK et al. (1986) of a seismically anomalous crust within large oceanic fracture zones, which presents low compressional wave velocities specially in the shallow crust, and very high velocity gradients.

The Puerto Armuelles Earthquake also generated a small local tsunami (LOCKRIDGE & SMITH, 1984). The tsunami was recorded in Bahia Honda, in the eastern shore of the Gulf of Chiriqui, by a tide gage aboard the U.S.S. Hannibal. The peak to through amplitude was 0.6 m, and the duration of the wave train in Bahia Honda was five hours eighteen minutes. This tsunami only caused minor damage along the western shores of the gulf. CRUZ & WYSS (1983), have found that the tsunamis along the Pacific coast of Mexico and Central America just cause local damage. Large tsunamis like those of Chile and Japan are not characteristic of this region.

The main earthquake was followed by four strong aftershocks on the same day: at 04h00m, Ms = 6.5; at 06h35m, Ms = 6.5; at 16h10m, Ms = 6.0; and at 17h00m, Ms = 6.9 (ACRES, 1982). The fourth aftershock was also strong enough to trigger the BHP accelerograph again. On July 21 at 10h49m another aftershock occurred, that registered a magnitude Ms = 6.75 (ACRES, 1982). Balboa Heigths Panama (BHP), located 350 km, away recorded fifty aftershocks between July 18 and July 26. Due to the July 21 event, cracks, several inches wide, appeared near the village of Progreso, extending across the Panama-Costa Rica border, with a NWW-SEE trend (LEEDS, 1978). This last strong aftershock was the one caused more damage, mostly in areas with extensive alluvium material. Thia was made worse by the fact that its epicenter was located on land, and that the buildings were already weakened after all these severe aftershocks. Most of the well constructed buildings just underwent minor damage (LEEDS, 1978; VIQUEZ & TORAL, 1988). Altogether, this group of events caused around two million 1934 U.S. dollars of damage.

PREVIOUS HYPOCENTRAL RELOCATION AND FOCAL PLANE SOLUTION.

The epicenters of the July 18, 1934 Puerto Armuelle Earthquake and its aftershocks were relocated for the first time by KELLEHER et al. (1973). Using a single event location computer program they obtained the results shown on table 1. A plot of the epicenters relocated by Kelleher in 1973 is on figure 2.

It has been found by PLAFKER (1973), ALGERMISSEN et al. (1974), PONCE et al. (1979), GETTRUT et al (1980), MIYAMURA (1980), MORALES (1984), and SINGH & LERMO (1984), that for events in the Pacific of Mexico and Central America the epicenters located teleseismically, with unadjusted travel times, lie tens of kilometers northeast of the true epicenter. Due to this shift to the northeast the events are usually located inland or very close to the coast when in reality they have an offshore location. Moreover, CRUZ & WYSS (1983) have studied tsunamogenic earthquakes along the Pacific coast of Mexico and Central America, and found that their teleseismic location plot 50 to 100 km inland from the coast. Like the other researchers mentioned before, they propose too, that these locations are biased by at least 75 km to the northeast and their depths are overestimated by approximately 20 km. According to them this has to be so, because major portions of the rupture areas must have been located at shallow depths under water so that tsunamis could have been generated.

Table 1
The July 18, 1934 Puerto Armuelles Earthquake and Aftershocks as relocated by KELLEHER et al. (1973)

Event #	Date	OT.	Lat. (N)	Long. (W)	Md (PAS)
1	7/18	013623.2	8.14	82.38	7.6*
2	7/18	040037.1	7.89	82.88	6.5
3	7/18	063533.0	8.31	82.37	6.0
4	7/18	160949.4	7.91	82.26	6.0
5	7/18	165938.8	7.81	82.15	6.9
6	7/21	103908.6	8.48	82.42	6.75
7	7/21	131918.3	7.84	82.87	6.0

* The magnitude of this first event was estimated by Abe (1981)

The focal mechanism of the main event has been previously estimated by MÜHLHAUSER (1956). From twenty three P wave first motion

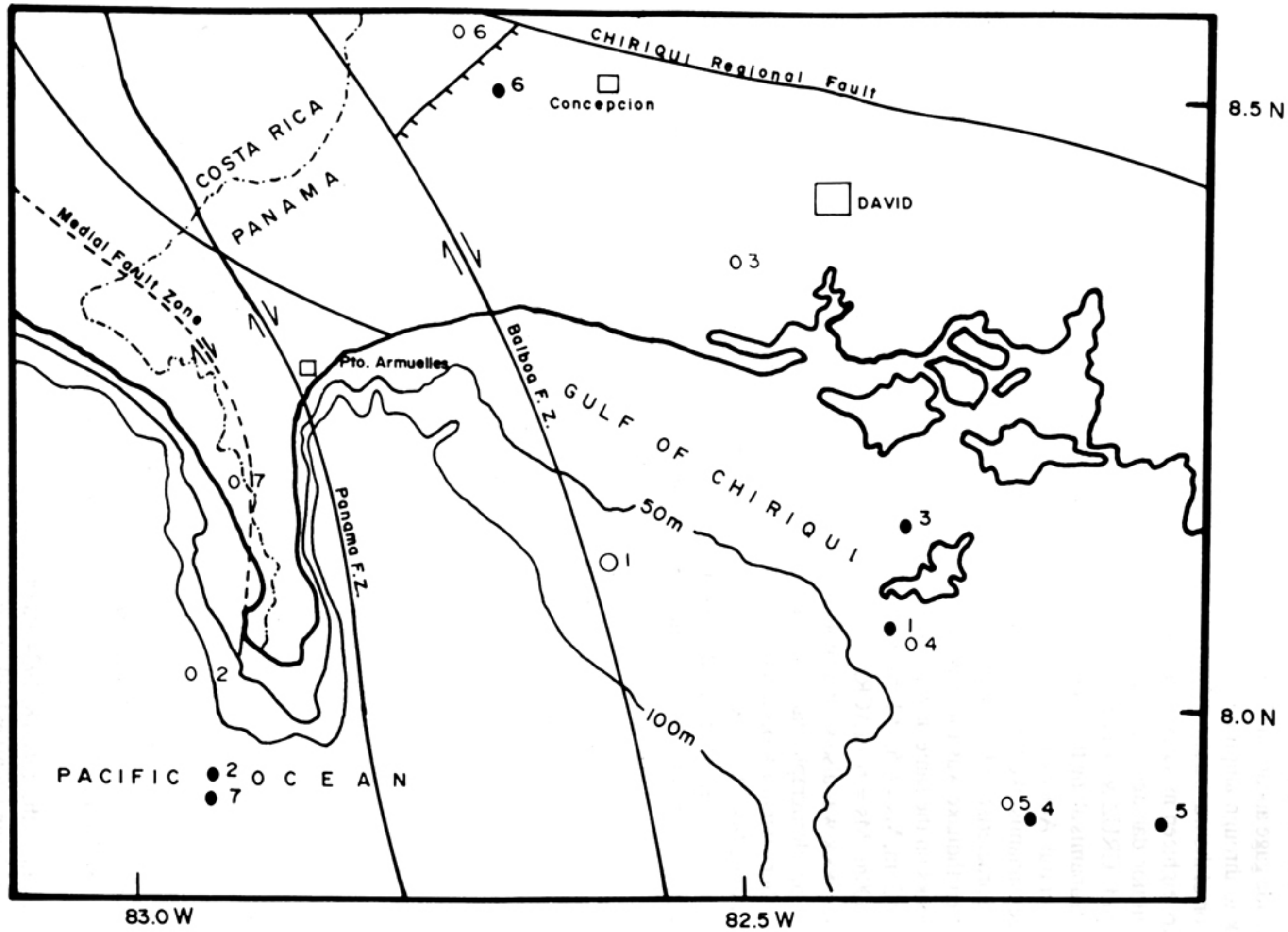

Fig. 2: Map with major tectonic features of soutwestern Panama, after BERANGE & THORPE (1988). Relative movements indicated by arrows and downthrown block by ticks. Black circles denote the epicenters of the July 18, 1934 and its major afterschocks as relocated by KELLEHER et al. (1973). The epicenters of the same events relocated using JHF89 are indicated by open circles. Note the shift to the northwest of the majority of the events.

readings he obtained a north south trending right lateral strike slip focal plane solution. It is important to note that five of the polarities employed by Mühlhauser are from stations located at more than 100 from the epicenter. Polarities from P wave first arrivals generally are not too reliable at these distances because the rays hit the earth´s core (STEIN, 1987). Furthermore one of the polarities used in his determination, SCO is listed in the station bulletin and in the International Seismological Summary with the opposite sign. Unfortunately the historical seismogram is no longer available. Another station GEO is very unlikely to be compressive, because historical seismograms from three canadian stations: OTT, SHF, and SAF with almost the same azimuth show clear dilatations.

An almost similar fault plane solution was obtained by WIECKENS & HODGSON (1967), employing a computer program to process the same data used before by Mühlhauser.

DATA AND ANALYSIS

In this study we have applied modern techniques to relocate the hypocenters of the main event and its aftershocks, and determine its focal plane solution.

Hypocenter Relocation

To relocate the main event and its aftershock we have used first arrivals times as listed in the 1934 International Seismological Summary, the Bulletin du Bureau Central Seismologuique, the United States Coast and Geodetic Survey Earthquake Report, and bulletins from several Mexican and South American stations.

With these data we fed a Joint Hypocenter Determination (DOUGLAS, 1967; DEWEY, 1971) computer program: JHD89 kindly provided by J. Dewey. This method has proved to be very succesful in reducing within group errors in studies with regional and teleseismic phases (DEWEY & ALGERMISSEN, 1974; VIRET, 1984).

We preferred a joint hypocenter determination (JHD) over a master event technique, even though the last one is easier to use, because many of the stations that recorded the 1934 events are no longer in operation. For either of these two techniques, the effect of travel time anomalies are minimized.

As calibration event we used the 1979 Puerto Armuelles Earthquake which was clearly and widely recorded at teleseismic distances. The International Seismological Centre Summary reports for this event the following parameters: OT 20h34m21s, 8.342° N, 82.980° W, and a focal depth of 30 km. Instead of using this depth we used the one determined by ADAMEK (1986). Using waveform modelling he determined a focal depth of 12 km for this event. DZIEWONSKI (1987) estimated for the same event a depth of 10 km.

We calculated the depth of the main event from four pP-P time intervals from historical seismograms. These readings correspond to the following stations: OTT, EDI, UCC, PAS, and SLM. Using the J-B travel times we obtained a depth of 24.2± 2.6 km, which may be a bit overestimated. In oceanic events due to the water layer the depth phases can be misidentified with water reberberations such as pwP or swP (MENDIGUREN, 1971; HERRMANN, 1976). Fortunately the bathymetry in this region is very shallow and the water layer does not affect the depth determination considerably. Moreover, the fact that this event caused a small tsunami and that these are generated by changes in the ocean floor following a shallow earthquake (MURTY, 1977) indicates that this event was shallow.

For the rest of the events we assigned "dummy" depths, based on what it is known for depths in this region from recent studies by WOLTERS (1983) and ADAMEK et al. (1988). The events located in the gulf were assigned a depth of 15 km, and those located inland were assigned a depth of 25 km. As has been stressed by DEWEY (1979) the effect of an uncertainty of approximately 15 km in depth, has a minimal effect on the teleseismically determined epicenter. Because of this it is better to use geophysical and tectonically reasonable estimates of depth, than try to compute it from inadequate data.

In this study instead of relocating the best recorded events using JHD and then recomputing the remainings events with a single event teleseismic location program, using stations delays and variances computed in the JHD, we relocated the whole set of seven events using JHD.

The epicenters relocated using joint hypocenter determination are on table 2.

Table 2.
The July 18, 1934 Puerto Armuelles Earthquake and its aftershock as relocated in this work using JHD89

Event #	Date	OT	Lat.	Long.	Ms	Depth
1	7/18	01h36m28.3s	8.12	82.61	7.7	25
2	7/18	04h00m40.4s	8.03	82.95	6.5	15
3	7/18	06h35m39.1s	8.38	82.50	6.5	25
4	7/18	16h09m54.5s	8.06	82.36	6.0	15
5	7/18	16h59m43.2s	7.91	82.26	6.9	15
6	7/21	10h39m14.7s	8.56	82.72	6.75	25
7	7/21	13h19m23.6s	8.18	82.90	6.0	15

A plot showing the location of the relocated epicenters with respect to the tectonic structures of the region is on figure 2. In this plot can be notice that the main event and the majority of its aftershocks have shifted to the southwest, and they are located in or within few kilometers of mapped faults. The main event, number 1 in the map is at less than 10 km from the Balboa Fracture Zone. Events 2 and 7 are close to the Burica Medial Fault Zone, a north trending rigth lateral strike slip fault system, almost coincident with the Panama-Costa Rica border, which was inferred by CORRIGAN (1986) based on stratigraphic evidence. The relocation of the sixth event lies close to the Chiriqui Regional Fault that extends north of the city of David, but this event could have also been caused by the Balboa Fracture Zone. The lack of a focal mechanism makes difficult to determine which of the two structures caused this event. Reports of cracks, with a NW-SW trend, near the town of Progreso (NEWMAN, 1936) would favor the Balboa Fracture Zone as the source fault for event 6. Three events: 3, 4, and 5, even though they do not correlate with any known tectonic structure, they show an alignment that parallels the trace of the Panama and Balboa Fracture Zone inland as occurrs with the two other fracture zones.

Focal Plane Solution

To determine the focal plane solution of the main event, we read the polarity of the first arrivals of twenty five historical seismograms from stations distributed in the four quadrants, with epicentral distances in the range between 19° and 98°. The great majority of the recording stations are located in Europe. Angles of incidence i_h were determined from standard tables (PHO & BIHE, 1972). The whole focal mechanism determination procedure can be found in HERRMANN (1975). The azimuths, epicentral distance, i_h angles and polarities corresponding to each of the twenty five station used in this study are on table 3.

Table 3
Stations used for the focal Plane Solution of the Puerto Armuelles Earthquake of July 18, 1934.

Station	ED(°)	Azimuth (°)	i_h	Polarity
SJP	19.9	56.0	50.0	D
CSC	25.8	3.0	38.7	D
LPB	28.6	149.0	36.7	C
SLM	31.2	350.0	36.3	D
OTT	37.6	8.0	34.5	D
SHF	39.3	10.6	33.9	D
SFA	40.2	12.4	33.7	D
PAS	41.7	314.0	33.3	C
BZM	44.8	332.0	32.1	C
MHC	46.3	316.0	31.6	C
BKS	46.4	316.0	31.5	C
UKI	47.7	317.0	31.3	C
SAS	48.1	340.0	31.1	C
LPA	49.0	153.0	30.8	D
SIT	63.6	331.0	26.3	C
HON	73.3	290.0	23.2	C
TOL	76.0	51.0	22.5	C
EDI	77.3	34.0	22.0	D
ALI	78.7	52.0	21.6	C
KEW	79.1	39.0	21.5	C
UCC	81.7	39.0	20.7	C
DBN	82.2	38.0	20.5	C
STU	84.9	41.0	19.4	C
UPP	88.0	30.0	18.7	C
API	91.8	256.0	18.2	D
PUL	94.0	27.0	18.1	C
CIZ	98.5	225.0	18.0	D

P wave first motion is indicated by C (compression) D (dilatation)

From these data we obtained a focal plane solution, that indicates a rigth lateral strike slip faulting with a normal component. The nodal planes are on table 4, and the focal plot is on Figure 3. As fault plane we have chosen plane A from table 4, because it correlates extremely well with the trend of the relocated aftershocks, and the bearing of the strike slip faults of the area under study. It is also worth of note that for stations SLM and LPB, located very near plane A, the amplitude of the S wave in the E-W component is much greater than in the N-S component.

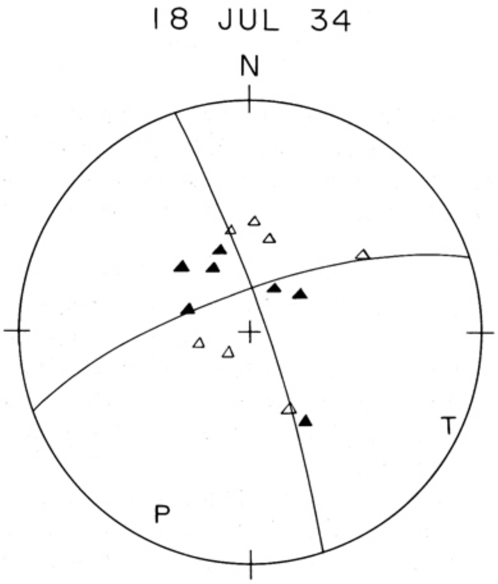

Fig. 3: P wave focal mechanism solution of the July 18, 1934 Puerto Armuelles earthquake. This diagram is an equal area projection of the lower hemisphere of the focal sphere. Solid triangles denote compressions and open triangles dilatation.

Table 4.
Fault Plane Solution of the Puerto Armuelles Earthquake of July 18, 1934.

	Strike (0)	Dip (0)	Slip (0)	Trend (0)	Plunge (0)
Plane A	341	86	-168		
Plane B	250	78	-04		
P axis				206	11
T axis				115	06

A strike slip focal mechanism does not contradict the fact that a local tsunami was generated by this event. Large earthquakes along major strike slip faults near the coasts of southeastern Alaska and British Columbia have generated tsunamis that were not observables at distances greater than about 100 km (ISAAKS et al., 1968; MURTY, 1977).

As can be notice from the focal plot on figure 3, the fault plane A correlates exceptionally well with the trace of Balboa Fracture Zone.

CONCLUSIONS

After relocating the hypocenter of the July 18, 1934 Puerto Armuelles Earthquake and its aftershocks, and having determined the focal mechanism of the main event we may conclude the following:

1. The dextral strike slip focal mechanism of the main earthquake, which ocurred at less than 30 km from the coast, seems to rule out the possibility that the Fracture Zones are subducting in the southwestern Panama continental shelf.
2. At least, the Panama Fracture Zone and the Balboa Fracture Zone can be extrapolated northward into the Panama southwestern continental margin were they curve into a northwest trending direction. Once inland they merge with a braided systems of faults, which run parallel to the southern margins of Western Panama and Costa Rica, as stated by BERRANGE & THORPE (1988).
3. The alignment of three of the aftershocks: 3, 4 and 5 in a northwest trending pattern, which parallels that of the Panama and Balboa Fracture Zones may indicate the extension of the Mykland fault through the continental shelf, up to connect with the regional Chiriqui fault, that runs to the north of the city of David.
4. The northern terminus of the braided Panama-Coiba Fracture Zone is seismically active and capable of generate events with magnitudes greater than Ms = 7.0.
5. The aftershock pattern of the 1934 Puerto Armuelles Earthquake may indicate that these parallel north trending rigth lateral strike-slip faults interact, at least, for large events.
6. Even though, the earthquakes in the continental shelf of southwestern Panama do not occur very often, as in other parts of the Middle American Arc, they pose a high risk to this whole region due to their magnitude and proximity to highly populated areas with many important infrastructures.

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REFERENCES

ABE, K., 1981: Magnitude of large shallow earthquakes from 1904 to 1980. - Phys. Earth Planet. Inter., 27: 72-92.

ACRES INTERNATIONAL LIMITED, 1981: Evaluación sísmica del proyecto hidroeléctrico Tabasará. - 53 págs.

ADAMEK, S.H., 1986: Earthquake studies in the Panama-Costa Rica region. - 211 págs. Universidad de Texas at Austin (tésis inédita).

ADAMEK, S.H., TAJIMA, F. & WIENS, D., 1987: Seismic rupture associated with subduction of the Cocos ridge. - Tectonics, 6: 757-774.

ADAMEK, S.H., FROHLICH, S. & PENNINGTON, W., 1988: Seismicity of the Caribbean-Nazca boundary: Constrains on microplate tectonics of the Panama region. - J. Geophys. Res., 93: 2053-2075.

ALGERMISSEN, S.T., DEWEY, J.W., LANGER, C.W. & DILLINGER, W.H., 1974: The Managua, Nicaragua Earthquake of December 23, 1972: location, focal mechanism and intensity distribution. - Bull. Seism. Soc. Am., 64: 993-1004.

BARRIT, S. & BERRANGE, J.P., 1987: An interpretation of a gravity survey of the Osa Peninsula and enviroments, Southern Costa Rica. - Overseas Gol. Mineral Res., 64: 23-56.

BERRANGE, J.P., 1989: The Osa Group: An auriferous Pliocene sedimentary unit form the Osa peninsula, southern Costa Rica. - Rev. Geol. Amer. Central, 10: 67-93.

CASE, J.E., HOLCOMBE, T.L. & MARTIN, R.G., 1984: Map of geologic provinces in the Caribbean Region. - Geol. Soc. Am. Memoir, 162 págs.

CORRIGAN, D.C., 1986: Geology of the Burica Peninsula Panama-Costa Rica: Neotectonic implications for the Southern Middle America Convergent Margin. - 152 págs. Universidad de Texas at Austin (thesis).

CRUZ, G. & WYSS, M., 1983: Large earthquakes, mean sea level, and tsunamis along the Pacific coast of Mexico and Central America. - Bull. Seism. Soc. Am., 73: 553-570.

DENGO, G., 1985: Mid America: Tectonic setting for the Pacific margin from southern Mexico to northwestern Colombia. - In: Nairn, A., Stehli, F. & Uyeda, S. (eds.): The Oceans Basins and Margins: 123-180; Plenum Press, New York.

DETRICK, R.S. & PURDY, G.M., 1987: Crustal structure of oceanic fracture zones from seismic reflection and refraction studies. - J. Geol. Soc., 143: 737-745.

DEWEY, J.W., 1971: Seismicity studies with the method of joint hypocenter determination. - 243 págs. Universidad de California Berkeley (thesis).

DEWEY, J.W. & ALGERMISSEN, S.T., 1974: Seismicity of the Middle America arc trench system near Managua, Nicaragua. - Bull. Seism. Soc. Am., 64: 1033-1047.

DEWEY, J.W., 1979: A consumer's guide to instrumental methods for determination of hypocenters. - Geol.Soc.Am.Reviews in Engineering Geol., Vol IV: 109-117.

DOUGLAS, A., 1967: A joint epicentre determination. - Nature, 215: 47-48.

DZIEWONSKI, A.M., FRANZEN, J.E. & WOODHOUSE, J.H., 1987: Centroid moment tensor solution for July-September 1979. - Phys. Earth Planet.Inter., 37: 234-235.

FISCHER, R., 1980: Recent tectonic movements of the Costa Rican Pacific coast. - Tectonophysics, 70: T25-T33.

GETTRUT, J.P., HSU, V., HELSLEY, C.E., HERRERO, E. & JORDAN, T., 1981: Patterns of local seismicity preceding the Petatlan Earthquake of 14 March, 1979. - Bull.Seism.Soc.Am., 71: 761-770.

GRIMM, P.J., 1970: Connection of the Panama Fracture Zone with the Galapagos Rift Zone, Eastern Tropical Pacific. - Mar.Geophys.Res., 1: 85-90.

GUTENBERG, B. & RICHTER, C.F., 1954: Seismicity of the Earth and associated phenomena. - 2nd ed., 310 págs.; Princenton University Press, Princenton.

HEIL, D.J., SILVER, E., MACKAY, M. & MOORE, G., 1986: Effect of obliquely subducting ridges on structural geometry and bathymetry: South Panama. - EOS, Trans.Am.Geophys.Union, 44: 1210.

HEIL, D.J.& SILVER, E.A., 1987: Forearc uplift south of Panama: A result of transform ridge subduction. - Geol.Soc.Am.Abstr.Programs, 19: 698.

HERRMANN, R.B., 1975: A student's guide to the use of P and S wave data for focal mechanism determination. - Earthquake Notes, 46: 29-39.

HERRMANN, R.B., 1976: Focal depth determination from the signal character of long period P waves. - Bull.Seism.Soc.Am., 66: 1221-1232.

ISACKS, B., OLIVER, J. & SYKES, L., 1968: Seismology and the new global tectonics. - J.Geophys.Res., 73: 69-103.

JEFFREYS, H. & BULLEN. K.E., 1967: Seismological Tables. - 50 págs. British Ass.Advancement of Science, Gray Milne Trust, Londres.

KANAMORI, H., 1988: Importance of historical seismograms for geophysical research. - In: LEE, W.H.K.,

MEYERS, H. & SHIMAZAKI, K. (eds.): Historical seismograms and earthquakes of the world: 16-33; Academic Press, San Diego. The World, Academic Press, New York.

KELLEHER, J., SYKES, L. & OLIVER, J., 1973: Possible criteria for predicting earthquake locations and their application to major plate boundaries of the Pacific and the Caribbean. - J.Geophys.Res., 78: 2547-2585.

LEEDS, D.J., 1978: Panama seismic history. - In: Proceedings, Central American Conference on Earthquake Engineering, Vol. 2: 107-116, San Salvador, El Salvador.

LOCKRIDGE, P. & SMITH, R., 1984: Tsunamis of the Pacific basin map 1900-1983 published by the National Geophysical Data Center and World Data Center A for Solid Earth Geophysics, scale 1:17,000,000.

LONSDALE, P. & KLITGORD, K.D., 1978: Structure and tectonic history of the eastern Panama basin. - Gol.Soc.Am.Bull., 89: 981-999.

LOWRIE, A., AITKEN, T., GRIMM, P., & MC RANEY, L., 1978: Fossil spreading center and faults within the Panama Fracture Zone. -Mar. Geophys. Res., 4: 153-166.

MC CANN, W.R., NISHENKO, S.P., SYKES, L.R., & J. KRAUSE, J., 1979: Seismic gaps and plate tectonics: Seismic potential for major boundaries. - Pageoph, 117: 1087-1147.

MENDIGUREN, J.A., 1971: Focal mechanism of a shock in the middle of the Nazca plate. - J.Gophys.Res., 76: 3861-3880.

MIYAMURA, S., 1980: Sismicidad de Costa Rica. - 190 págs.; Editorial Universidad de Costa Rica, San José.

MOLNAR, P. & SYKES, L.R., 1969: Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity. - Geol.Soc.Am.Bull., 80: 1639-1684.

MOORE, G., KELLOG, D., SILVER, R., TAGUDIN, J., HEIL, D., SHIPLEY, T. & HUSSONG, D., 1985: Structure of the South Panama continental margin: A zone of oblique convergence (abstract). - EOS Trans.Am.Geophys.Union, 66: 1087.

MORALES, L.D., 1984: Los temblores sentidos en Costa Rica durante 1973-1983, y su relación con la sismicidad del país. - Rev.Geol.Am.Central, 1: 29-56.

MORALES, L.D., 1985: Las zonas sísmicas de Costa Rica y alrededores. - Rev.Geol. Am.Central, 3: 69-101.

MORALES, L.D., 1986: Características de la sismicidad y tectónica de Panamá. - Bol.Est. Sism. Univ. Panamá, 9: 1-10.

MÜHLHAUSER, S., 1957: Herdmechanische Vorgänge bei einigen zirkumpazifischen Erdbeben. - Tellus, 9: 104-109.

MURTY, T.S., 1977: Seismic sea waves: Tsunamis. - Bull.Fisheries Res. Board of Canada, 198: 1-5.

NEWMANN, F., 1936: United States Earthquakes 1934. - U.S.Department of Commerce Coast and Geodetic Survey., Serial No. 593: 41-56.

OKAYA, A. & BEN AVREHAM, Z., 1987: Structure of the continental margin of southwestern Panama. - Bull.Geol.Soc.Am., 99: 792-802.

PENNINGTON, W., 1981: Subduction of Eastern Panama Basin and seismotectonics of Northwestern South America. - J.Geophys.Res., 86: 10753-10770.

PHO, H.T. & BIHE, L., 1974: Extended distances and angles of incidence of P waves. - Bull. Seism. Soc. Am., 62: 885-902.

PLAFKER, G., 1973: Field reconnaissance of the effects of the earthquake of April 13, 1973, near Laguna Arenal, Costa Rica. - Bull. Seism. Soc. Am., 63: 1847-1856.

PONCE, L., McNALLY, K., SUMIN, V., GONZALEZ, J., DEL CASTILLO, A., GONZALEZ, L., CHAEL, E. & FRENCH, M., 1978: Oaxaca, Mexico earthquake of 29 November 1978: A preliminary report on spatiotemporal pattern of preceding seismic activity and main shock relocation. - Geofis.Intern., 17: 109-126.

SILVER, E. A., REED, D. L., TAGUDIN, J. E. & HEIL, D.J., 1990: Implications of the north and south Panama thrust belts for the origin of the Panama orocline. - Tectonics (in print).

SING, S.K. & LERMO, J., 1984: Mislocation of Mexican earthquakes as reported in International Bulletins. - Rev. Geofísica, 21: 1-17.

SPRECHMANN, P., 1984: Manual de Geología de Costa Rica. Vol 1: Estratigrafía. - 320 págs.; Editorial de la Universidad de Costa Rica, San José.

STEIN, S., 1987: Introduction to seismology, earthquakes and earth structure. - 520 págs.; Blackwell Scientific Publications, London.

TERRY, R.A., 1941: Notes on submarine valleys off the Panamanian coast. - The Geographical Review, 31: 377-384.

VERGARA, A., 1988: Tectonic patterns of lhe Panama Block deduced from seismicity, gravitational data and earthquake mechanism: Implications to the seismic hazard. - Tectonics, 154: 253-267.

VIQUEZ, V. & TORAL, J., 1988: Sismicidad histórica sentida en el Istmo de Panama. - Rev.Geofísica, 27: 26-70.

VIRET, M., BOLLINGER, G.A., SNOKE, J.A. & DEWEY, J.W., 1984: Joint hypocenter relocation studies with sparse data sets - A case history: Virginia Earthquakes. - Bull.Seism.Soc.Am., 74: 2297-2311.

WEYL, R., 1980: The Geology of Central America. - 371 págs.; Gebrüder Borntraeger, Berlin.

WICKENS, A.J. & HODGSON, J.H., 1967: Computer reevaluation of earthquake mechanism solutions 1922-1962. - 230 págs., Crescent Observatory Contrib. No. 103.

WOLTERS, B., 1983: Seismicity and earthquake focal mechanisms and their tectonic implications in southern Central America and northwestern South America. - 89 págs.; University of Stanford (thesis).

WOLTERS, B., 1986: Seismicity and tectonics of southern Central America and adjacent regions with special attention to the surroundings of Panama. -Tectonophysics, 128: 21-46.