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Seismicity and Tectonics of the Southeastern Caribbean

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We present 33 new focal mechanisms for SE Caribbean earthquakes (1963–1988). We use these mechanisms, in conjunction with 28 previously available mechanisms, to distinguish between two models of plate boundary zone interaction in the SE Caribbean: the trench-trench transform and hinge faulting model, and the right oblique collision model. Shallow (0–70 km) and intermediate (70–200 km) depth earthquakes occur in the study region; we focus on the tectonic causes of these events and the motions they delineate. The shallow earthquakes are in a broad linear zone which trends NE from the Paria Peninsula of Venezuela towards Barbados. Intermediate depth earthquakes cluster beneath and NW of the Peninsula, and deepen to the NW, perpendicular to the NE-trending shallow events. The vertical distribution of the earthquakes suggests a slab with steep NW dip. Shallow, dextral strike slip on E-striking faults is restricted to a 60-km-wide linear zone between the Gulf of Cariaco and the western margin of the Gulf of Paria. Dextral strike slip is active only as far east as the Gulf of Paria, and not within or east of Trinidad. Shallow thrust events with ENE-striking planes, distributed between the Araya Peninsula and the Gulf of Paria, indicate collision at crustal levels between South America and Caribbean, and that folding and thrusting are still active over a 60-km interval south of the Araya-Paria isthmus. Active thrusting in Venezuela corroborates predictions of transpression between Caribbean and South America and discounts transtensional motions between the two plates in the SE Caribbean. The conjunction of shallow thrust, strike slip, and normal earthquakes in the Gulf of Paria at around 62.3° may be the expression of unpartitioned oblique compressive deformation in the plate boundary zone. Intermediate (165 km $> h >$ 70 km) depth thrust and dip slip events within the NW-dipping slab indicate that oceanic lithosphere, probably originally attached to South America, subducts to the NW beneath the Caribbean plate. Shallow normal faulting events E and NE of Trinidad are expressions of plate bending about near-horizontal axes parallel to the Lesser Antilles subduction zone. We conclude that the earthquake mechanisms provide strong support for the right oblique collision model of Caribbean-South American plate interaction.

INTRODUCTION

We have examined earthquakes (1963–1990) of the southeastern Caribbean near Trinidad and northeastern Venezuela (Figure 1) to help resolve the complex and poorly established structures and motions within the Caribbean (Ca)-South American (SA) plate boundary zone. There has been little consensus on these parameters for several reasons: the earthquake distribution is very heterogeneous and previously has not been fully analyzed, there is no through going well-identified fault zone, and there is no direct gauge of Caribbean-South American relative motion such as a ridge-transform system. As a consequence, at least three kinematic models of the plate boundary zone have been formulated, one postulating hinge faulting and subduction of Atlantic oceanic lithosphere beneath an east-moving Caribbean plate [*Molnar and Sykes*, 1969]; a second model, proposed by *Jordan* [1975], involving dextral oblique collision of the Caribbean and South American plates; and a third model proposing dextral oblique extension [*Sykes et al.*, 1982]. Velocity magnitude estimates for the three models vary significantly between 0.5 and 4.0 cm/yr. The primary objectives of our study have been to analyze the seismicity of the plate boundary zone, to deduce the tectonic cause or causes of the earthquakes, to apply these deductions to the problem of motions within the eastern Ca-SA plate boundary zone, and to test the postulated models of the plate interactions.

Our approach has been threefold. First, we have analyzed the distribution of the frequent regional earthquakes in order to determine as precisely as possible the spatial relationships between hypocenters and surface geologic features, the loci of shallow and deeper zones of current motions, and the correlation of hypocenters to zones predicted to be active by the proposed models of Ca-SA kinematics mentioned above. Second, we have made an exhaustive analysis of focal mechanisms of all earthquakes large enough (4.9 m_b) for mechanisms to be determined. We have produced 33 new focal mechanisms for regional earthquakes, and we have collected 28 more mechanisms from published studies and from the Harvard centroid-moment tensor catalogue. The mechanisms are used to indicate senses of motions occurring on active faults within the study region and to test the proposed plate boundary models. Finally, we analyze the distribution of earthquake principal strain axes for the available shallow earthquake focal mechanisms in order to better understand the relative plate motions.

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Fig. 1. The geography of the Caribbean region. Martinique, St. Lucia, and Grenada lie along the Lesser Antilles island arc, which is the eastern boundary of the Caribbean plate. The heavy-bordered box (inset) indicates the study area. Bathymetric contours at 200 m and every kilometer deeper are also shown, based on *Speed et al.* [1984].

We find that neither the hypocenter distribution nor the focal mechanisms support the hinge faulting model. Instead, the Caribbean plate, or terranes moving wholly or partly with the Caribbean plate, is obliquely colliding with and overriding South America. Oceanic lithosphere originally attached to South America subducts beneath the Caribbean plate. Seismogenic right-lateral strike slip on vertical EW-striking faults in the plate boundary zone is restricted to areas west of Trinidad throughout the period of this study (1963–1990) and since the beginning of instrumental recordings of seismicity in the region, around 1920 [*Russo et al.*, 1992].

PLATE TECTONIC FRAMEWORK

Caribbean-South America Plate Velocity

We briefly review the current state of knowledge of the Ca-SA plate boundary. No directly measured relative motion vector for Caribbean-South America exists [*Minster and Jordan*, 1978; *Stein et al.*, 1988]. A vector can be inferred from Caribbean-North America and North America-South America motions. However, two data sets have been used to constrain North America-Caribbean motion: the Cayman Trough ridge-transform system and earthquake slip vectors of the northern Lesser Antilles subduction zone. These yield significantly different North America-Caribbean Euler poles. The pole based on Cayman Trough features predicts an ESE vector and a rate of approximately 1.5 cm/yr of Caribbean motion relative to South America at Trinidad [*Jordan*, 1975; *DeMets et al.*, 1990]. The Euler pole derived from the northern Lesser Antilles slip vectors predicts an ENE vector, 4.2 cm/yr at Trinidad [*Sykes et al.*, 1982]. Reasons for the discrepancy may include rotation of faults used as azimuth constraints (ESE vector) and misidentification of Caribbean intraplate deformation earthquakes as interplate slip events (ENE vector). We can conclude that the Caribbean is moving generally eastward relative to South America and its attached Atlantic oceanic lithosphere but has a significant normal component of motion relative to South America. The effects of this normal motion, whether extensional or compressional, should be discernible in the regional geology of the Caribbean-South American boundary zone, and current motion directions in the boundary zone may be constrained by analysis of the active regional seismicity.

Eastern Caribbean-South America Plate Boundary Zone

The northern boundary of the eastern Caribbean-South American plate boundary zone (Figure 2), identified by sed-

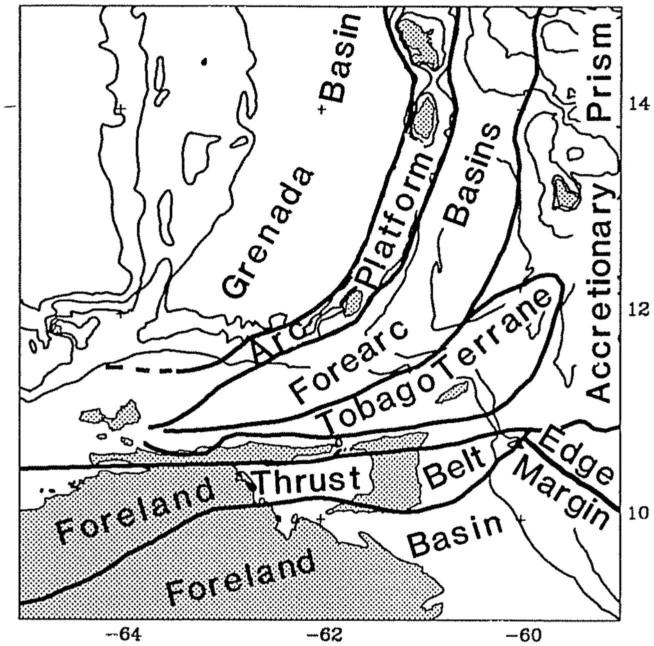


Fig. 2. Large-scale tectonostratigraphic units of the Caribbean-South America plate boundary zone. Heavy lines are surficial boundaries between tectonic units discussed in the text.1

iment deformation and faulting [*Pinet et al.*, 1985], may lie as far north as the southern end of the Grenada basin, at around 12°. Its southern limit may be indicated by blind thrusts [*Rossi et al.*, 1987] and folding of sediments [*Bellizzia et al.*, 1976] in Venezuela's Maturin basin south of 9°. Within the plate boundary zone a number of tectonic units are identified. Three units associated with the Caribbean plate are (from north to south) the Lesser Antilles arc platform [*Speed et al.*, 1984] that extends NE from Margarita, upon which, between Grenada and Martinique, the Lesser Antilles volcanic chain developed in the Neogene; the Tobago Trough and Carupano forearc basins, characterized by largely undeformed sediments of varying thickness (3–12 km [*Speed et al.*, 1989]); and the Tobago terrane [*Speed et al.*, 1989], consisting of Mesozoic oceanic crust and arc rocks [*Snoke et al.*, 1990] and sedimentary cover, which surfaces south of the forearc basins and probably is the crystalline basement below them. The terrane is exposed on Tobago, along the north shore of the Araya Peninsula, and in wells in the Carupano Basin [*Periera et al.*, 1986], and may continue north as far as the arc platform, and perhaps into the southern Venezuela basin [*Speed and Walker*, 1991].

South of and structurally beneath the Tobago terrane is the Paria-Trinidad terrane. This unit, composed of low-grade schists which evolved from marine protoliths most likely deposited on the South American continental slope [*Algar and Pindell*, 1991], is exposed on the Paria Peninsula in Venezuela and in the Northern Range of Trinidad. The 25-Ma age of metamorphism of the terrane [*Foland et al.*, 1992] invalidates previously published correlations of these rocks with units outcropping further west in Venezuela (Cordillera south of Caracas).

The foreland thrust belt south of the Paria-Trinidad terrane contains thrust and reverse faults and folds that reflect NNW-SSE contraction of at least 40 km [*Rossi et al.*, 1987] and SSE overriding by Caribbean terranes [*Speed*, 1985]. The belt also includes SSE-striking faults with dextral strike slip displacements; these indicate the deformation includes a component of clockwise rotation. The diachroneity of thrust belt development is demonstrated by the ages of sediments overlapping faults [*Salvador and Stainforth*, 1968].

The foreland basin is asymmetric: its little-deformed southern flank is a long, shallowly north-dipping ramp, whereas its northern flank is a deformation front bounded by the frontal sheets of the foreland thrust belt [*Hedberg*, 1950; *Salvador and Stainforth*, 1968]. The history of the foreland basin implies basin subsidence caused by tectonic loading of the lithosphere to the north, southward migration of the axis of maximum subsidence, and progressive sedimentary filling from west to east in Neogene time. The tectonic load was supplied by the emplacement of terranes above the northern edge of South American lithosphere, which began in the Oligocene near 64° W, and, to a minor degree, by crustal thickening within the foreland thrust belt [*Speed*, 1985].

Below and south of the foreland thrust belt and basin are Precambrian continental crust and its cover of mainly Mesozoic and Paleogene shelf strata. The Precambrian basement emerges as the Guyana Shield south of the foreland basin [*Feo-Codecido et al.*, 1984].

Faults of the Plate Boundary Zone

Several faults or fault systems within the plate boundary zone have been postulated as current loci of large displacements. These include (Figure 3) the North Coast Boundary fault [*Bassinger et al.*, 1971; *Ramroop*, 1986; *Robertson and Burke*, 1989], the El Pilar fault [*Metz*, 1968; *Vierbuchen*, 1984], whose displacement senses and/or magnitudes are disputed; and faults within the fold and thrust belt (described above), in particular the ENE striking Pirital thrust [*Rossi et al.*, 1987], the NW-WNW striking dextral strike slip Urica fault [*Munro and Smith*, 1984], and El Soldado and Los Bajos faults *Wilson*, 1968; *Perez and Aggarwal*, 1981; *Speed*, 1985]. The range of estimates for displacement magnitude and direction on these faults, however, is enormous, and none can be shown with certainty to have large, recent slip. Those which have been carefully examined on site cannot be shown to have displacements more than around 25 km [*Salvador and Stainforth*, 1968; *Wilson*, 1968, *Metz*, 1968; *Vierbuchen*, 1984). Therefore there is no evident principal displacement surface within the plate boundary zone, and thus displacements are probably distributed in the zone, at least at shallow depths.

Former Northern South America Passive Margin

Before the onset of Ca-SA plate boundary tectonics in the Oligocene, continental South America in northeastern Venezuela and Trinidad terminated at a north-facing passive margin that was a product of Jurassic or (and) Cretaceous rifting of Pangaea and the separation of North America and South America [*Pindell*, 1985; *Klitgord and Schouten*, 1986]. Rift basins and related sediments and basalt are known by drilling below the shelf and foreland basin strata in eastern Venezuela [*Moticska*, 1987; *Feo-Codecido et al.*, 1984] and probably extend northward below the foreland thrust belt beyond the current coastline. The edge of rifted continental crust was almost certainly joined to Atlantic oceanic lithosphere of mid-Mesozoic age. In Venezuela, this lithosphere has been totally overridden by colliding terranes, but it still exists below the seafloor northeast and east of Trinidad.

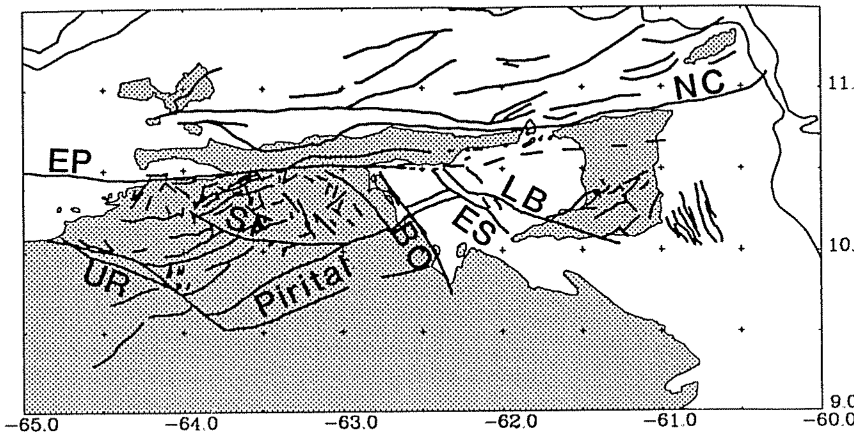


Fig. 3. Fault traces of the Venezuela-Trinidad fold and thrust belt, based on *Speed et al.* [1989], *Rossi et al.* [1987], and *Leonard* [1983]. Important faults mentioned in the text are: EP = postulated El Pilar Fault zone; LB = Los Bajos fault; ES = El Soldado fault; UR = Urica fault; SF = San Francisco fault; BO = Bohordal fault. ENE-trending faults are N-dipping thrusts. NNW-striking faults to the east of Trinidad are normal faults with displacement down to the east.

Distribution of Earthquakes in the Southeastern Caribbean

Earthquakes recorded by eight or more stations during the period from 1963 to 1990 and tabulated by the USCGS (1963–1977) and the USGS (Preliminary Determination of Epicenter, 1977–1990) are shown in Figures 4 and 5. Hypocentral depths are both shallow (0–70 km) and intermediate (as deep as 200 km). Hypocentral uncertainties of the larger magnitude events (i.e., those with mechanisms) are approximately ±10 km in latitude and longitude, and ±20 km in depth. Smaller magnitude events may be mislocated by greater amounts, but comparison of National Earthquake Information Center (NEIC), International Seismological Centre (ISC), Trinidad Network locations [*Shepherd and Aspinall*, 1983], and locations from a recent Venezuelan local network study (E. Gajardo, personal communication, 1992) reveals that the characteristics

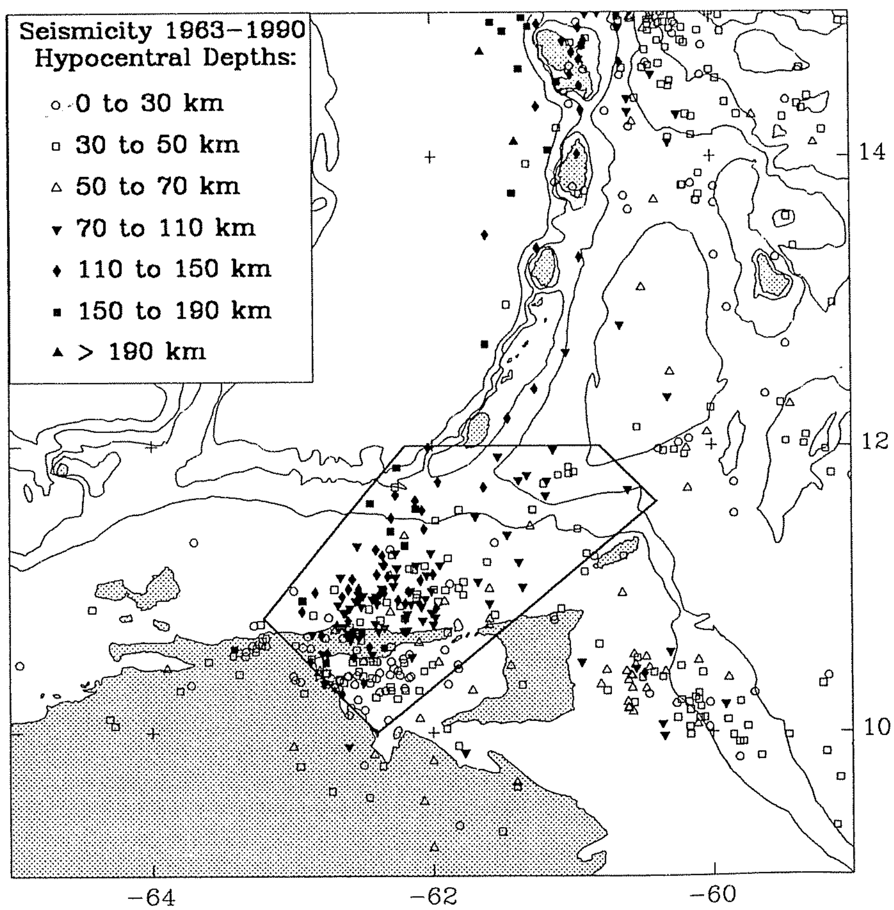


Fig. 4. Hypocenters (USCGS, 1963-1977; USGS, 1977-1990) of the SE Caribbean. Hypocentral depths indicated in key (top left). Only those hypocenters based on eight or more arrival times are shown. Polygonal box outlines Paria cluster. Events E of Trinidad are March 10, 1988, event and aftershocks.

of the regional seismicity we discuss below are common to all three data sets.

The map view (Figure 4) of the seismicity clearly shows the distinct cluster of seismicity south of 12° N, defined by increasing frequency of shallow and intermediate depth earthquakes. We refer to these earthquakes as the Paria cluster. This group of earthquakes includes those shallow and intermediate events which lie north of the Paria Peninsula and extend in a wide zone to the ENE towards Barbados and the earthquakes within the Gulf of Paria as far south as 10° N latitude. We do not include earthquakes to the east of Trinidad, nor those west of 63° W longitude in the Paria cluster. West of the Paria cluster, the concentration of shallow earthquakes diminishes, and the deeper earthquakes ($h > 70$ km) cease entirely. Microearthquakes were recorded in the Araya-Paria isthmus as far west as the Gulf of Cariaco by *Perez and Aggarwal* [1981] and *Bizot* [1985]. Scattered shallow events also occur south of 10° N along the Venezuelan Gulf of Paria coast.

The deeper earthquakes (70–200 km) of the Paria cluster are distributed beneath and to the north and northeast of the Paria Peninsula. Hypocenters of these earthquakes deepen to the northwest, perpendicular to the trend of the wide linear zone of shallow earthquakes. Figure 5 shows a series of vertical projections of the better located (20 stations or more) cluster hypocenters which reveal a broad tabular zone dipping about 60° to the northwest in continuity to around 200 km. The depth and distribution of these earthquakes have led others to conclude that they represent subduction seismicity of lithosphere attached to South America and/or Atlantic oceanic lithosphere [*Speed*, 1985; *Shepherd and Aspinall*, 1983; *Perez and Aggarwal*, 1981].

Earthquakes west of the Paria cluster in Venezuela are shallow (0–50 km) and are divisible into a group of events in the central Araya-Paria isthmus (Figure 4), and a scattering of events without apparent clustering in the Venezuelan fold and thrust belt and beneath the Orinoco delta. The group in the isthmus may be associated with motions on a fault or faults within the Paria-Trinidad terrane, but the clustering does not permit clear definition of a single fault or faults. The group does appear to have a long axis trending ENE, extending some 35–40 km. We note that this direction is parallel to mapped faults (Salazar, Tacarigua, Laguna Grande [*Schubert*, 1971]) further west in the Araya Peninsula. The earthquakes scattered throughout the thrust belt are not sufficiently numerous to definitively establish their relationships with any of the mapped faults of the deformed belt.

East of Trinidad, the linear, northwest trending group of epicenters is the expression of the March 10, 1988 m_b 6.2 earthquake and its aftershocks (Figure 4). These earthquakes are of extreme interest since before the main shock, little seismic activity was detected in this region; the earthquakes occur between 25 km and 100 km deep. These numerous, smaller magnitude aftershocks exhibit a linear trend WNW-ESE, however, this trend may be spurious,

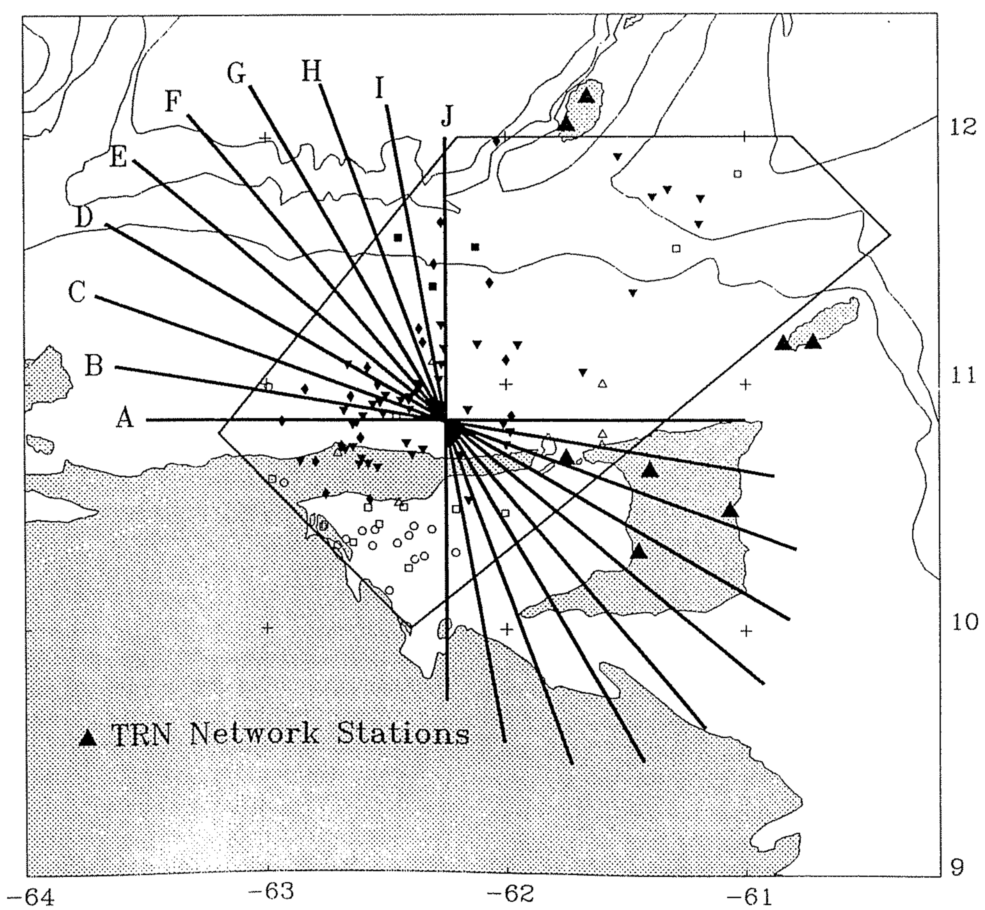


Fig. 5. Map and vertical projections of Paria cluster events (20 or more recording stations). Event symbols as in Figure 4. Vertical sections (A-J) correspond to section lines on map. Slab is clearly defined to approximately 150 km, on section F. Dip is around 60° W.

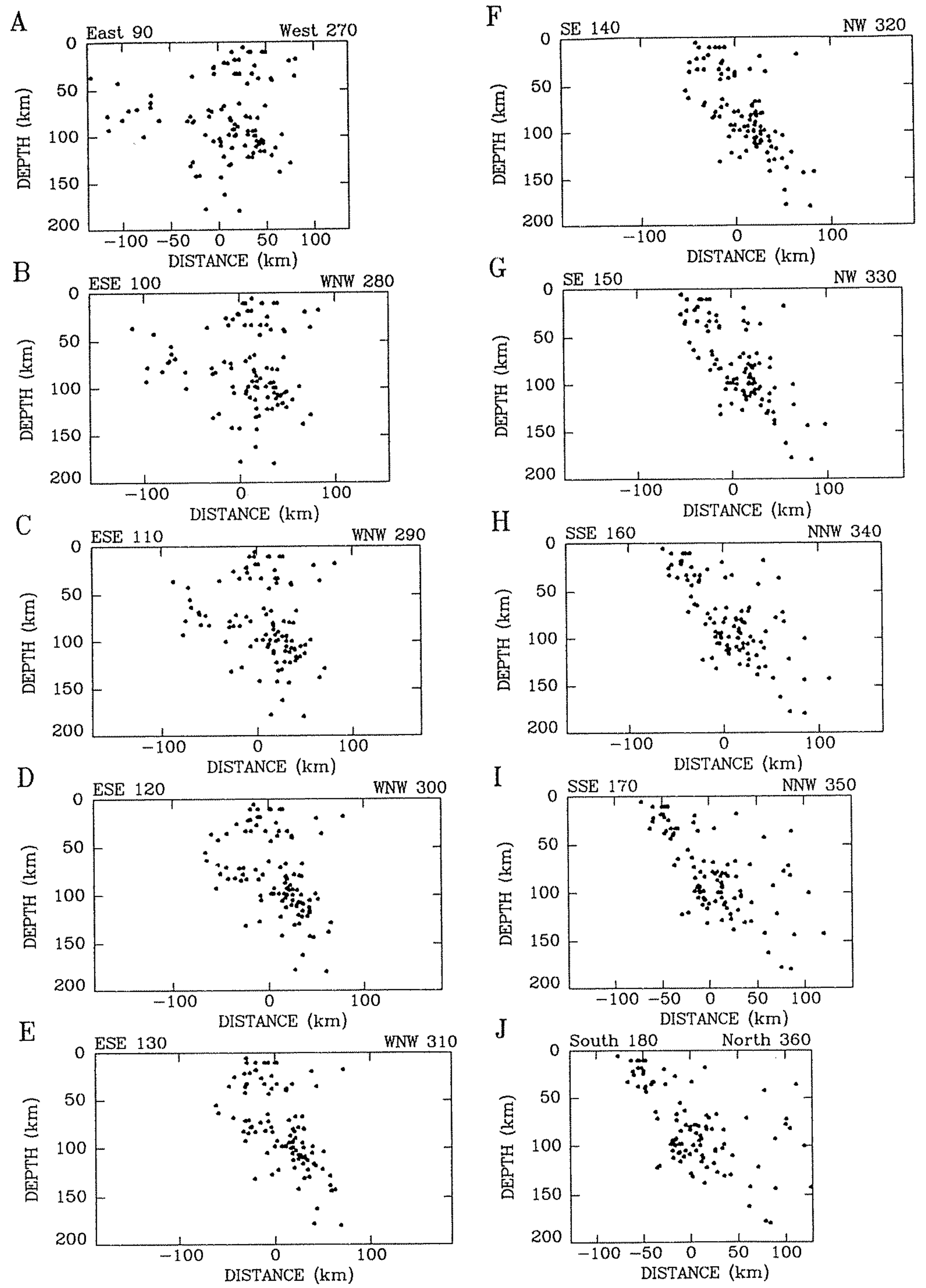


Fig. 5. (continued)

caused by mislocations of the smaller events of the series. Locations reported by the ISC with stations in all four azimuthal quadrants (Figure 9) define a cluster centered to the north of the largest shocks of the series and do not apparently lie on the ENE trend. The ENE aftershock trend, if real, is nearly parallel to the trend of the South American continental slope to the east of Trinidad.

Between Grenada and the northern end of St. Lucia, along the Lesser Antilles subduction zone, the frequency of shallow and intermediate depth earthquakes is less than that of the Paria cluster, as can be seen in Figure 4 [*Tomblin*, 1975; *Dorel*, 1981; *Stein et al.*, 1982; *Wadge and Shepherd*, 1984]. The earthquakes that do occur in this region are distributed throughout a wide zone extending from just west of the Lesser Antilles arc platform to the eastern edge of the Tobago Trough. Earthquakes deeper than 150 km occur beneath the island arc, and in general the easternmost events are shallow. The significant maximum depths attained and the westward deepening of the events are suggestive of a Wadati-Benioff zone. The depth of the seismicity, taken in conjunction with the unbroken continuity of the active volcanic arc and the Bouguer gravity minimum, suggests that a subducting slab is present along this segment of the Lesser Antilles. The cause of the reduced seismicity between

Grenada and St. Lucia may be explained by (1) subduction of enough sediments to lubricate or decouple the two plates in the subduction zone, resulting in primarily aseismic motion; (2) strengthening, caused by the extremely thick accretionary prism overburden which here lies above the shallow reach of the subduction zone.

The increased earthquake frequency north of St. Lucia is clear in Figure 4. The seismicity pattern reveals a fully developed Wadati-Benioff zone extending to a depth of 200 km, with a dip of approximately 45 degrees to the west [*Molnar and Sykes*, 1969; *Dorel*, 1981; *Stein et al.*, 1982; *Girardin and Gaulon*, 1983].

Fault Plane Solutions and Tectonic Interpretations

Data pertinent to the earthquake focal mechanisms used in this study are detailed in Table 1 and Appendix A. Hypocentral locations and depths of earthquakes after 1966 derive from ISC catalogues. We relocated the pre-1967 events (1–5) for this study using ISC reported P and S times and a hypocentral inversion routine described by *Russo et al.*, [1992)] in order to homogenize epicenters to two decimal places. We also adopt ISC reported depths constrained by pP - P times for those events including six or more such arrivals (see Table 1). Earthquake magnitudes are between 4.9 m_b and 7.3 m_b. We present 33 new first motion focal mechanism solutions. Five more solutions were published in previous studies [*Molnar and Sykes*, 1969; *Tomblin*, 1975; *Rial*, 1978], and we produced mechanisms for these events which are in good agreement with those of the previous studies. To date, 22 solutions are available from the Harvard Centroid-Moment Tensor (CMT) data set [*Dziewonski et al.*, 1981, 1983a, 1983b, 1983c, 1984, 1985a, 1985b, 1986, 1987a, 1987b, 1988a, 1988b, 1988c, 1988d, 1989a, 1989b, 1989c]. We have also produced first motion mechanisms for six of these earthquakes. Four of our solutions agree with the CMT solutions. The two earthquakes for which mechanisms are discrepant are the August 14, 1977 (27) and October 4, 1977 (30) events. First motion picks for the August 14, 1977 earthquake are consistent with the CMT mechanism except for less trustworthy picks at distant African stations, and therefore we accept the CMT mechanism as valid and use it in our analyses in place of the first motion mechanism. First motion picks for the October 4, 1977 earthquake are not consistent with the CMT solution, especially for the near stations of the Trinidad Local Network. We are confident in our first motion picks for these stations and therefore we have chosen to use our first motion mechanism in our analysis rather than the CMT mechanism. Details of the comparison of the our mechanisms and the CMT mechanisms are given in Appendix B. The following discussion is therefore based on a total of 61 focal mechanism solutions.

The focal mechanisms can be divided into two groups, shallow earthquakes ($h \leq 70$ km) and intermediate earthquakes ($h > 70$ km). The shallow events (Figure 6) are further divisible into four groups of earthquakes with similar focal parameters (Figure 8), all located south or east of the Lesser Antilles island chain. Several shallow events do not fit into these categories. The intermediate depth events (Figure 7) likewise fall into several groups of events with similar mechanisms.

Shallow Right-Lateral Strike-Slip Earthquakes

These earthquakes (Figures 6, 8a) are shallow ($h < 55$ km) and indicate either right lateral motions along near-vertical east-west planes, or left-lateral motions along north-south striking fault planes. Similar mechanisms for the July 14, 1963 (1) and May 14, 1966 (5) earthquakes were determined by *Molnar and Sykes* [1969], and a virtually identical mechanism to our June 12, 1974 (15) mechanism was published by *Rial* [1978]. In addition, two CMT mechanisms are included, for one of which we also produced a first-motion mechanism (June 11, 1986, 50).

Molnar and Sykes [1969] first associated these almost pure strike slip mechanisms with the El Pilar fault, assuming that the east-striking nodal plane was active and that motions on the east-striking fault were thus dextral. These earthquakes occurred within an approximately 60-km-wide zone, north to south, that extends from 63.5° W to 62.3° W longitude. Given the width of this zone, the smaller uncertainty in epicentral locations (±10 km), and the wide range of depths (5 to 55 km) it seems unlikely that these earthquakes can be assumed to have occurred on a single fault, such as the El Pilar. Instead, we believe these earthquakes occurred on several distinct east-striking faults within a zone of distributed dextral simple shear. The east-to-west length of the right-lateral strike slip (RLSS) earthquake zone indicates an apparent restriction in the geographic extent over which the dextral strike slip earthquakes occur, and implies that dextral strike slip earthquakes are not occurring east of the Paria Peninsula. Furthermore, data from the Trinidad local network recorded between 1977 and 1988, shows no evidence for seismic activity on the postulated El Pilar fault east of Paria. An examination of instrumentally recorded historical seismicity of this region [*Russo et al.*, 1992] demonstrates that the geographic restriction of RLSS events is a constant feature of the regional seismicity back to the 1920s. Therefore we suggest that right-lateral displacements within the Araya-Paria isthmus are distributed and do not indicate a single, active El Pilar fault, and that east-striking dextral strike slip is restricted to points west of 62.3° W. The significant depths attained by two of the events (5 and 29) may indicate that dextral shear is distributed vertically, or that a separate shear zone exists at depth.

Shallow Thrust and Dip-Slip Earthquakes

The earthquakes of the second group (Figures 6, 8b) are characterized by thrust, reverse, or dip slip mechanisms and are of shallow depths (10–65 km). The events were within the Paria cluster, to the west of the cluster in the Araya-Paria isthmus, and beneath Trinidad. Each mechanism contains a possible fault plane that strikes between E-W and NE-SW, but several of the mechanisms also have nodal planes that strike nearly N-S.

Six events of this group (Figure 8b) are predominantly thrust earthquakes, four that occurred at crustal depths (30, 33, 45, 52) and two located somewhat deeper (24 and 51). The four shallow events do not obviously lie along any of the recognized thrusts of the Venezuelan fold-thrust belt; instead, they seem to occur in a narrow E-W trending zone from the center of the Araya-Paria isthmus, in the west, to the western Gulf of Paria. Note that this is approximately the same area in which the shallow RLSS earthquakes (see

TABLE 1. Fault Plane Solutions

Date	Time, UT	Epicenter N lat.	Epicenter W long.	h, km	pP-P Depth,[a] km	Strike φ, deg	Dip δ, deg	Slip λ, deg	Reference	Event
Jul. 14, 1963[b]	0541:41.0	10.36	62.60	19	51 ±19 (2)	350	67	-33	R, M	1
Aug. 10, 1964[b]	1658:44.3	9.12	62.03	58	78 ±5 (6)	30	80	202	R	2
Apr. 30, 1965[b]	1145:27.2	10.82	62.49	87	90 (1)	153	79	210	R	3
Jan. 9, 1966[b]	0911:30.0	11.44	62.24	156	161 ±4 (9)	79	53	20	R	4
May 14, 1966[b]	2027:30.1	10.35	63.05	34	55 ±3 (8)	265	83	157	R, M	5
Jan. 4, 1967	2015:59.0	10.93	62.52	94	87 ±2 (31)	263	87	309	R, M	6
Sep. 20, 1968	0600:03.3	10.76	62.70	103	103 ±1 (53)	70	76	90	R, T	7
Oct. 12, 1968	2321:34.1	10.81	62.63	97	93 ±3 (11)	50	73	90	R	8
Oct. 17, 1968	1734:51.2	11.68	61.66	120	148 (1)	41	72	-172	R	9
Oct. 22, 1969	1252:22.8	10.92	62.55	87	81 ±1 (41)	71	54	90	R	10
Jan. 3, 1972	0725:24.0	10.66	62.79	70	63 (1)	161	70	-28	R	11
Mar. 10, 1972	1025:03.8	10.82	62.98	129	123 ±1 (8)	96	85	90	R	12
Aug. 29, 1972	0329:25.0	10.99	62.35	84	83 ±3 (8)	77	53	35	R	13
Oct. 7, 1973	1706:01.1	9.01	61.16	52	25 ±6 (5)	57	79	-161	R	14
Jun. 12, 1974	1625:45.2	10.61	63.47	11	11 ±2 (15)	94	71	172	R, Rial	15
Oct. 29, 1974	0310:16.9	10.58	63.45	33	—	94	53	26	R	16
Dec. 24, 1974	1937:09.7	11.02	62.47	131	98 ±7 (3)	345	82	135	R	17
Apr. 15, 1975	0947:44.8	9.42	61.47	52	46 ±14 (7)	111	53	26	R	18
Jun. 8, 1975	2359:32.1	11.45	62.25	142	157 ±5 (5)	327	66	149	R	19
Aug. 24, 1975	0105:15.1	10.75	62.65	111	102 ±3 (4)	40	74	64	R	20
Jan. 22, 1976	1206:48.0	8.80	60.30	63	—	322	76	90	R	21
Feb. 9, 1976	0233:05.5	11.63	62.34	161	165 ±3 (9)	73	57	65	R	22
Aug. 23, 1976	1356:12.3	11.07	62.36	90	78 ±2 (3)	111	59	35	R	23
Oct. 13, 1976	1735:50.7	10.81	61.53	63	62 ±4 (4)	43	57	136	R	24
Nov. 11, 1976	1931:42.6	12.45	61.23	126	—	175	61	123	R	25
Nov. 29, 1976	1302:37.2	11.81	61.33	84	76 ±1 (2)	123	85	106	R	26
Aug. 14, 1977	0422:49.7	10.94	62.36	110	112 ±1 (63)	230	51	122	R, CMT	27
Sep. 3, 1977	1525:16.1	10.42	62.28	35	—	83	88	111	R	28
Sep. 21, 1977	1605:13.7	10.42	62.56	42	—	78	74	190	R	29
Oct. 4, 1977	1344:54.7	10.38	62.32	42	22 ±5 (6)	28	77	63	R, CMT	30
Sep. 5, 1980	1145:25.3	12.23	59.32	34	33 ±2 (4)	69	55	-34	CMT	31
Mar. 2, 1981	0754:07.4	12.32	60.26	65	64 ±2 (18)	245	61	-32	CMT	32
Jun. 23, 1981	2257:39.0	10.53	63.36	11	—	94	63	120	R	33
Sep. 19, 1981	1249:08.2	10.17	62.86	36	35 ±3 (9)	36	86	90	R	34
Dec. 4, 1981	2144:58.3	10.52	61.42	65	—	46	82	107	R	35
Dec. 25, 1981	1235:48.3	10.94	62.36	96	103 ±6 (3)	155	51	-30	R	36
Jan. 20, 1982	1515:49.2	13.76	60.47	78	70 ±1 (14)	64	83	29	R, CMT	37
May 10, 1982	0125:57.3	10.70	62.51	100	100 ±3 (12)	271	86	-111	R, CMT	38
Sep. 20, 1982	1626:43.8	11.25	60.77	1	—	309	72	35	R	39
Mar. 8, 1983	1706:37.0	11.03	62.34	84	83 ±1 (58)	260	7	120	CMT	40
Mar. 26, 1983	0920:10.9	11.21	62.15	90	94 ±3 (5)	271	88	-97	R	41
Apr. 11, 1983	0818:10.2	10.43	62.71	38	45 ±3 (11)	3	43	-57	CMT	42
Jan. 23, 1984	2136:50.8	10.72	62.69	120	—	200	81	167	R	43
Feb. 11, 1984	1357:45.2	12.09	60.00	63	60 ±4 (6)	348	53	-142	CMT	44
Aug. 20, 1984	2355:11.9	10.45	62.45	10	12 ±6 (8)	100	63	135	R, CMT	45
Oct. 5, 1984	1030:50.9	11.71	60.16	63	56 ±3 (6)	172	57	-150	CMT	46
Jan. 24, 1985	2231:42.0	10.72	62.22	19	—	204	61	240	R	47
Nov. 28, 1985	0014:00.0	11.76	61.37	75	68 ±2 (20)	201	27	124	CMT	48
Apr. 11, 1986	1259:05.3	12.26	59.38	39	50 ±2 (4)	230	54	90	R	49
Jun. 11, 1986	1348:04.0	10.60	62.93	33	16 ±2 (30)	87	63	176	R, CMT	50
Oct. 21, 1986	1557:53.2	10.38	62.59	46	—	67	65	70	R	51
Nov. 14, 1986	1726:24.0	10.75	63.24	10	7 ±1 (4)	80	57	90	R	52

TABLE 1. (continued)

Date	Time, UT	Epicenter N lat.	Epicenter W long.	h, km	pP-P Depth,[a] km	Strike ϕ, deg	Dip δ, deg	Slip λ, deg	Reference	Event
Jun. 1, 1987	0340:32.7	11.98	62.03	141	144 ±3 (21)	62	36	178	CMT	53
Mar. 10, 1988	0617:17.0	10.24	60.54	12	53 ±2 (20)	256	38	-67	CMT	54
Mar. 11, 1988	1601:05.3	10.18	60.59	36	46 ±1 (19)	213	38	-132	CMT	55
Mar. 12, 1988	0432:10.2	10.19	60.62	51	51 ±1 (55)	42	31	-133	CMT	56
Mar. 16, 1988	0548:02.9	10.24	60.62	48	48 ±1 (50)	40	45	-118	CMT	57
Mar. 25, 1988	1620:44.0	10.14	60.68	26	31 ±1 (11)	16	63	-174	CMT	58
Apr. 12, 1988	1941:42.8	10.71	62.85	96	103 ±2 (14)	66	45	137	CMT	59
Jun. 24, 1988	0857:51.0	10.18	60.56	24	51 ±1 (39)	238	44	-89	CMT	60
Jul. 12, 1988	1759:12.8	10.13	62.48	5	64 ±26 (3)	104	50	-166	CMT	61

References: R, this study; M, *Molnar and Sykes* [1969]; T, *Tomblin* [1975]; Rial, *Rial* [1978]; CMT, centroid-moment tensor solution.

[a] Number in parentheses is number of observations.

[b] Relocated for this study.

above) occur. One pure thrust earthquake (52) occurred north of the Araya-Paria coastline. These thrusts are consistent with oblique collision at crustal levels between the Caribbean terranes and South America. Slip vectors for these shallow events constrain the trend of convergence to be approximately NW-SE. Of the two deeper thrust events, event 24 at 63 km may also be related to overthrusting of Caribbean terranes over South America. Event 24, however, has nodal planes that strike nearly N-S, and the event occurred some 70 km east of the other thrusts.

The three remaining earthquakes (28, 34, 35) shown in Figure 8b are probably dip slip events, rather than thrusts. They occurred somewhat deeper than the shallow thrusts (35 to 65 km) mentioned above. Two of these events (34

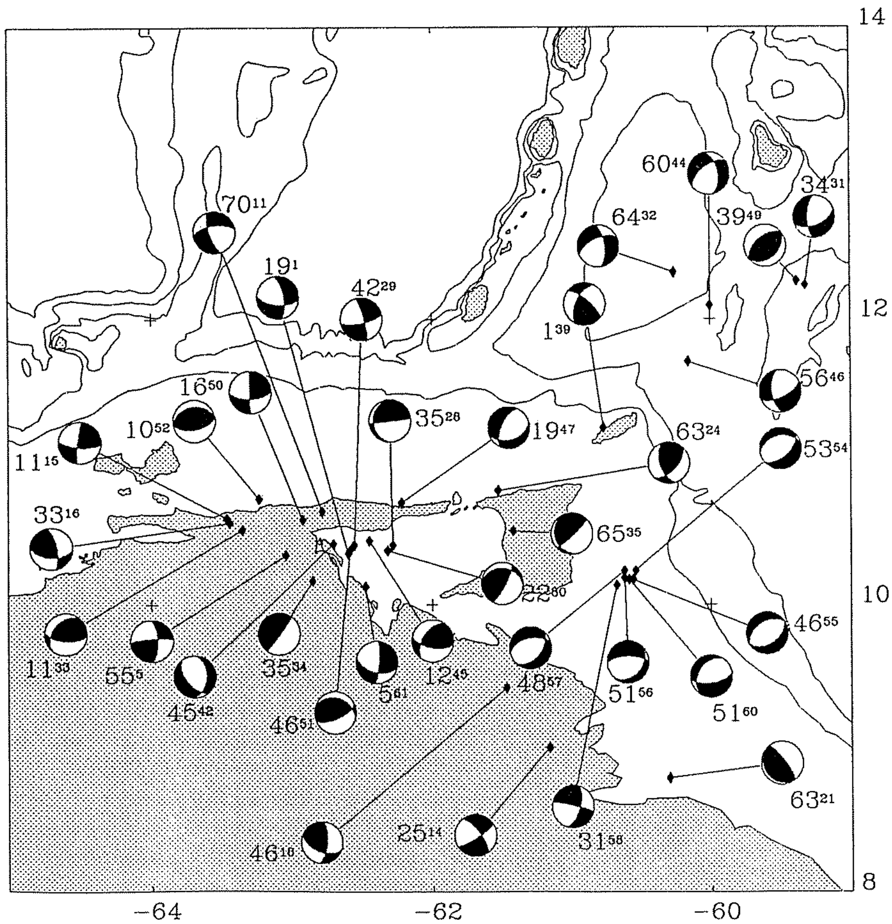


Fig. 6. Focal mechanisms of shallow Ca-SA plate boundary zone earthquakes. Numbers next to beach balls are hypocentral depths in kilometers, superscripts are event numbers (Table 1). Compressional quadrants shaded.

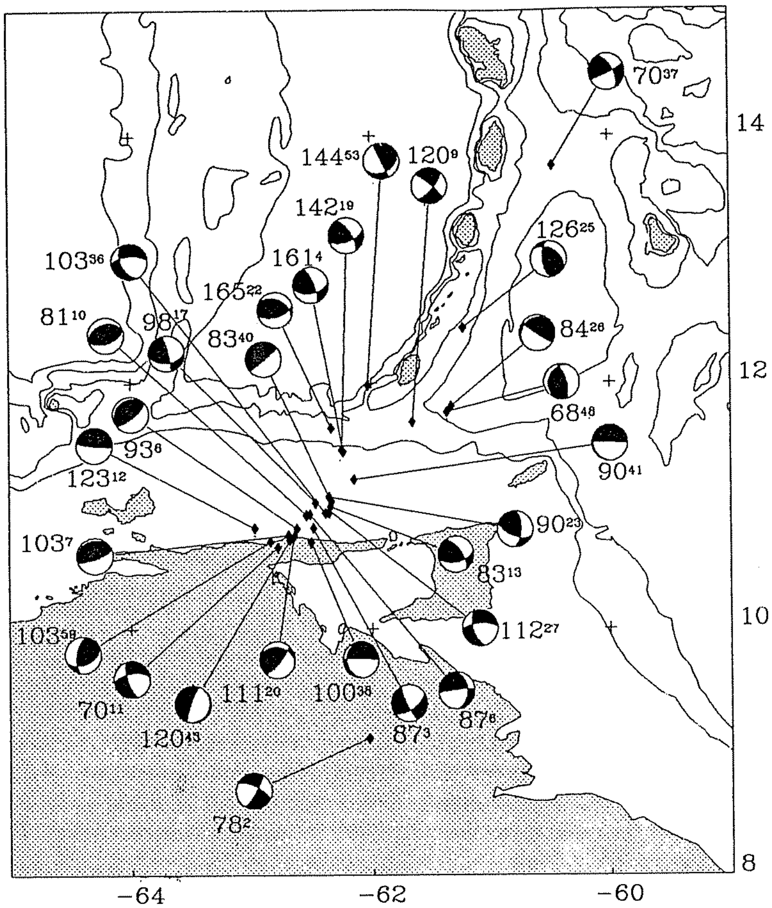


Fig. 7. Focal mechanisms of intermediate depth plate boundary zone earthquakes. Numbers next to beach balls are hypocentral depths in kilometers, superscripts are event numbers (Table 1). Compressional quadrants shaded.

and 35) each have one near-vertical nodal plane striking nearly NE, and the third event (28) has an ENE-striking vertical nodal plane. If these planes are the fault planes, then these earthquakes have slip sense down to the NW or N, also consistent with Caribbean overriding of South America, but perhaps also indicative of slab detachment as proposed by *Russo and Speed* [1992]. The depths of these events and their mechanisms indicate that the plate boundary zone processes here are probably heterogeneous with depth.

Shallow Mixed Thrust and Strike-Slip Earthquake

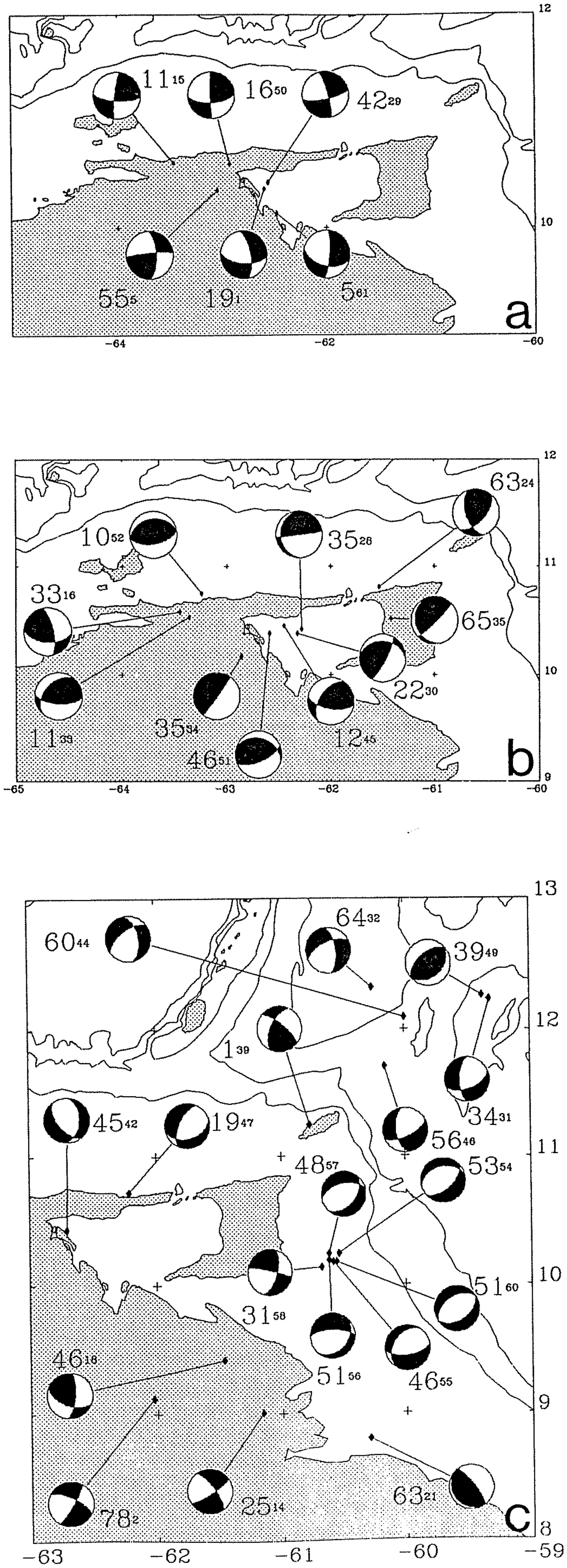
The October 29, 1974 earthquake (16; Figure 8b) occurred in the Araya-Paria isthmus and has an E-W striking potential plane, but its slip is sinistral along this surface, in contrast to the dextral mechanisms of the RLSS group. If this event is well located, it may represent dextral motion along an as yet unrecognized NNW striking dextral fault of the Venezuelan fold-thrust belt. Such a fault might be similar to the NNW striking dextral San Francisco and Urica faults, or the El Soldado-Los Bajos faults discussed above (see Figure 3). However, the epicenter does not correlate with any known surface fault.

Shallow Normal Faulting Earthquakes

The earthquakes of this group are normal faulting earthquakes (events 31, 32, 42, 44, 46, 47, 54, 55, 56, 57, 58, 60; see Figure 8c). Depths of these events range from 19 km to 64 km, and epicenters are distributed in three areas: in the Paria cluster, in the Tobago Trough-Barbados forearc region, and off the east coast of Trinidad, comprising the March 10, 1988 (m_b 6.2) earthquake and its larger magnitude aftershocks.

There are two events in the Paria cluster: January 24, 1985, (47); and April 11, 1983, (42). These two earthquakes are quite different in their fault plane orientations and may be indicative of two different tectonic processes: the April 11, 1983 event has fault planes striking N-S and NNW-SSE. The NNW strikes are roughly parallel to the Bohordal normal fault inferred to exist by *Rossi et al.* [1987] along the western margin of the Gulf of Paria, and this earthquake could be evidence of extension within the transpressive E-W trending simple shear zone. The second shallow normal faulting earthquake, January 24, 1985, has fault planes striking NE-SW and ENE-WSW. This earthquake may be due to down bending of South American lithosphere.

The second subgroup of normal faulting events is composed of four earthquakes to the northeast of Tobago, in the Tobago Trough-Barbados forearc region (31, 32, 44, 46; Figure 8c). We include in the discussion of these events the thrust mechanism (April 11, 1986; 49) that also occurred in this region. These earthquakes have depths to 64 km, and deepen from SE to NW, towards the Lesser Antilles subduction zone. Because the nodal planes of these events are approximately parallel to the Lesser Antilles arc, it seems likely that these events are due to down bending of the oceanic plate as it moves toward the subduction zone to



the west. That is, the normal faulting events occur in the extended upper portion of the bending oceanic plate, and the one thrust perhaps took place in the deeper levels of the lithosphere that are contracted by the bending. The depths of events 32, 44, and 46, 56 km to 64 km, are unusual: it is unlikely that the depths are incorrect because they are constrained by *pP* arrivals, but perhaps the extremely thick accretionary prism (25 km [*Speed et al.*, 1984]) that lies above the oceanic lithosphere here has depressed the zone of bending-caused extension.

The March 10, 1988 earthquake and its aftershocks form the third group of normal fault events in the study region (events 54, 55, 56, 57, 58, 60; Fig. 8c, Figure 9). Comparison of the focal mechanisms of this subgroup with the observed WNW-ESE epicentral trend (Figure 4) reveals that the mechanisms do not have nodal planes which are clearly related to the trend of the aftershock sequence. The available focal mechanism solutions (Figure 8c) show predominantly normal slip on moderately to steeply dipping, ENE-WSW striking planes. The fault planes are also not parallel to near surface normal faults [*Leonard*, 1983], which strike NNW-SSE. As mentioned above, the aftershock pattern may be spurious, a result of mislocated small events. Aftershocks located with recording stations in all four azimuthal quadrants cluster without an obvious trend (Figure 9). The picture is further complicated by the mechanism of the March 25, 1988 aftershock (58), which has a clear strike slip mechanism (CMT). Nodal planes of this event are also not parallel to the WNW-ESE aftershock trend visible in Figure 4. It is possible that this earthquake series is also a result of downbending of South America as described above. Slip vectors of both these events and the forearc normal events trend NNW-SSE with moderate plunges, but orientations of second slip vectors for these subgroups are more varied. This observation suggests that NE-ENE striking fault planes of these earthquakes may be the active planes.

Mechanisms of the four remaining shallow earthquakes, those which are not included in the four groups already discussed, are shown in Figure 8c. We also include in this discussion one intermediate depth event (2; Figure 7, Figure 8c) which is also anomalous. The August 10, 1964 (2), 07 Oct 1973 (14), April 15, 1975 (18), and January 22, 1976 (21) earthquakes occurred beneath the young, thick Orinoco delta. The depths of these events (2, 14, 18 constrained by *pP* times) render it difficult to relate the earthquakes to loading ascribable to the delta sediments. The events also lie significantly inboard of the passive margin edge (Figure 2). These events, with strike slip, mixed thrust and strike slip, and thrust mechanisms, and depths ranging from 25 km to 78 km may be expressions of hitherto unknown plate boundary processes south of Trinidad. Whether this deformation is part of the Caribbean-South America plate boundary zone or occurs strictly within South America is an open question. The September 20, 1982 (39) earthquake

Fig. 8 Divisions of shallow event focal mechanisms, as discussed in the text. Symbols as in Figures 6 and 7. (a): Dextral strike-slip events. (b): Shallow thrust and dip-slip earthquakes. Note that one shallow mixed thrust and strike-slip event (16) is included. (c): Shallow normal faulting, Barbados forearc events, and unclassified events. Barbados forearc events include one thrust (49). Six events to east of Trinidad are March 10, 1988, event(54) and aftershocks. Mechanism shading and hypocenter depths as in previous figures.

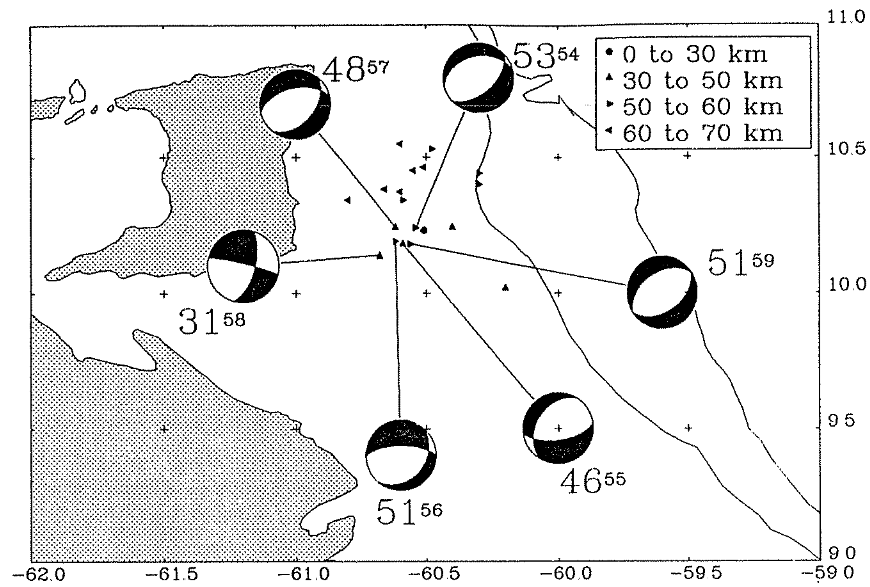


Fig. 9. Detailed view of the March 10, 1988, earthquake and its aftershocks with mechanisms. Also shown are aftershocks (ISC) recorded at stations in all four azimuthal quadrants.

occurred on a fault inferred to exist at the south end of Tobago [*Morgan et al.*, 1988].

Intermediate Depth Slab Dip-Slip Events

As mentioned above, the intermediate depth earthquakes of the region (Figure 7) can also be divided into events of like mechanism, and presumably similar tectonic causes. Ten earthquakes shown in Figure 7 (7, 8, 10, 20, 22, 25, 40, 43, 48, 59) each have at least one nodal plane that strikes approximately parallel to the local strike of the subduction zone. Their depths are between 70 km and 165 km, and they also all exhibit slip with a down-to-the-northwest sense on one moderately to steeply dipping nodal plane. Nine of the mechanisms have tension axes oriented down the dip of the subducting slab. Because the nodal planes are more or less parallel with the local slab strike, because of the down-dip tension axes of these dip slip events, and because of their depths, these earthquakes are probably the result of the sinking of the slab. The orientation of the tension axes indicates that the subducting slab is sinking under its own weight.

Intermediate Depth Slab Lateral Bending Events

The remaining intermediate depth earthquakes can be divided into two types, which we discuss in this and the following sections. The focal mechanism solutions of six events (3, 4, 13, 17, 19, 23; Figure 7) are characterized by predominantly thrust displacement, mixed with right-lateral slip on NNW-SSE striking planes, or alternatively, by left-lateral slip on E-striking planes. Two more events (27, 36) have mixed normal and strike slip mechanisms. The nodal planes of these events strike NNW or E, and strike slip components are dextral on the E-striking planes and sinistral on the NNW-striking planes. All the events lie within the Paria cluster and their depths range from 80 km to 160 km.

These events may be intraplate bending earthquakes [*McCaffrey et al.*, 1985; *Cardwell and Isacks*, 1978; *Fitch and Molnar*, 1970] in the subducting South American oceanic lithosphere. Thus, these earthquakes would represent the bending of the slab about a down-dip axis. Bending would result in compressional stresses on the concave side of the slab and extensional stresses on the convex side. Figure 10a shows a schematic of the bending plate. The six mixed thrust mechanisms do not correspond exactly to this model because they do not have null axes down the dip of the slab, as expected. However, the total stress field in the slab may be the sum of bending stresses and down-dip tension as the slab sinks into the mantle, resulting in the characteristic focal mechanism of this group, and causing the reorientation of the moment tensor principal axes, as shown in Figure 10b. The two mixed normal events are probably also slab bending events. They are most likely the product of extension in the convex portion of the bending slab.

Other Intermediate Depth Events

The second type of intermediate depth events (Figure 7; events 6, 9, 12, 26, 36, 37, 41, 53), are characterized by mechanisms with one or more nodal planes that strike at a high angle to the local strike of the subduction zone. The mechanisms include almost pure dip slip and almost pure strike slip events, and their depths range from 70 km to 145 km. Several of the predominantly dip slip events have significant components of strike slip (i.e., 37, 53, 6, 9), but the sense of slip is not systematic. The four events north of 11.5° N may be caused by motion on tears in the subducting South American oceanic lithosphere, similar to such events observed elsewhere [*Lundgren et al.*, 1988].

The four earthquakes of this type shown in Figure 7 that lie south of 11.5° N (6, 12, 36, and 41) each have an E-striking, near-vertical fault plane, and a predominant component of down-to-the-north slip. One of these events (6) was also studied by *Molnar and Sykes* [1969], who found a mechanism virtually identical to ours. Two of the events have secondary components of strike slip, but this slip is sinistral along the near-vertical plane in one case and dextral in the other. We cannot rule out the possibility that these events may be hinge faulting tears as originally envisioned by *Molnar and Sykes* [1969], but it seems unlikely that this should be so, given the depths of the earthquakes, which are all deeper than 70 km. Presumably, hinge faulting would occur most frequently at shallow depths where brittle tearing would first take place, instead of at inter-

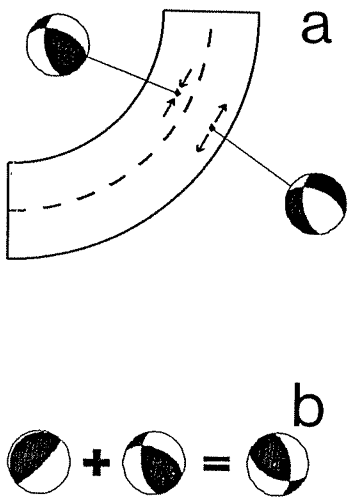


Fig. 10. Schematic interpretations of the lateral bending earthquakes. (a): Down-dip view of curving, subducting slab, with lateral compression directions indicated by arrows. Compression dominates on convex side of neutral surface within the slab, but extension occurs on the concave side. Expected focal mechanisms are shown. (b): Schematic representation of reorientation of principal axes. Superposition of down-dip stress regime, indicated by intermediate depth thrusts, with lateral bending stresses reorients principal directions of the earthquake moment tensor, as shown, giving rise to characteristic bending earthquakes.

mediate depths where asthenosphere on the southern side of the already truncated slab could flow ductilely with the slab. In any case, these earthquakes are also consistent with slab overriding and detachment of the slab from continental South America as postulated for this region by *Russo and Speed* [1992].

The Paria Cluster

The Paria cluster earthquakes are shallow and intermediate depth events lying in a broad ENE-trending linear zone extending from the Gulf of Paria towards Barbados. These earthquakes deepen from the SE, in the Gulf of Paria, to the NW, where the deepest events attain depths of 200 km. The deeper (70–200 km) hypocenters define a steeply NW-dipping (60°) slab which we believe is subducting oceanic lithosphere attached to the South American continent. In addition to the NW dip of the slab, mechanisms of the deeper (70–120 km) Paria cluster thrust earthquakes (see above) show that thrusts or dip slip displacements with down-to-the north sense are active, indicating that the Caribbean plate or terranes moving wholly or partly with the Caribbean (i.e., Tobago terrane and/or Paria-Trinidad terrane) are overriding lithosphere attached to South America. That this subducted slab is South American lithosphere seems likely given that the extant passive margin along the east coast of South America must have extended along the continent's north coast as well, after Triassic rifting of North and South America [*Klitgord and Schouten*, 1986; *Pindell and Dewey*, 1982].

Both the distribution of Paria cluster earthquakes and their mechanisms belie the validity of the hinge faulting model of Lesser Antilles subduction termination. The ENE strike and NW dip of the subducting slab delineated by the Paria cluster are inconsistent with the hinge model, which predicts a northerly strike for the subduction zone, and deepening of earthquakes to the west. An E-trending zone of earthquakes should also extend east of Trinidad to the toe of the Lesser Antilles accretionary prism, according to the model, but this is not observed. The hinge model predicts earthquakes with NNE-striking nodal planes and down-to-the-west sense at 70–200 km depths, and shallow (0–70 km) earthquakes on E-striking faults with down-to-the-north sense. The Paria cluster earthquakes do not include such mechanisms. Instead, the deeper events have ENE-striking nodal planes with down-to-the-north motion, and the shallower earthquakes are a complex mixture of ENE-striking thrusts, E-striking strike slip events, and a variety of normal events.

Continuity of Paria subducted slab with the Atlantic oceanic lithosphere subducting beneath the Lesser Antilles arc to the north seems likely, given the postulated origin of the Paria slab at the aforementioned passive margin, and the continuity of tectonic units (i.e., arc platform), recent volcanism, gravity and magnetic anomalies, and the persistent, if diminished, seismicity in the 70–200 km depth range between the two portions of the subduction zone. The westward termination of the Paria slab is characterized by an abrupt cessation of the 70–200 km depth earthquakes, and the diminution of shallow earthquakes to very low numbers, as described above. Delay-time tomography of this region [*Van der Hilst*, 1990] provides evidence that the high-velocity Paria subducting slab is present beyond the western terminus of seismicity, and also indicates that this slab is detached from, and progressively farther south of, the northern Venezuela coast west of Paria [*Russo and Speed*, 1992].

Shallow Deformation of the Plate Boundary Zone

Comparison of the strikes of thrust faults of the plate boundary zone with shallow thrust earthquakes (events 30, 33, 45, 51, 51) in the zone reveals that the strikes of nodal planes and the faults are parallel, generally striking ENE. The earthquakes with these mechanisms do not appear to occur only on thrust faults of the fold and thrust belt. Shallow thrusts within the Paria-Trinidad terrane and the Tobago terrane, and perhaps even the interface between these units and the emplacement surface of the Paria-Trinidad terrane over the thrust belt, are also active (33, 52). Furthermore, west of Trinidad, the thrust events are distributed with depth (10 to 46 km), indicating that thrust displacements are active throughout, and perhaps even beneath, the crust in the plate boundary zone.

In the western Gulf of Paria, shallow active thrusting is occurring in the fold and thrust belt. Three earthquakes that exhibit a strong thrust or reverse component and a smaller strike slip motion (30, 45, 51) occurred in the western Gulf of Paria. Although the three earthquakes may have been caused by different tectonic processes, as is perhaps indicated by their range of depths (12–46 km), all three mechanisms have one nodal plane which strikes nearly E-W, and although these planes dip both shallowly north and steeply south, the sense of strike slip is dextral on all three planes.

Strike slip earthquakes are distributed within the Paria-Trinidad terrane in Venezuela, and within or beneath the fold and thrust belt south of the boundary between the two tectonic units. These events show that significant dextral motions on E-striking faults distributed in the vicinity of the interface between the Paria-Trinidad terrane and the Venezuelan fold and thrust belt are occurring. It is possible, given the conjunction of shallow thrust and strike slip events, that strain partitioning and strike slip fault generation are developing diachronously along the interface. Thus to the east, in Trinidad where dextral strike slip earthquakes are not observed, the terranes have been juxtaposed along thrust or reverse faults, but partitioning into strike slip and convergent components of displacement along discrete faults has not yet occurred. The western, Venezuelan portion of the interface has already undergone partitioning, as indicated by the coincident thrust and strike slip earthquakes along the Paria-Trinidad terrane-fold and thrust belt interface. The locus of currently active partitioning may be in the western Gulf of Paria, where the thrust faulting earthquakes mentioned above occurred in the same area as several of the easternmost dextral strike slip events. The depths of the strike slip events, like the thrust earthquakes, range from shallow crustal levels (15, 61) to depths that are almost certainly subcrustal.

Known shallow normal faulting and dip slip earthquakes (28, 34, 42, 47) within the plate boundary zone are less numerous than the thrust or strike slip earthquakes discussed above. Although all four earthquakes have undoubtedly normal faulting or dip slip mechanisms, no two mechanisms are alike. Thus of the three seismogenic types of faulting in the plate boundary zone, shallow extension or dip slip is the most variable with respect to fault orientation. The September 3, 1977 (28) earthquake occurred along the south coast of the Paria peninsula, just to the east of the strike slip September 21, 1977 (29) earthquake, to which it is probably related. Both events have a steeply S-dipping nodal plane striking just north of east, and the normal faulting earthquake mechanism has small component of dextral displacement. Thus the two September 1977 earthquakes may represent coupled motions: the first shock, the down-to-the-north dip slip event, perhaps caused by loading of the Paria-Trinidad terrane, moves the terrane also slightly eastward relative to the fold and thrust belt, and thus may have extended the portion of the terrane just to the west of the epicenter. This elastically extended area then may have rebounded, giving rise to the second, strike slip earthquake.

The conjunction of the earthquakes has several interesting implications. The active thrust faulting in the vicinity of the strike slip faults indicate that the fold and thrust belt is still active, and that the strike slip faults may be moving southward. The stability of the faults' locations depends on whether thrust displacements are occurring on steep reverse faults, akin to motions responsible for the 1983 Coalinga earthquake [*Stein and King*, 1984], or whether low angle decollements are developed. The presence of active dextral strike slip on N-NNW striking faults in this area (event 16) may indicate that decollements are active. The N-striking fault plane may curve into a more ESE striking plane, as do the Los Bajos and El Soldado faults further east, and therefore this motion may be similar to motion on Riedels to the dextral strike slip faults. Riedel shears typically have helicoidal shapes [*Sylvester*, 1988; *Naylor et al.*, 1986]. Motion on such faults should introduce vertical torsional stress gradients in rocks which are displaced. The torsion can have the effect of differentially rotating rocks at different depths along the fault surface, and for sedimentary rocks, with natural, near-horizontal discontinuities, development of low angle shears may be favored. The active thrust faulting also implies that shallow levels of the elastic lithosphere around the Araya-Paria isthmus are under compression in the N-S or NW-SE direction, although it is unclear whether this compression is due to a regional tectonic stress [*Zoback et al.*, 1989] or is caused by stress refraction signaling strike slip faults of very low shear strength [*Mount and Suppe*, 1987].

Stereonet plots of principal axes of the focal mechanisms of shallow earthquakes from the region between Trinidad and the Gulf of Cariaco are shown in Figure 11. This region includes all the mechanisms discussed in the paragraphs above. P axes of these earthquakes lie predominantly in two clusters, both with shallow to moderate plunges, trending NW and SE. The T axes best fit girdle strikes approximately NE-SW, and dips nearly 45° NW; the null axes lie along a plane striking ENE-WSW, dipping approximately 45° SSE.

The consistency of the P axes trends and the girdle distribution of T and null axes implies that compressional tectonic stresses cause the shallow regional deformation, and that the orientations of T and null axes are partly independent of the neotectonic stress field. For example, the principal strain axes are consistent with strain fields predicted for an E-W striking simple shear zone caused by compression in the NW-SE direction [*Sylvester*, 1988], and motion along inherited structures may explain the girdling of T and N axes. The relationship between the P, T, and B axes of the shallow earthquakes in the vicinity of the El Pilar fault indicates that the area may be considered a deformation domain. The coexistence of the different earthquake types within this small region is also consistent with observed structures in simple shear zones.

The differences between the trends and plunges of principal axes of the thrust earthquakes and those of the RLSS events may be highly significant. In both groups, the P axes form the tightest clusters among the principal axes. The mean P axes of the two groups plunge shallowly in almost opposite directions, due northwest for the RLSS events, but SSE for the thrusts. The discrepancy in trend is perhaps the result of strain partitioning in the plate boundary. Thus the RLSS P axes may represent the true direction of maximum compressive tectonic strain, but the thrust P axes are rotated to be more nearly perpendicular to the basement slope over which hanging walls are moving. In this case, the slope would be the former South American continental passive margin. The fact that the two groups of P axes plunge in opposite directions may also be related to the northward dip of the basement interface along which the plates interact: the strike slip events reflecting a compressive force directed slightly from below, and the thrusts rotated to southward plunges reflecting the additional confining forces of the sloping interface, overburden, and the strength of thrust sheet's hanging wall. Overall, the P axes indicate that interplate compressive forces are concentrated at some depth below the Earth's surface.

The El Pilar Fault

Our field structural geology study of the Araya-Paria isthmus and Paria region indicates that faults of EW strike and significant displacement do not exist onshore at the

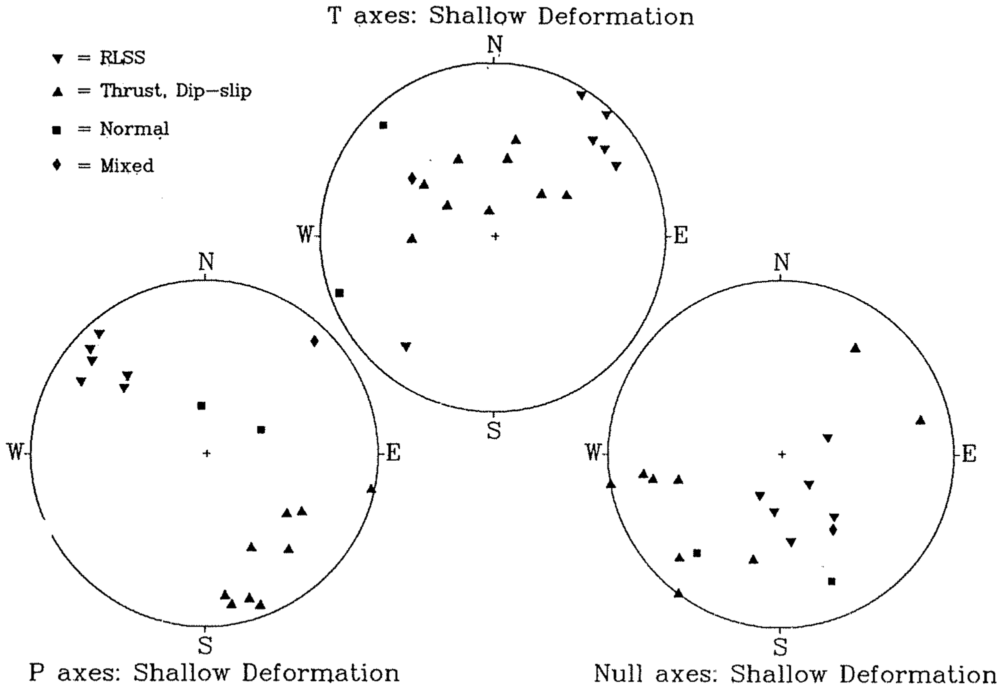


Fig. 11. Stereonet plots of principal axes of all shallow earthquakes in the Paria Peninsula region. These include right-lateral strike-slip events, shallow thrusts, shallow normal faulting events, and one shallow mixed thrust-strike-slip earthquake. Pressure axes trend NW-SE with shallow plunges. Tension axes lie in a girdle striking approximately NE-SW, with intermediate to steep plunges. The girdle dips NW. The null axes are also girdled with trends NE-SW but with plunges more to the S-SW.

surface (R. C. Speed and R. M. Russo, unpublished data, 1992). In particular, we have found no clear evidence of vertical dextral faulting on East-striking faults or associated shear deformation in Miocene (Alvarez et al., 1985) to recent sediments anywhere between the western isthmus (Casanay) and the eastern tip of the Paria Peninsula (Macuro). These sediments should be good, unequivocally interpretable recorders of any such recent deformation, and we note that they are deformed. We confirm observations of southward thrusting of the Paria-Trinidad rocks over these sediments [*Alvarez et al.*, 1985; *Russo and Speed*, 1992], and of thrusting of the Tobago terrane onland over the Paria Trinidad terrane along the north coast of the Araya-Paria isthmus [*Bladier*, 1979].

Within the plate boundary zone, the distribution of earthquakes, the varied shallow-depth focal mechanisms, the moment-release partitioning of the earthquakes with mechanisms, and the results of on-site field studies together point to the absence of a through going strike slip fault, such as the canonic El Pilar fault. Instead, on the basis of our analysis of the regional seismicity, reported geologic data, and our ongoing field studies in Venezuela and Trinidad, we believe that strike slip within the plate boundary zone is occurring on distinct E-striking faults within the Paria-Trinidad terrane and the fold and thrust belt, between the central Araya-Paria isthmus and the western Gulf of Paria. However, none of these seismically active fault segments is identified in the field, and the regional fault pattern (Figure 2) includes few E-striking faults. The choice of several strike slip faults in place of the one entails limits on the amount of dextral strike slip displacement that has occurred between the Caribbean and South American plates: the normal progression of simple-shear zone development proceeds from separate shear zones of small displacement to a single zone of great displacement [*Ramsay and Graham*, 1970]. Thus the absence of a through going strike slip fault implies that eastward transport of the Caribbean plate relative to South America may be of limited magnitude. A complicating factor in this type of displacement estimate is that, in the case of the Ca-SA plate boundary zone, oblique interaction of Caribbean and South America may have caused diachronous development of structures within the zone, and thus along-strike variations in shear zone development are to be expected.

Evaporite Deposits and Vertical Strain Partitioning

Earthquakes with RLSS mechanisms on EW-striking planes exist distributed over a north-to-south width of 60 km in the plate boundary zone. These events occur predominantly deeper than 10 km, and as deep as 55 km. (N.B. Although the July 12, 1988 (61) event was located by the ISC to 5 km, the three *pP* times they report suggest a deeper hypocenter.) This observation, in conjunction with the lack of expression of these faults in surface geology, implies that RLSS on EW planes occurs in a middle and (or) lower crustal zone but not in the shallow crust. We explain this with a model that the shallow crust in Araya-Paria, taken as the allochthon of terranes (Paria-Trinidad and Tobago), overlies a very weak fault zone and moves with full Ca-SA oblique motion relative to cratonal South America. Below that fault zone, Ca-SA motion may be partitioned into EW strike slip and NS contractile components. We thus reconcile the observations of southward thrust deformation at the surface and throughout the crust and the depths of the RLSS strike slip events. Our model (Figure 12) explains the very weak fault zone below the allochthon by the existence

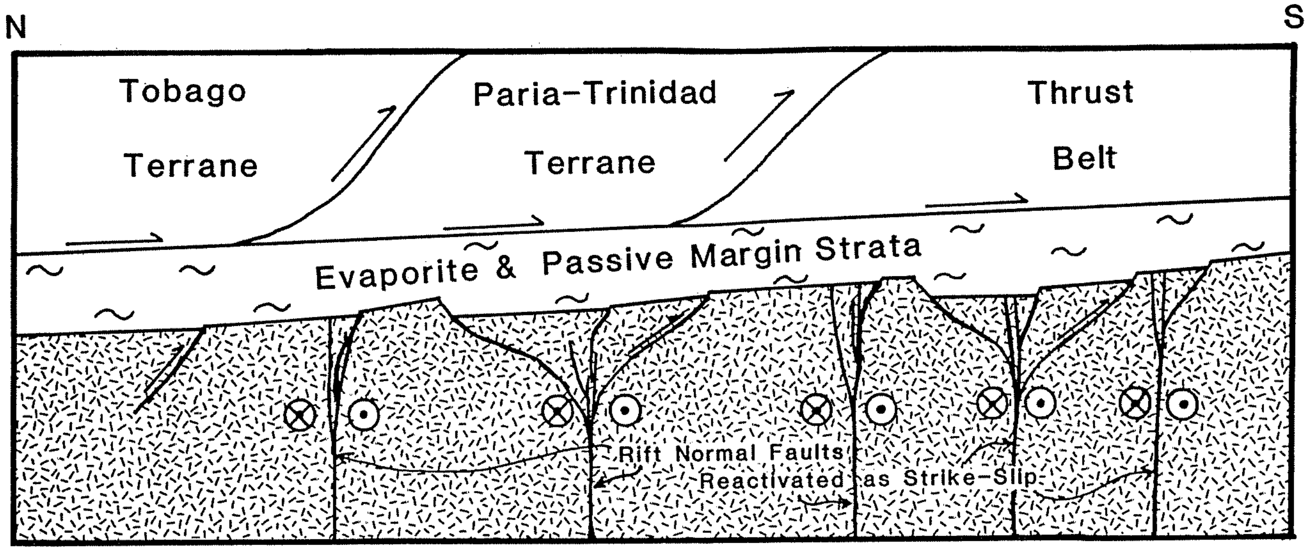


Fig. 12. Schematic vertical section of plate boundary zone. Evaporite layer, passive margin strata, and normal faults, remnants of Triassic rifting, localize and partition boundary parallel (dextral slip) and convergent (thrust) motions. The weak evaporitic layer effectively decouples the motions vertically. Rift normals are reactivated and develop into strike-slip fault zones at mid or deep crustal levels.

of evaporites in the zone [*Davis and Engelder*, 1987] and the strike slip in the continental crust below the allochthon by reactivation of faults of EW strike that were a product of Mesozoic rifting of northernmost South American continent, as discussed above.

The existence of evaporites above the underthrust continental crust is indicated by two lines of evidence. First, the widely held idea that northern South America has a Mesozoic rifted margin implies that evaporites are an expected constituent in the rift phase deposits, which would be deep within or at the base of the passive margin strata (Figure 12) that have been detached and thrust south during Neogene oblique collision. Second, evaporitic rocks of known or suspected Early Cretaceous age exist in outcrop or drillholes at or near the southern margin of the Paria-Trinidad terrane in the eastern Paria region [*Gonzales de Juana et al.*, 1965], the Gulf of Paria [*Eva et al.*, 1989], and in western Trinidad *Kugler*, 1959]. Each of the evaporite occurrences is in a tectonic slice that may have emerged in thrust sheets that ramped up from the basal detachment zone.

CONCLUSIONS

The earthquake mechanisms described above provide decisive constraints on the allowable kinematic models for Caribbean-South America plate interaction. A brief summary of these constraints follows. Shallow, dextral strike slip on E-W planes is restricted to a linear zone between the Gulf of Cariaco and the western margin of the Gulf of Paria, for the time period of this study (1963–1990), and as far back as 1922 [*Russo et al.*, 1992]. This indicates that the dextral strike slip on E-striking faults is active only as far east as the Gulf of Paria, and not to the east of Trinidad. P axes of these earthquakes clearly indicate that maximum compression is NW-SE. The dextral strike slip earthquakes are distributed among several faults in the Paria-Trinidad terrane and the fold and thrust belt, but do not lie on a single through going fault.

Shallow thrust events with ENE-WSW striking planes, distributed in a linear zone between Araya and the Gulf of Paria, indicate collision at crustal levels between South America and Caribbean, and that folding and thrusting are still active in South America over a 60 km interval south of the coastline of the Araya-Paria Peninsulae. The locations of these active thrusts imply that both the Paria-Trinidad terrane and the Tobago terrane are obliquely colliding with South America, and override the Venezuelan fold and thrust belt. Slip vectors for these earthquakes trend NNW-SSE. Active thrusting in Venezuela corroborates predictions of transpression between Caribbean and South America by *DeMets et al.* [1990], *Ladd* [1976], and *Jordan* [1975], and discounts transtensional motions between the two plates [*Sykes et al.*, 1982] in the southeastern Caribbean. Shallow thrusts in the Gulf of Paria and Trinidad, in conjunction with active E-W dextral slip and normal faulting at around 62.3° W, may be the expression of a zone of coupled SE-directed thrusting and E-directed dextral strike slip. This zone is the result of west-to-east diachronous development of the plate boundary. Shallow oblique thrust earthquakes may be lateral ramps at shallow levels of the fold and thrust belt, analogous to the San Francisco and Urica faults (Rossi et al., 1987; Munro and Smith, 1984), or to the Los Bajos-El Soldado fault systems of the Gulf of Paria [*Rossi et al.*, 1987; *Speed*, 1985; *Perez and Aggarwal*, 1981; *Wilson*, 1968]. These faults are also evidence of decollements beneath the terranes and portions of the fold-thrust belt.

Intermediate (140 km $> h >$ 70 km) depth thrust earthquakes within the steeply NW dipping, hypocentrally defined slab, indicate that oceanic lithosphere, probably originally attached to South America, is subducting to the northwest beneath the Caribbean plate. The subducting slab is beneath, and to the north of the Paria Peninsula. Probable fault planes are near vertical, striking NE-ENE. Intermediate depth mixed-motion earthquakes with thrust and strike slip on NNW-SSE or E-W planes may indicate bending of the subducting slab at deeper levels.

Neither the shallow nor the intermediate depth thrusts are properly oriented or distributed to have been caused by hinge faulting. Also, strike slip displacement does not

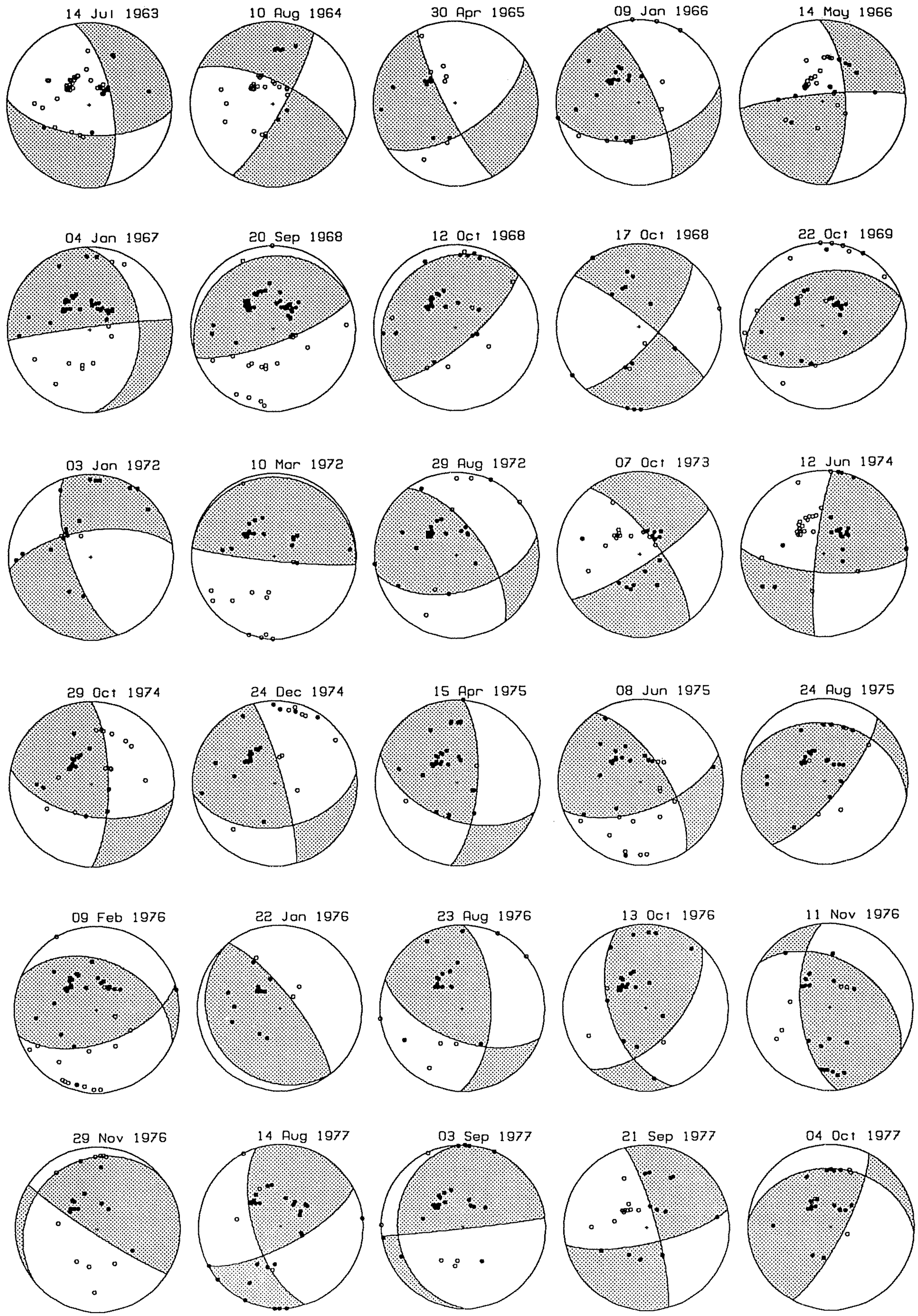


Fig. A1. Lower hemisphere projections of focal mechanisms constrained in this study. Compressional quadrants shaded, solid circles compressional first arrival, open circles dilatational first arrival.

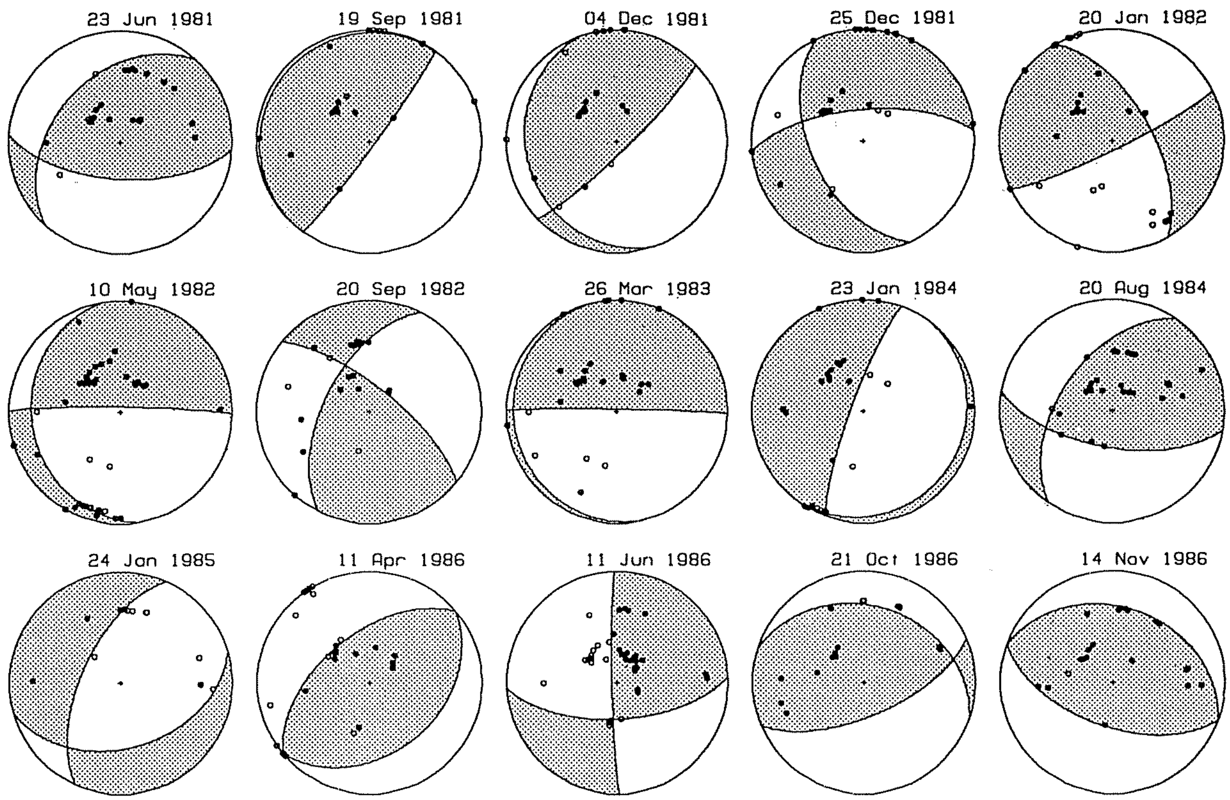


Fig. A1.**(continued)**

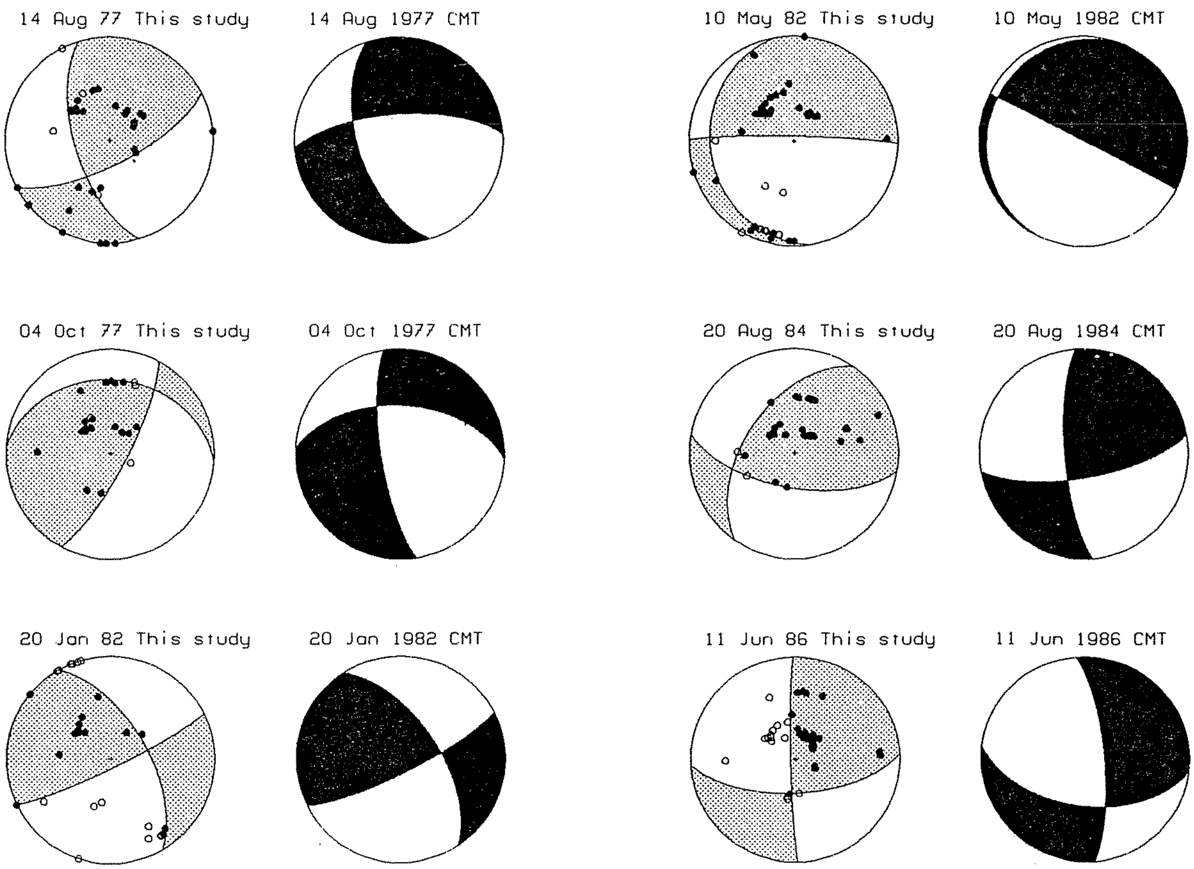


Fig. B1. Comparison of focal mechanisms constrained in this study with available CMT mechanisms. Lower hemisphere projections, compressional quadrants shaded. Solid circles are compressional first arrival; open circles are dilatational first arrival.

extend from the Gulf of Paria to the toe of the accretionary prism to the east of Trinidad, as predicted by the hinge faulting model.

Shallow normal faulting mechanisms to the E and NE of Trinidad are expressions of plate bending about near-horizontal axes parallel to the Lesser Antilles subduction zone. Deep normal faulting within the Paria cluster is due to slab bending about axes oriented down the dip of the slab. The bending is caused by lateral compression due to the tight radius of curvature of the Lesser Antilles arc. Shallow normal faulting within the collision zone may be related to plate flexure, or extension parallel to convergence direction. The earthquake focal mechanisms provide strong support for the right oblique collision model of Caribbean-South American plate interaction.

APPENDIX A: FOCAL MECHANSIM DATA

First motion focal mechanism solutions produced for this study are shown in Figure A1. Sources of data include the Regional World-Wide Standard Seismograph Network (WWSSN) Data Center at Northwestern University, the Seismology Film Chip Collection at Lamont-Doherty Geological Observatory, Trinidad Local Network records at the University of the West Indies Seismic Research Unit and records from the local network run by the Institut de Physique du Globe (IPG), Paris, on Martinique and Guadeloupe. In all cases, data are plotted on lower hemisphere equal-area polar projections. Compressional quadrants are shaded. R.M.R. made all first motion picks from WWSSN records and Trinidad local network records, but E.A.O. and IPG scientists made picks for approximately 10 readings for Martinique and Guadeloupe data. Event locations, origin times, and fault plane orientations are in Table 1.

APPENDIX B

Comparison of focal mechanisms produced for this study with those from the Harvard Centroid Moment Tensor solutions are shown in Figure B1. Mechanisms for August 14, 1977, and October 4, 1977, are discordant. The first motion picks for the August 14, 1977, earthquake are compatible with the CMT mechanisms, provided the first motion picks for WWSSN stations in Africa are incorrect. Given the epicentral distance and magnitude of the event, it is likely that these two picks are wrong. Therefore we have used the CMT solution in preference to our own in this analysis.

The October 4, 1977, earthquake presents a somewhat different problem. We are confident in the first motion picks, especially those from stations in the Lesser Antilles themselves, which provide the constraints for the north-dipping plane of the first motion mechanism. Therefore we have opted to use the first motion mechanism in the analyses, rather than the CMT mechanism. The remaining mechanisms for which there are both CMT solutions and first motion solutions do not present real problems in interpretation, since the discrepancies between the mechanisms are slight. The January 20, 1982, and June 11, 1986, earthquakes are especially good examples of the agreement between the two methods.

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