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Relocation and waveform modeling of the 1924 Orotina, Costa Rica, earthquake (M_S 7.0)

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ABSTRACT

We have determined the location and focal mechanism for the 1924 Orotina earthquake using two different relocation algorithms developed for the analysis of historic earthquakes and forward waveform modeling of teleseismic body waves. Our relocation results suggest that the 1924 earthquake occurred ~50 km southeast of Orotina near the Pacific coast. The heavy damage reported in the Orotina region, coupled with a low population density to the southeast, had led previous researchers to believe that the earthquake occurred near Orotina, possibly on the Tarcoles or Bijagual faults. Our waveform modeling results indicate rupture on a thrust fault at a depth (25±5 km) near the plate interface with M_w 6.4–6.7. These are inconsistent with slip on any mapped surface faults located near Orotina and with the mechanism of the nearby 2004 M_w 6.4 Damas earthquake that indicates transtensional deformation in the upper crust. This suggests that the 1924 event may be one of a sequence of events (1924, 1990, 1999) generated by subduction of the central Costa Rica seamount belt.

1. Introduction

The 1924 Orotina Earthquake is considered one of the most destructive earthquakes of Costa Rica. Its name is derived from the damage caused by the earthquake to the city of Orotina (Fig. 1) and also to its aftershocks, accompanied by noises that were felt there. It damaged localities of central Costa Rica close to the central Pacific coast and caused geologic effects like fracturing of the ground, landslides, liquefaction and changes in the groundwater level. A remarkable fact of this earthquake is that no one in Orotina and surrounding regions was killed; the few reported casualties are from the southeastern side of the previously proposed epicentral area (Montero, 1999).

The International Seismological Summary (ISS) reported the first location for this earthquake. Sapper (1924) (quoted in Montero, 1999) pointed out that the epicenter of the main event could have been located in the vicinity of the Pacific Ocean. Jacob et al. (1991) showed a focal mechanism for the event and Ambraseys and Adams (1996) and Montero (1999) macroseismically located the event. Montero (1999) linked the earthquake to a hypothetical tectonic boundary.

In this study we analyze phase data tabulated by the ISS to obtain several estimates of the earthquake's location (with associated uncertainties). We also model teleseismic waveform data collected from seismic stations around the world to determine the earthquake's focal depth and faulting processes. Our results are compared with previous epicentral determinations and related to the tectonic features of the study area.

2. Tectonic framework

Costa Rica is part of the Central America Volcanic Arc formed by the subduction of the Cocos plate under the Caribbean plate. The most important tectonic feature of Costa Rica is the Middle American Trench (MAT) located on the Pacific side of the country. Other relevant tectonic structures are the Panama Fracture Zone (PFZ), the North Panama Deformed Belt (NPDB) and the Tarcoles and Candelaria faults.

The MAT is the junction of the Cocos and Caribbean plates (Fig. 1). The present convergence rate increases along the trench from about 7.3 cm/yr off Mexico and Guatemala (DeMets, 2001) to 9.9 cm/yr in southern Costa Rica (Montero, 2000). The northeast dipping slab has descended to a maximum depth of 200 km in western Costa Rica (Protti et al., 1994) and to only 70 km off southern Costa Rica (Arroyo, 2001). The shallowing of the subduction at the southern terminus of the MAT is related to the subduction of young, buoyant, rough ocean crust that arrived at the trench ~5 Ma (de Boer et al., 1995), causing a decrease in the volcanic activity. This oceanic crust includes the Cocos ridge and a seamount belt that generates high uplift and significant deformation of the arc during their subduction beneath the Caribbean plate.

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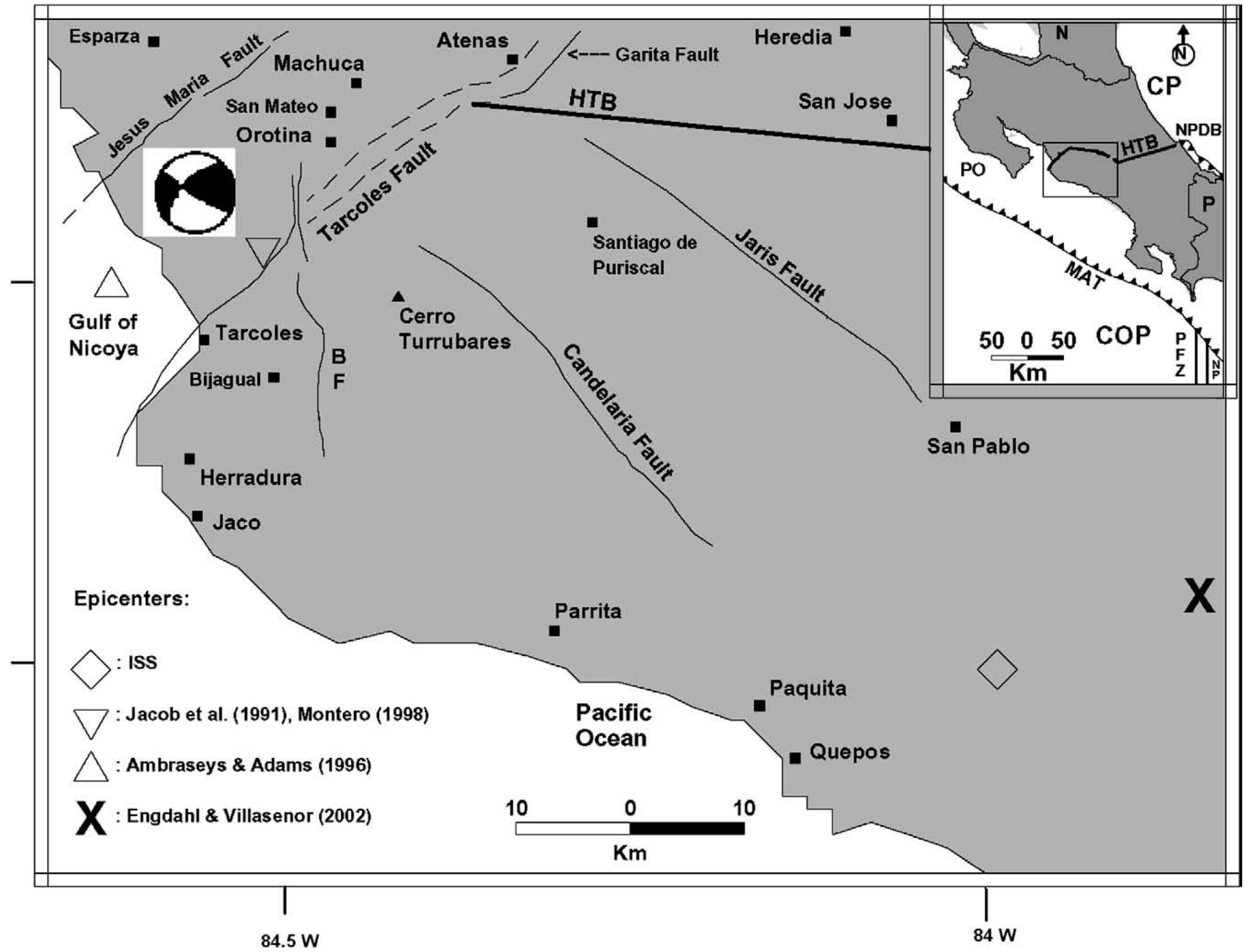

Fig. 1. Tectonic framework of Costa Rica and previous instrumental and mascroseismic epicenters of the 1924 Orotina earthquake. The inset map at the upper right shows major tectonic features and the location of the larger map (box). The tectonic features shown on the inset map include the Middle America Trench (MAT), the Panama Fracture Zone (PFZ), and the North Panama Deformed Belt (NPDB). HTB is the hypothetical tectonic boundary between the Caribbean plate and Panama microplate proposed by Montero (1999), Fan et al. (1993), Güendel and Protti (1998), and Marshall et al. (2000). In the inset map COP is Cocos plate, CP is Caribbean plate, N is Nicaragua, NP is Nazca plate, P is Panama, and PO is Pacific Ocean. On the larger map BF is the Bijagual fault and ISS is the International Seismological Survey. Squares denote towns/cities. Focal mechanism for the 1924 Orotina earthquake is from Jacob et al. (1991).

The Panama Fracture Zone is the plate boundary between the Cocos and Nazca plates. It is a north–south striking, dextral, oceanic transform fault zone that extends from near the Equator to 6°N, where it splits into a series of parallel, north–west trending, dextral strike-slip faults. The PFZ is a very active tectonic boundary that has generated events of magnitude larger than 7.0.

The NPDB is an overthrust feature of the Caribbean which extends offshore from the Panama–Colombia border (not shown) up to the shoreline northwest of Limón in Costa Rica. This deformed belt can be explained by a movement of blocks within the Caribbean plate (Adamek et al., 1988; Silver et al., 1990). Recently recorded seismicity in north central Panama associated with the convergence between the Caribbean plate and the Panama block indicates that events in this region can reach depths of up to 70 km (Fernández et al., 2007).

The Tarcoles fault is a long, northeast trending fault (Fig. 1). It first appears onshore at Tarcoles, a community located on the east coast of the Gulf of Nicoya. However, it is agreed that the tectonic deformation associated with this fault begins in sea-floor of the Gulf of Nicoya. It takes a straight path northeastward through the valley of Tarcoles River to southern Orotina where it intersects the Bijagual fault system, the only major north–south trending fault in the area. From the vicinity of its intersection with the Bijagual fault system, the Tarcoles fault becomes a diffuse structure with no distinctive single trace as in the southwest. According to Denyer et al. (2003), the Tarcoles fault crosses the Bijagual fault system and continues as two companion branches to the southwest end of the Garita fault. In an undeviating course the trace of the Tarcoles fault passes just east of Orotina and connects to the Garita fault. Uplifts, basins, and displaced recent sediments are evidence of activity along this fault (Montero, 1999). Madrigal (1970) inferred normal slip along the Tarcoles fault, but Denyer et al. (2003) considered that this fault is a left-lateral strike-slip structure.

The Candelaria fault is one of the largest northwest striking faults of Costa Rica. Its trace is prominent in the southeast where it follows the Cajón and Candelaria rivers and shows linear valleys. According to Arias and Denyer (1991) and Montero (1999) this is a dextral strike-slip fault with a reverse component of motion.

A hypothetical and multi-named strike-slip structure (i.e. the transcurrent fault of Costa Rica, Astorga et al. (1989); the diffuse transcurrent fault zone of Costa Rica, Fan et al. (1993); the shear zone of Costa Rica, Güendel and Protti (1998); the Central Costa Rica Deformed Belt, Marshall et al. (2000)) has been proposed as the tectonic boundary between the Caribbean and hypothetical Panama microplate (HTB, Fig. 1). However, Fernández Arce (2009) did not find evidence of the proposed subparallel strike-slip faults that would form this suggested strike-slip tectonic boundary.

3. Previous work

The 1924 Costa Rica earthquake was initially located by the International Seismological Summary (ISS). The epicentral coordinates obtained (Fig. 1) were 9.5°N and 84.0°W (Table 1). The earthquake depth was not determined.

Jacob et al. (1991) were the second group to try to locate the earthquake. They located the event near Orotina (see Fig. 1). They also determined a focal mechanism for the event from waveform modeling (Pacheco, pers. commun., 2006), although this was not stated in the publication and no results of the waveform modeling process were shown. In fact, the coordinates of the epicenter, the focal mechanism orientation, and the depth of the earthquake were not given in the publication. Their focal mechanism indicated predominantly strike-slip motion with a reverse component (Fig. 1). One nodal plane of their solution had a northwest–southeast strike with a high angle of dip (~80°) to the southwest, while the other nodal plane had a northeast–southwest strike with a ~50–60° dip to the northwest.

Later, Ambraseys and Adams (1996) carried out the first macroseismic location of the 1924 earthquake. Their epicenter lies within the Gulf of Nicoya (Fig. 1). They indicated that the area of maximum damage in 1924 was located between Machuca and Orotina in the north and the Pacific shoreline in the south. They mention the total ruin of rural settlements and some deaths in the Turrubares region (located near Cerro Turrubares, Fig. 1). Most interestingly, they report heavy damage and some casualties in the region east of the Candelaria fault. Damage was heavy in San Jose, but minor in Esparza and Jaco. Ambraseys and Adams (1996) indicated that the earthquake foci were shallow but they did not give a specific depth.

Montero (1999) located the 1924 earthquake by using structural effects like damage to houses, buildings, and a railroad line, and non structural effects like landslides, rock falls, ground fracturing, changes in groundwater flow pattern and liquefaction. The determined mesoseismal area included Orotina, San Mateo and Esparza where the maximum intensity was IX. Surprisingly, in distant eastward localities like Heredia and San Jose the maximum intensity was VIII. The IX and VIII isointensity contours of Montero (1999) are discontinuous southeast of Orotina, indicating that the intensities are not well constrained in this area. According to Montero (1999) the earthquake occurred near Orotina (Fig. 1) at 15 km depth and was generated by the Tarcoles fault. However, his publication includes a paragraph of a transcribed conference about the earthquake (dictated in the beginning of April 1924) in which Dr. Sapper suggested that the epicenter of the 1924 Costa Rica earthquake could have occurred near the coast due to the damage observed in Herradura, Paquita and Quepos.

Finally, Engdahl and Villaseñor (2002) relocated the earthquake using instrumental information and the Engdahl et al. (1998) relocation algorithm. Their location (X, Figs. 1 and 2) places the earthquake about 75 km southeast of Orotina at a depth of 35 km.

4. Earthquake relocation

We relocated the 1924 earthquake using two techniques that are specifically designed for the study of historic earthquakes that often have poor distributions of phase data and highly variable quality of phase data (see Table 1 for location details). We used 38 P and 16 S phases tabulated by the ISS for our analysis (Table 2). The closest station to the earthquake was in Balboa Heights, Panama ($\Delta = 4.4°$).

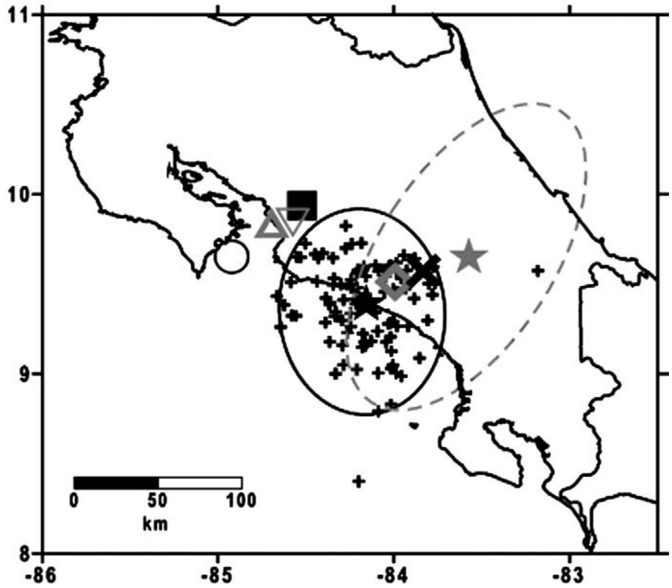

Fig. 2. Results of relocations. The black square indicates the location of the city of Orotina. The black oval represents the 95% confidence ellipse for relocations (plusses) using the Petroy and Wiens technique. The best-fit epicenter for this technique is indicated by the black star. The gray star and dashed gray error ellipse were obtained using the jloc method of Lee and Dodge. The open gray diamond is the ISS location, the open gray triangle is Ambraseys and Adams' location based on macroseismic data, the open gray inverted triangle is the location of Jacob et al. (1991) and Montero (1999), and the X represents the instrumental relocation of Engdahl and Villaseñor (2002). The open circle is the 1990 Gulf of Nicoya earthquake.

The first location technique, developed by Petroy and Wiens (1989), uses a bootstrap approach where random subsets of the phase data are used to repeatedly locate the earthquake. The cloud of relocations is then used to define an error ellipse for the location. Fig. 2 shows the results of 100 relocations of the earthquake (plusses) and the error ellipse (solid black line) representing the 95% confidence interval for these locations. We used the Jeffreys and Bullen (1940) velocity model for these relocations. Note that the ellipse lies to the southeast of Orotina (black square), with the optimal epicenter (black star) located near Quepos.

The second location technique (jloc) was developed by Lee and Dodge (2006). This method uses a grid search technique followed by downhill simplex search algorithm to find the epicenter that minimizes the observed travel times. An L1 minimization is used because it is less sensitive to large travel time outliers at a few stations. The algorithm uses the IASPEI91 velocity model. The error ellipse is estimated assuming that the travel time data are uncorrelated and have equal variance. Fig. 2 indicates that the jloc epicenter (gray star) is east of both Orotina and the bootstrap location, however its error

Table 1
Earthquake relocations.

Method	Latitude	Longitude	Error ellipse (length of major and minor axes in km, strike of major axis)	Depth (km)
Original (ISS)	9.5	−84.000	–	–
Jacob et al. (1991)	9.83	−84.58	–	–
Ambraseys and Adams (1996) (macroseismic)	9.8	−84.7	–	–
Montero (1999) (macroseismic)	9.83	−84.58	–	15
Engdahl and Villaseñor (2002) (instrumental)	9.56	−83.84		35
Bootstrap	9.376	−84.164	131, 107, 173°	–
Jloc	9.637	−83.581	214, 119, 33°	–

Table 2
Stations used for earthquake relocations.

Station name	Phase	Distance (degrees)	Azimuth (degrees)
BHP	P, S	4	100
TAC	P, S	17	306
SJP	P	20	63
MAZ	P, S	25	306
SLM	P	29	351
CLH	P	30	196
GEO	P	30	195
WAS	P, S	30	195
LPZ	P	31	148
CHI	P	32	356
ITH	P, S	33	11
TUO	P, S	33	316
TNT	P	34	7
NRT	S	36	15
HAL	P	39	24
MHC	P	43	315
BRK	S	44	316
LPA	P, S	51	152
VIC	P	50	327
RDJ	P, S	52	129
ESK	P	77	35
BID	S	77	37
EDI	P, S	77	35
WBE	P	78	38
PAR	P, S	81	42
FBR	S	81	50
UCC	P, S	82	40
ALG	P, S	82	54
DBN	P, S	82	39
STR	P, S	84	42
HAM	P, S	85	37
ZUR	P, S	85	43
INN	P	87	43
FIR	P	87	46
VEN	S	88	44
RDP	P	89	48
VIE	P	90	41
PUL	P	94	27

ellipse (dashed gray line) overlaps with that of the bootstrap location. Note that the Engdahl and Villaseñor location is within the region of overlap between the two location error ellipses we have obtained. These results suggest that the 1924 earthquake occurred near the western coast of Costa Rica southwest of Orotina and likely did not involve movement on the Tarcoles fault.

5. Waveform modeling results

We collected seismograms of the 1924 earthquake from seismograph stations located around the world. Information on seismographs that recorded waveforms of sufficient quality for our waveform modeling study are given in Table 3. Seismograms were digitized from scanned images using the SeisDig software package (Bromirski and Chuang, 2003).

Our analysis used the forward modeling technique developed by Baker and Doser (1988). We modeled vertical P, transverse S (obtained from rotation of the two horizontal S-wave components) and vertical PP (using Hilbert transformed PP waveforms following the method of Ruff and Kanamori (1983)). First-motion observations at Tacubaya ($\Delta = 17°$) and Pasadena (short-period instrument) were also used to constrain the starting model (Fig. 3). Our velocity model at the source was taken from Protti et al. (1995). At the receivers we used a 3 layer model with 15 km thick upper crust ($V_p = 6$ km/s, $V_s = 3.5$ km/s, $\rho = 2600$ kg/m^3), a 25 km thick lower crust ($V_p = 6.5$ km/s, $V_s = 3.7$ km/s, $\rho = 2700$ kg/m^3), and mantle half space with $V_p = 8$ km/s, $V_s = 4.2$ km/s, and $\rho = 3300$ kg/m^3.

The compressional first-motion observations for the 1924 event (Fig. 3) at stations PAS and TAC in North America suggested a focal mechanism with a large component of reverse/thrust motion — more reverse motion than the mechanism published by Jacob et al. (1991) (dashed lines, Fig. 3). Although we tested a variety of fault orientations, including the Jacob et al. (1991) mechanism, the observed seismograms were best fit with a thrust fault having a strike similar to that of the subduction zone (solid lines, Fig. 3). The Jacob et al. mechanism produced nodal SH waveforms at GTT and did not match the SH waveform shape at MHC. Our focal mechanism strike is well constrained by SH waveforms at European stations (308° ± 15°). A strike of 318° produces a nodal SH waveform at GTT and a strike of 293° greatly overestimates SH amplitudes (factor of 3 or more) at all stations. The angle of dip is low (<30°) but difficult to resolve with available information. The rake (110 ± 15°) is also well constrained by the European SH waveforms. A rake of 125° greatly overestimates SH amplitudes in Europe and a rake of 95° produces a nodal waveform at GTT. The focal depth of 25 ± 5 km, combined with a relocation near the Pacific coast (Fig. 2), places the event near the plate interface (based on the 3-D models of DeShon et al. (2003)). It was difficult to estimate the total duration of the earthquake. The minimal estimate of the event's seismic moment is 4×10^{18} N m ($M_w = 6.4$) and it could be as high as 1.2×10^{19} N m ($M_w = 6.7$). This is lower than the magnitude estimates of 6.9 (m_b) to 7.0 (M_S) by Abe (1981) for this event.

In order to further verify the focal mechanism of the 1924 earthquake we felt that it would be useful to search for a recent, large magnitude event that occurred close to the 1924 event and was recorded at the same seismograph station locations as in 1924. Our best candidate for this comparison was the March 25, 1990 Nicoya Gulf earthquake ($M_w = 7.0$) (open circle, Fig. 2) with a focal depth of ~20 km (Protti et al., 1995). Fig. 4 shows seismograms recorded at stations DBN and PUL for both events. Although the instrumentation is not exactly the same in 1924 and 1990, the similarities of the waveform shapes suggest similar mechanisms for the two events. The 1990 event has a longer duration, as expected for an event with greater moment release.

6. Discussion

Our relocation and waveform modeling results suggest that the 1924 earthquake occurred on a thrust fault near the depth of the plate

Table 3
Information on seismograph stations used in waveform modeling portion of this study.

Station waveform(s)[a]	Distance (deg), azimuth (deg)	Seismometer period (s)[b]	Galvanometer period (s)[c]	Magnification
De Bilt (DBN) PZ, PPZ, SH	82, 39	25 (H) 10 (V)	25 (H) 10 (V)	310 (H) 740 (V)
Göttingen (GTT) SH	85, 32	12	4 (D)	157
Pulkovo (PUL) PZ, PPZ	94, 27	12.2	13.1	212
Mt. Hamilton (MHC) SH	43, 315	6	11 (D)	300
Sverdlovsk (SVE) PPZ	54, 19	13	13	462
Uppsala (UPP) SH	87, 30	9	4 (D)	187

[a] PZ = vertical P, PPZ = vertical PP phase, SH = transverse S.
[b] H = horizontal component, V = vertical component.
[c] D indicates a mechanically damped seismograph, where D is the damping coefficient.

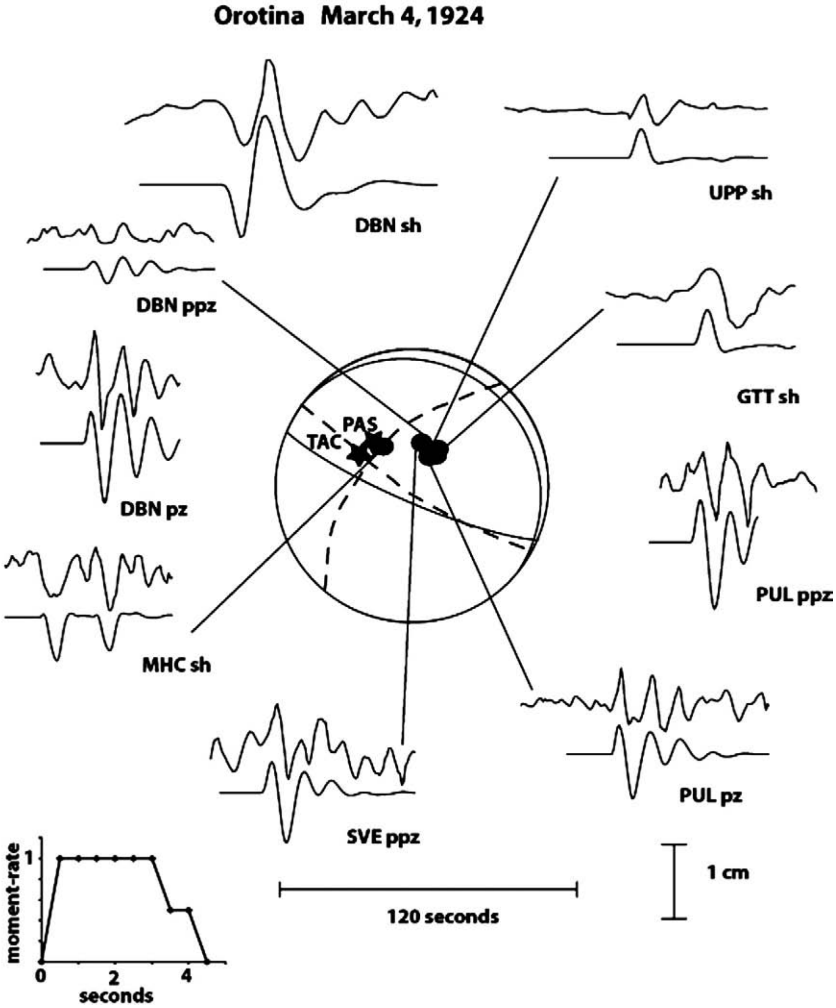

Fig. 3. Waveforms (top observed, bottom synthetic) of the 1924 earthquake. See Table 3 for explanation of station abbreviations. Solid lines represent our best-fit mechanism, dashed lines indicate the mechanism of Jacob et al. (1991). Stars labeled PAS and TAC represent compressional first-motion observations at Pasadena and Tacubaya. Amplitude of source-time function at lower left has units of 10^{18} N m/s.

interface in a region southeast of Orotina near the Pacific coast. Although previous macroseismic studies suggested a location nearer Orotina (Figs. 1 and 2), these estimates were based on damage to buildings and secondary effects such as ground deformation, landslides, soil failure and liquefaction. Ambraseys and Bilham (2003) have stated that liquefaction, landslides, and rock falls are not criteria suitable for the assessment of intensity. Musson (1998) has shown that even small ($M_L < 4$) earthquakes can produce liquefaction. Rupture directivity may have also played a role in the intensity of shaking observed in the Orotina and San Jose regions.

Montero's (1999) intensity results are not well constrained southeast of Orotina due to the lack of population and structures in that area in the 1920s. Communities such as Parrita and Quepos grew substantially after 1930 when banana plantations moved from the Costa Rican Atlantic to Pacific coast due to the effect of disease on banana production along the Atlantic coast. Indeed, Sapper (1924) (quoted in Montero (1999)) observed that the 1924 earthquake caused heavy damage in Herradura, Paquita and Quepos, and he felt that the epicenter could have been located southeast of Orotina near the Pacific coast. Montero (1999) indicated that he could not find any written reports of the damage observed in these localities to verify Sapper's claims.

Our focal mechanism is also inconsistent with rupture on either the northeast–southwest striking Tarcoles or north–south striking Bijagual fault systems near Orotina. The strike of one nodal plane of our focal mechanism is similar to that of the Candelaria and Jaris faults, but is inconsistent with the strike-slip nature of these faults. The focal mechanism is also inconsistent with strike-slip rupture along faults associated with the east–northeast striking hypothetical boundary between the Caribbean and Panama microplate. In 2004 the M_w 6.4 Damas earthquake occurred at 24 km depth (Pacheco et al., 2006) in a location very near the epicenter we determined for the Orotina event using the Petroy and Wiens method (black star, Fig. 2). The Damas event had a strike-slip mechanism with a large component of normal dip-slip motion that Pacheco et al. (2006) interpret as representing transtensional deformation of the entire forearc crust. These observations would suggest that the Orotina event is most consistent with slip on the plate interface, as none of the mapped surface faults in the epicentral region is a thrust fault, and the recent Damas event indicates that transtensional deformation is occurring in the upper crust.

7. Conclusions

Our relocation and waveform modeling analysis of the 1924 Costa Rica earthquake suggest that it occurred along the plate interface and that it represents subduction of the central Costa Rica seamount belt, similar to recent earthquakes located to the north (1990 Gulf of Nicoya; Husen et al., 2002) and south (1999 Quepos, Bilek and Lithgow, 2005) of the 1924 epicentral region. The strong shaking

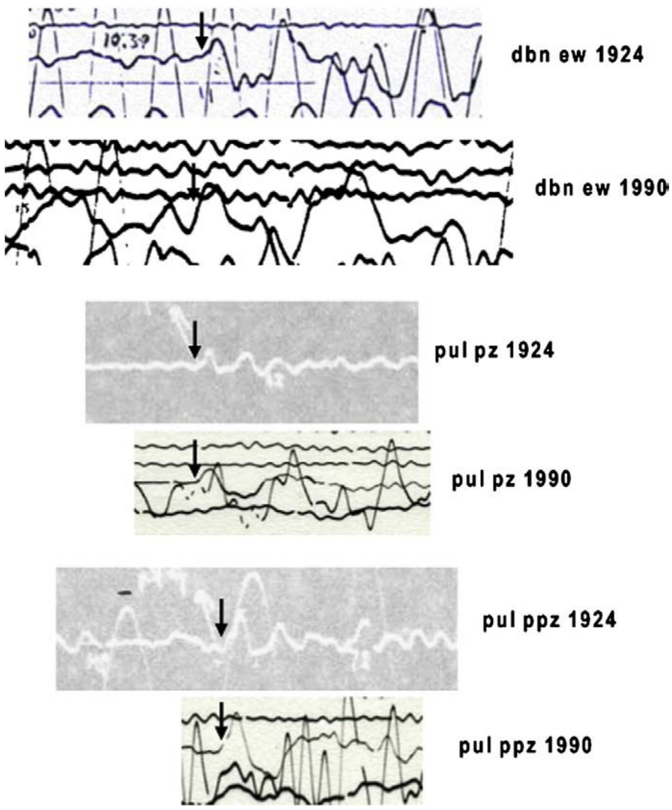

Fig. 4. Raw (unprocessed) seismograms of the 1924 and 1990 earthquakes recorded at De Bilt (dbn) and Pulkovo (pul). The arrival of the S (dbn ew), P (pulp z) and PP phase is indicated by arrows. Seismograms have been scaled to the same horizontal time scale. Although the seismographs had different responses in 1924 and 1990 and the 1990 event had a greater moment, the initial portions of the waveforms appear similar.

observed in Orotina may have been related to rupture directivity. The lack of population/settlements in the epicentral region in the 1920s likely skewed macroseismic locations of this event.

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