Source Processes of Large (M≥6.5) Earthquakes of the Southeastern Caribbean (1926-1960)

Diane I. Doser and Shelley R. VanDusen
Department of Geological Sciences
University of Texas at El Paso
El Paso, Texas, USA, 79968

Abstract

Body waveform inversion studies have been conducted for 13 earthquakes of magnitude ≥6.5 that have occurred between 1926 and 1960 in the southeastern Caribbean, a region extending from Barbuda, Lesser Antilles, to Cumana, Venezuela. A goal of this research is to provide a better understanding of the long term spatial and temporal patterns of seismicity and deformation within the region. The results suggest that the six shallow (focal depths of 1 to 30 km) earthquakes studied reflect intraplate deformation. Shallow events in eastern Venezuela show predominantly right-lateral strike-slip motion, while an event west of Trinidad shows normal faulting. An event in the Barbados trough exhibits right lateral strike-slip faulting. Moderate depth events (40 to 70 km) show normal faulting at 44 km depth near Trinidad, but possible interplate reverse faulting near Martinique at 52 km depth. Intermediate depth events (>70 km) show left-lateral strike-slip motion beneath the Paria peninsula. A mixture of normal and strike-slip faulting, generally along trends oblique to the arc, is found within the Lesser Antilles. The deformation rate estimated from the seismic moment release between 1926 and 1960 is only 4% of the estimated plate convergence rate for the region.

Introduction

The Caribbean region has been the site of frequent large (M≥6.5) earthquakes in historic time. The region is an area of complex plate interaction that is poorly understood. One of the problems in understanding the plate motion of the region is that motion at the plate boundaries has been either strike-slip, convergent or some mixture of the two, yielding few structures that can be used to determine relative plate motions.

This study focuses on determining the source parameters of 13 large (M≥6.5) earthquakes occurring along the southeastern boundary of the Caribbean plate between 1926 and 1960 (Figure. 1). Several studies (e.g. Stein et al., 1982; Russo et al., 1992; Russo et al., 1993) have examined historic and recent seismicity along this boundary, but none includes a waveform modelling/inversion study of historic earthquakes. A detailed study of these historic events should help verify how much intraplate movement is occurring, how intraplate and interplate events are related to segmentation of downgoing oceanic lithosphere, and help sort out the complexities of plate interaction along the southeastern plate margin. Moment rate information for the region can also be compared to various estimates of plate deformation rates in an effort to determine how much plate deformation is being released seismically.

Analysis Methods

This study focuses on historic earthquakes of magnitude ≥6.5 to ensure that body waveforms for the events were large enough to be well recorded at teleseismic distances. The earthquakes should also reflect the greatest deformation and moment release within the region. Requests for seismograms and instrumental response information were sent to numerous seismic observatories in North America, South America and Europe, but available seismograms were limited, especially for earthquakes occurring prior to 1940.

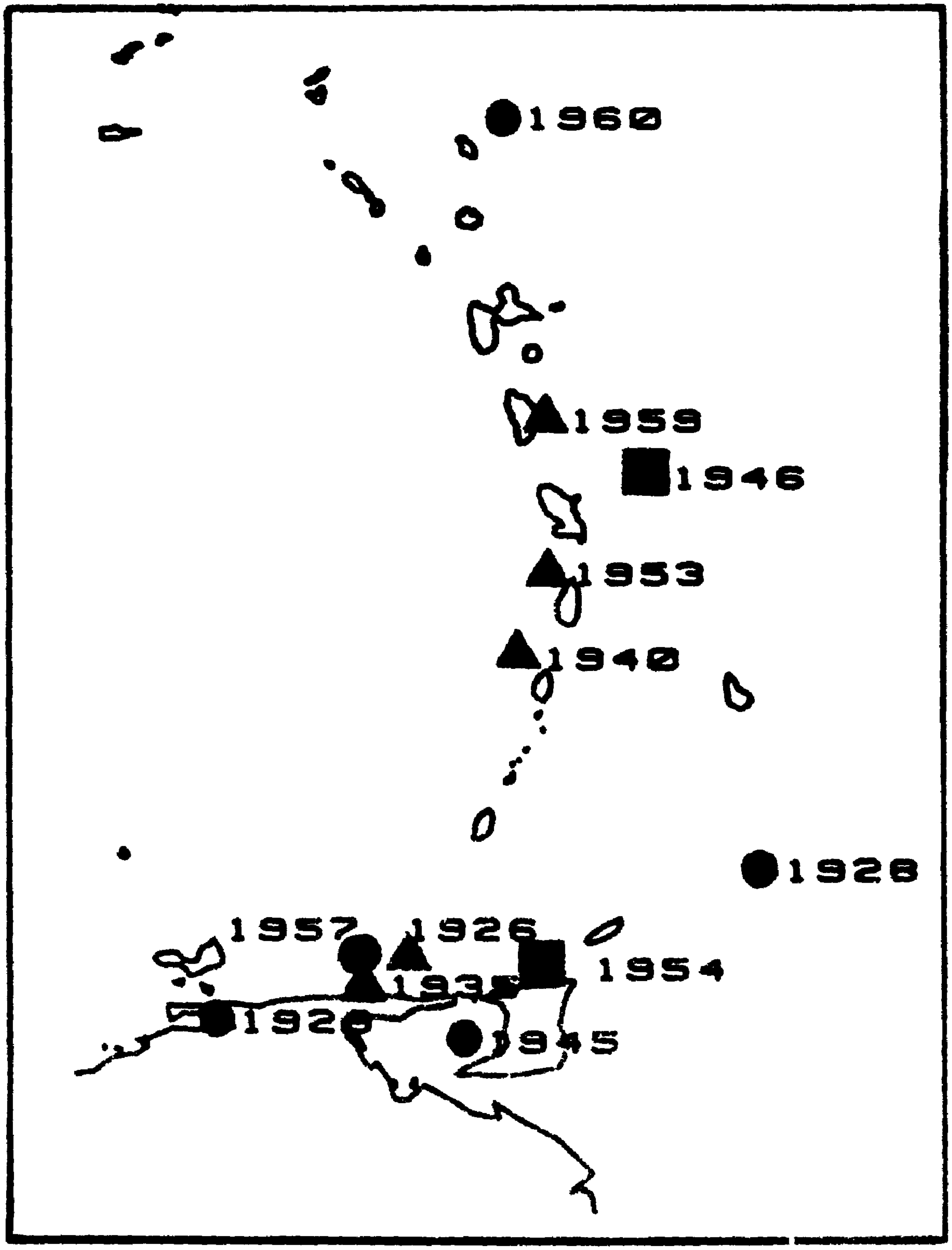

FIGURE 1: Historic earthquakes of $M \geq 6.5$ examined in this study shown by year of occurrence. Two earthquakes occurred in the same area in 1957. Dots are earthquakes <40 km in depth, squares are earthquakes from 40 to 70 km deep, triangles are >70 km deep.

Seismograms obtained from observatories were hand digitized and then re-sampled at an evenly spaced sample interval of 0.5 sec. Digitized seismograms were overlain on originals to ensure digitization accuracy. Vertical seismograms received no additional processing, but horizontal seismogram components were rotated to obtain radial P and transverse S waveforms. Instrumental response information was added to the seismogram files after processing.

Waveforms were modelled using the multi-step inversion technique of Baker and Doser (1988) that solves for focal mechanism (strike, dip, rake), source-time function shape, and focal depth, and their related uncertainties using a priori estimates of source parameters. A priori estimates of source parameters were based on first motion studies, aftershock alignments, and/or trends of local geologic structure whenever this information was available. Generally, the inversion procedure is found to be the most stable when short segments (5-10 sec) of the waveforms are used to obtain an initial estimate of focal mechanism. Depth and moment are then progressively determined as the waveforms used in the inversion are lengthened. In regions where little geological or seismological information existed to help determine a priori models, we used a number of a priori models.

The original inversion routine of Baker and Doser (1988) only allowed for halfspace source and receiver models. Therefore, we have used the original inversion routine to obtain initial estimates of source parameters. We then used forward modelling techniques that allowed inclusion of more complicated source structure, to finalize our source parameter estimates for events >50 km deep or in regions of deep (>1 km) water.

An example of the results from the inversion process is shown in Figure 2 for the 1929 Cumana, Venezuela earthquake. Note that only seismograms for two stations were available for this analysis. The positions of the stations, however, provided good constraints on the nodal plane orientations. Three a priori starting models were tried for this earthquake, an east-west striking right-lateral fault, an east-west striking left-lateral strike-slip fault and an east-west striking reverse fault, based on the observations of Paige (1930). Although the focal mechanism is reasonably well resolved, the waveforms could not constrain the focal depth to more than ±8 km (Table 1).

Table 1: Source Parameters of Historic Earthquakes obtained from this study

Date (mo/da/yr)	Strike (deg)	Dip (deg)	Rake (deg)	Depth (km)	Moment (x 10^{18} N-m)
02/01/26*	90	80	-20	157	1.0
09/27/28	58±40	88±20	-170±15	28±10	6.6±2.1
01/17/29	77±11	89±15	180±15	14±8	12.0±2.0
04/10/35*	90	80	0	100	2.0
07/06/40	349±24	90±20	-95±40	160±15	1.8±0.5
12/23/45	57±18	66±11	-90±14	34±7	4.0±0.6
05/21/46	322±18	57±11	54±20	52±5	2.5±1.6
03/19/53	278±26	53±14	-74±27	130±10	14.6±4.5
12/04/54	191±28	57±7	-74±24	44±11	2.0±0.3
10/02/57	43±17	89±19	-150±25	9±5	3.4±0.5
10/04/57	80±27	39±22	152±27	1±1	7.0±4.0
01/08/59	288±28	91±29	-2±26	140±15	4.7±1.0
05/31/60	347±20	55±18	85±35	23±4	0.7±0.2

*parameters determined from forward modelling, all others from inversion of waveforms

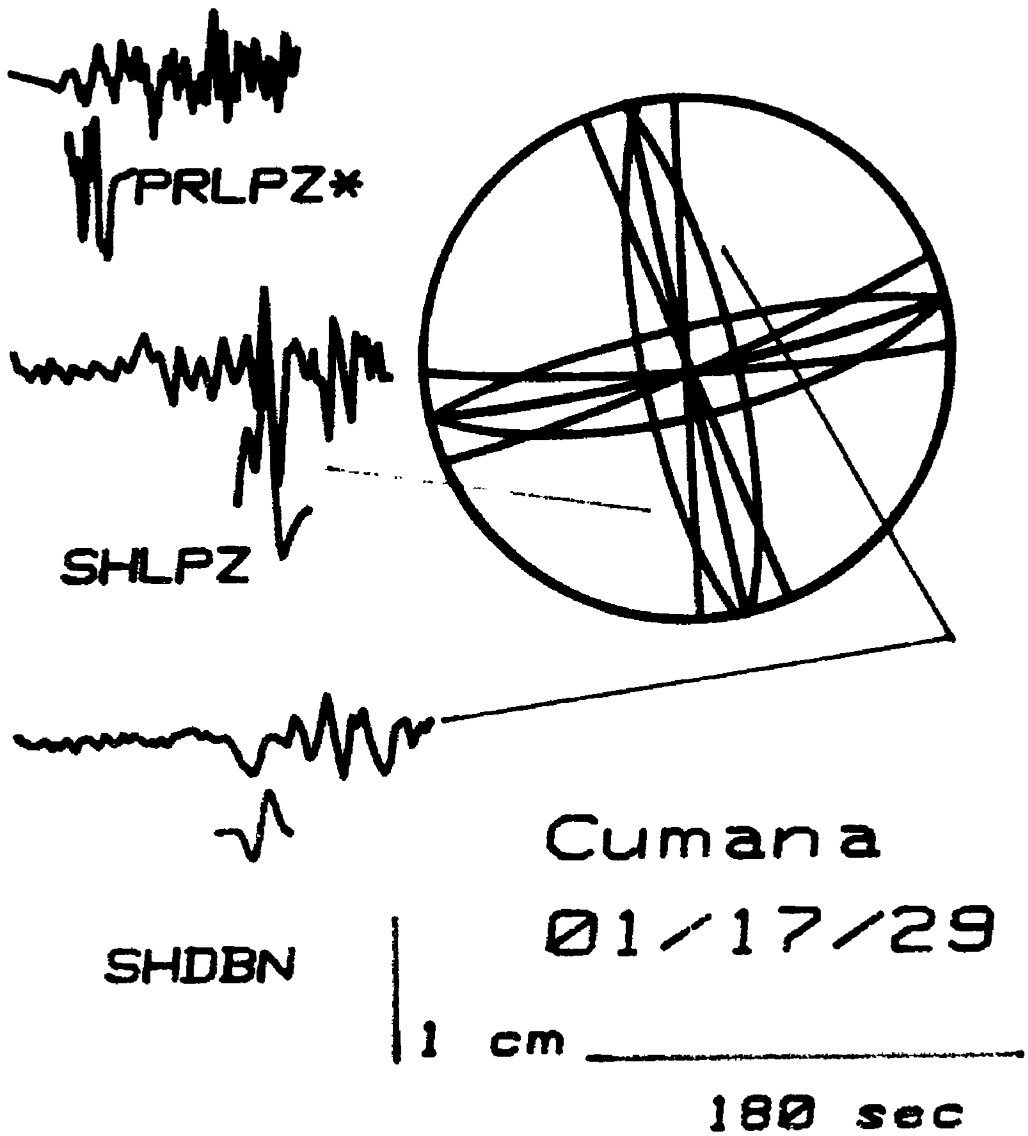

FIGURE 2: Example of waveform inversion for the 1929 Cumana, Venezuela earthquake. Top seismogram of each pair is observed, bottom is synthetic. PR = radial P, SH = transverse S, LPZ = La Paz, Bolivia, DBN = DeBilt, Netherlands. Asterisk denotes that seismograms were enlarged by a factor of two from the vertical scale shown at the bottom. The range of uncertainties in focal mechanism orientation obtained from the inversion is also shown.

Results

Results of source parameter inversions for the Cumana event and other earthquakes are noted in Table 1. Note that waveform information for the 1926 and 1935 Paria Peninsula events were too limited to use in the inversion process outlined above. For these earthquakes a number of starting models (based on the focal mechanisms of recent deep earthquakes studied by Russo et al., 1993) were used in a forward modelling process to estimate the source parameters. In most cases, focal mechanisms that had previously been determined from first motion studies of some of the historic events were in good agreement with our inversion results.

Focal mechanisms obtained from the waveform modelling and inversion process are shown in Figure 3. Results show that shallow earthquakes in eastern Venezuela have predominantly strike-slip mechanisms. To the east in Trinidad, both shallow and moderate depth earthquakes exhibit normal faulting. These mechanisms are similar to those of smaller, more recent earthquakes studied by Russo et al. (1993). The intermediate depth events beneath the Paria Peninsula both show left-lateral faulting and are not as consistent with the results of Russo et al. (1993).

Within the Barbados Trough, the 1928 earthquake shows right-lateral strike-slip faulting. The results of Russo et al. (1993) show a mixture of normal and left-lateral oblique faulting to the north of this earthquake.

Along the Lesser Antilles arc, intermediate depth earthquakes show normal or strike-slip faulting. For the 1953 (St. Lucia) and 1959 (Dominica) events, the faulting is oblique to the strike of the arc. Previous studies (Stein et al., 1982; Russo et al., 1992) have suggested that these earthquakes are related to deformation within the downgoing slab, possibly controlled by fracture zones within the slab. The 1940 St. Vincent earthquake occurred on a normal fault trending parallel to the arc and may be related to plate bending stresses in the downgoing slab.

The only two historic earthquakes that may be related to interplate deformation are the 1946 Martinique and 1960 Barbuda earthquakes. Both exhibited reverse faulting along nodal planes that parallel the plate boundary at depths of 23 to 54 km.

We have summed the moment release of the historic earthquakes we have studied and have compared this moment rate to moment rates for more recent earthquakes in Table 2. For the more recent estimates, we have summed the moments of all M>5.9 earthquakes. We have taken the moments either from the CMT (Harvard) solution listed in the United States Geological Survey's Preliminary Determination of Epicentres or from Stein et al. (1982). The higher moment rate between 1960 and 1992 was primarily a consequence of the occurrence of the December 25, 1969 (M_S=7.5) earthquake.

Table 2: Moment Rates and Seismic Deformation Rates for the Southeastern Caribbean Region

Time Period	Moment Rate (x 10^{18} N-m/yr)	Deformation Rate (cm/yr)
1926-1960	1.8	0.04
1960-1992	4.6	0.11
1926-1992	3.1	0.07

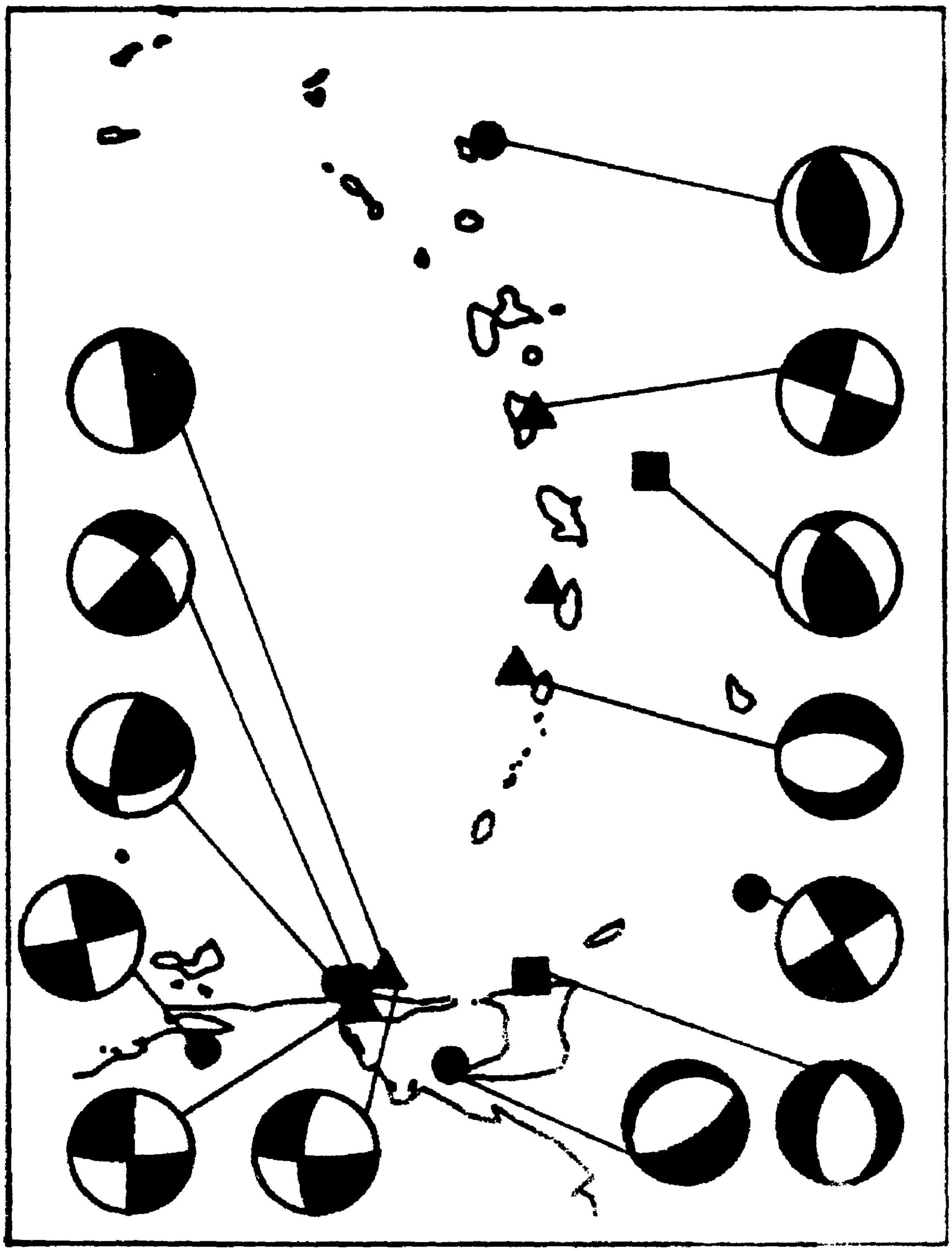

FIGURE 3: Focal mechanisms obtained for historic earthquakes studied. Mechanisms are lower hemisphere projections with shaded compressional quadrants. See Table 1 for additional source parameter information.

Molnar (1979) has related moment release in a region to the deformation rate through the use of the expression:

$$M_o = |2 \mu l_1 l_2 r / K|$$

where l_1 and l_2 are the width and depth of the region undergoing deformation, M_o is the moment rate, r is the deformation rate, μ is the shear modulus, and k is an empirical constant (~ 0.75). We have calculated deformation rates for the southeastern Caribbean region assuming a 300 km wide zone of deformation (the general width of the seismic zone throughout the region) and a depth of 160 km (the maximum depth of M>6.0 earthquakes within the region). Deformation rates between 1926 and 1992 are summarized in Table 2. Note that in no case do deformation rates exceed 0.11 cm/yr. In comparison, the average convergence rate between the Caribbean and South American plate is estimated to be about 1 cm/yr (DeMets et al., 1990) and about 2 cm/yr between the Caribbean plate and the Atlantic plate (Stein et al., 1982). This suggests that seismic activity, at most, only accounts for 11% of the total estimated plate convergence.

Conclusions

Studies of 13 historic earthquakes of M≥6.5 occurring within the southeastern Caribbean between 1926 and 1960 suggest that most shallow seismicity reflects intraplate deformation. The focal mechanisms are similar to recent seismicity of smaller magnitude events, except within the Barbados Trough where waveform modelling of a M=6.5 earthquake that occurred in 1928 suggests right-lateral strike-slip faulting. Intermediate depth earthquakes along the Lesser Antilles arc suggest significant deformation of the slab, controlled in part by features that strike at an angle to the trend of the arc. Only two historic earthquakes along the Lesser Antilles arc had mechanisms and depths suggesting they could be interplate events.

Seismic moment rates between 1926 and 1992 were used to estimate a deformation rate for the southeastern Caribbean. This rate is 11% or less than the estimated plate convergence rate, suggesting much deformation within the region occurs aseismically.

Acknowledgements

We wish to thank William Ambeh for providing the initial interest and encouragement to begin this project. Ray Russo has also been exceedingly helpful and encouraging to us throughout our work.

References

Baker, M.R. and Doser, D.I. (1988). Joint inversion of regional and teleseismic earthquake waveforms. J. Geophys. Res., 98: 2037-2045.

DeMets, D.C., Gordon, R.G., Argus, D.F. and Stein, S.A. (1990). Current plate motions. Geophys. J. Int., 101: 189-212.

Molnar, P. (1979). Earthquake recurrence intervals and plate tectonics. Bull. Seism. Soc. Am., 69: 115-133.

Paige, S. (1930). The earthquake at Cumana, Venezuela, January 17, 1929. Bull. Seism. Soc. Am., 20: 1-10.

Russo, R.M., Okal, E.A. and Rowley, K.C. (1992). Historical seismicity of the southeastern Caribbean and tectonic implications. Pure Appl. Geophys., 139: 87-120.

Russo, R.M., Speed, R.C., Okal, E.A., Shepherd, J.B. and Rowley, K.C. (1993). Seismicity and tectonics of the southeastern Caribbean. J. Geophys. Res., 98: 14299-14320.

Stein, S.A., Engeln, J., Wiens, D., Fujita, K., and Speed, R. (1982). Subduction seismicity and tectonics in the Lesser Antilles arc. J. Geophys. Res., 87: 8642-8644.

The March 1988 East of Trinidad Earthquake Sequence

William B. Ambeh[1] and Raymond M. Russo[2]
1. Seismic Research Unit
The University of the West Indies
St. Augustine, Trinidad & Tobago
2. Department of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, NW
Washington, DC 20015, USA

Abstract

On 10 March 1988 at 0617 UTC, a moderate earthquake (Ms 6.5) occurred about 50 km off the east coast of Trinidad in an area where no significant seismicity had been detected since 1953 when the number of seismograph stations operating in the Eastern Caribbean increased. This earthquake was widely felt in the southeastern Caribbean although the maximum Modified Mercalli intensity experienced (VI in Trinidad) only resulted in minor damage. It was not preceded by any detected foreshock but was followed by significant aftershock activity, with 9 of the aftershocks having magnitude $m_b \geq 5.0$. Activity in this area has generally continued to date, albeit at a much reduced rate.

In this paper, we examine in detail the earthquakes that have occurred to the east of Trinidad during the period March 1988 to December 1992 with a view to elucidating their tectonic significance.

Study of Seismicity and Stress Patterns in the Southwestern Part of the Puerto Rico (P.R.) Trench

Lillian Soto and Klaus Bataille
University of Puerto Rico
Department of Geology
P.O. Box 5000
Mayaguez, P.R. 00681
Puerto Rico

Abstract

To improve our understanding of the tectonics of the North American-Caribbean Plate boundary at the Puerto Rico Trench, body wave inversion solutions for two of the largest earthquakes in the zone since 1964 were determined. The November 3, 1966, M=5.6, and the November 3, 1988, M=5.9 earthquakes are studied in this paper. These solutions show a predominantly horizontal motion with a small convergent component along a dipping fault coincident with the Wadati-Benioff zone associated with the P.R. Trench. The slip vector associated with the 1966 event has an azimuth and plunge of S86 ^{o}W and 5^{o} respectively, while for the 1988 earthquake they are S63 ^{o}W and 0^{o}. If the movement along these faults is representative of the average motion within the plates, then our solution falls between the previously proposed plate motion models of:

(1) Minster and Jordan (1978) and De Mets et al. (1990), which is almost strike-slip motion at the P.R. Trench on their global plate motion analysis.

(2) Larue et al. (1990) and Mason and Scalon (1991), which propose an extensional movement along the Puerto Rico Trench, based on Long-range sidescan sonar images and seismic reflection data.

(3) Molnar and Sykes (1969), Sykes et al. (1982) and McCann and Sykes (1984), proposing a convergent component of motion for this region. Molnar and Sykes (1969) slip vector calculation for the 1966 event has an azimuth of S66^{o}W with a plunge of 8^{o}.

The seismicity in this region occurs mainly along the Wadati-Benioff zone, in contrast to eastern Hispaniola, where significant motion takes place along the Muertos trough. Thus it seems likely that for this region, the motion along the P.R. trench resembles the relative plate motion. Therefore, the analysis for more earthquakes will further constrain the motion between these plates.