Chapter 4

Seismotectonic and the Hipothetical Strike – Slip Tectonic Boundary of Central Costa Rica

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Additional information is available at the end of the chapter

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1. Introduction

The studied area is comprised of the Central Volcanic Range (CVR) of Costa Rica, the northwest flank of the Talamanca Cordillera, and the space between them, known as the Central Valley of Costa Rica (Figure 1). The Central Valley separates volcanic rocks of the CVR from intrusive rocks of the Talamanca Cordillera. The zone is characterized by low seismicity in the north and high seismicity in the South (Montero, 1979; Montero & Dewey, 1982; Montero and Morales, 1984).

Astorga et al. (1989, 1991) proposed the existence of a strike-slip fault across Costa Rica extending from the Pacific to the Caribbean and passing through the central part of the country. Fan et al. (1993) stated that a diffuse transcurrent fault zone trending northeast-southwest and composed of various subparallel strike-slip faults exists in Central Costa Rica. According to Fan et al. (1993), the fault zone extends from the Pacific coast to the Caribbean across central Costa Rica, and may represent a possible plate boundary for the proposed Panama Block. Jacob et al. (1991), Fisher et al. (1994) and Marshall (2000) asured that the strike-slip tectonic boundary traverses the Central Valley of Costa Rica. The prior proposals were mentioned in many other works [Seyfried et al. (1991), Fisher y Gardner (1991), Güendel y Pacheco (1992), Fan et al. (1992), Goes et al. (1993), Lundgren et al. (1993), Marshall et al. (1993), Gardner et al. (1993), Escalante y Astorga (1994), Protti y Schwartz (1994), Montero (1994), Marshall (1994), Montero et al. (1994), Fernández et al. (1994), Barboza et al. (1995), Marshall y Anderson (1995), Marshall et al. (1995), Suárez et al. (1995), Di Marco et al. (1995), Colombo et al. (1997), Güendel y Protti (1998), López (1999), Lundgren et al. (1999), Montero (1999), Yao et al. (1999), Quintero y Güendel (2000), Montero (2001), Trenkamp et al. (2002), Husen et al. (2003), Linkimer (2003), Montero (2003), DeShon et al. (2003), Norabuena et al. (2004), Pacheco et al. (2006), Marshall et al (2006), Camacho et al. (2010)] what spread the idea of the existence of a tectonic boundary in Central Costa Rica.

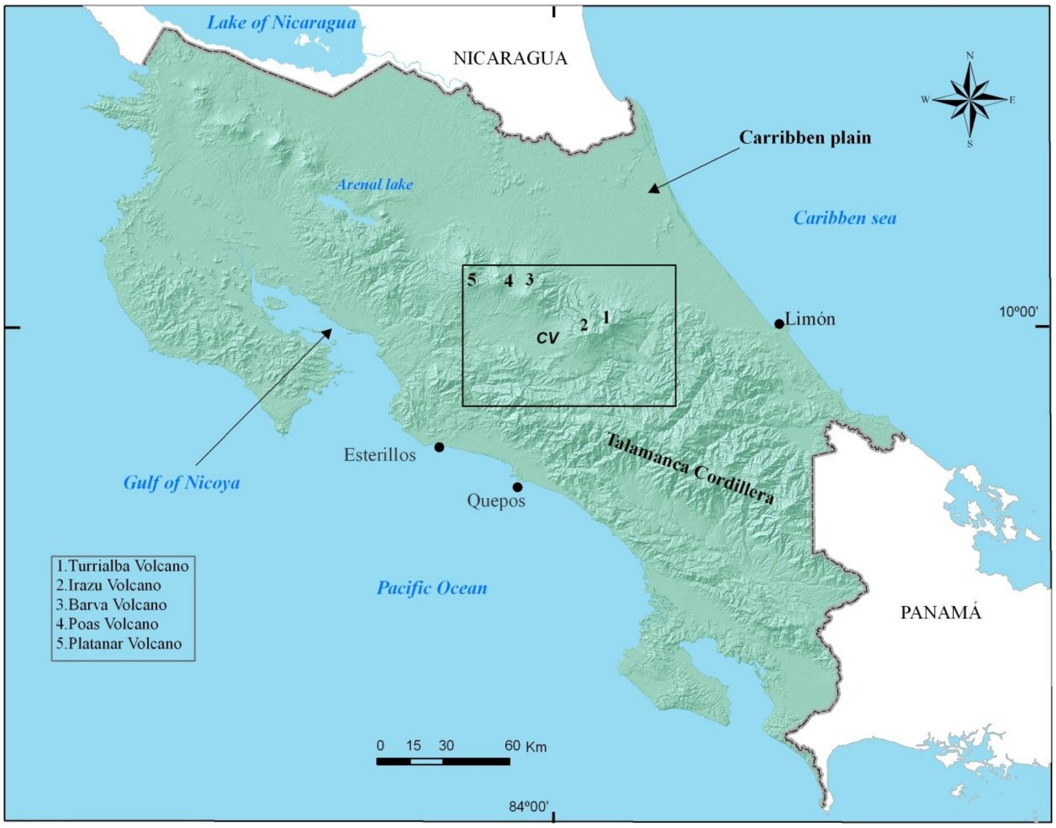

Figure 1. The area of interest is indicated by the rectangle and covers part of the Central Volcanic Range (numbers mark key volcanoes), the Central Valley (CV) of Costa Rica and Talamanca Cordillera. The Central Valley is a depression located between the ranges and contains the largest population centers of Costa Rica.

Older references have been used to support the hypothetical tectonic boundary of Central Costa Rica [Van Andel et al. (1971), Stoiber y Carr (1973), Burbach et al. (1984), Adamek et al. (1988), Carr y Stoiber (1990) and Mann et al. (1990)] but they are not appropriate to justify the boundary because they refer to a segmentation in the Cocos Plate not in the Caribbean Plate.

This paper analyses and discusses the seismicity and faulting of Central Costa Rica in search for evidence of the strike-slip fault proposed by Astorga et al (1989, 1991), the subparallel strike-slip fault system reported by Fan et al. (1993) and the plate boundary trace in the Central Valley of Costa Rica suggested by Jacob et al. (1991), Fisher et al. (1994) and Marshall et al. (2000).

2. Data and method

Available data on faulting, historic earthquakes, instrumentally recorded shocks and source mechanisms are provided in this work. Information on faulting is compiled from Fernández & Montero (2002); and Denyer et al., (2003). The seismic data has come from the data file compiled by the RED SISMOLOGICA NACIONAL (RSN: ICE-UCR) operated by the University of Costa Rica (UCR) and the Instituto Costarricense de Electricidad (ICE). This seismic network monitors the seismic activity of Costa Rica with 20 analog, short-period vertical-

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component seismometers (black triangles, Figure2) and 9 digital three-component stations (open triangles, Figure 2). The signals from analog stations are telemetered to the University of Costa Rica at San Jose where they are digitized by an A/D converter and recorded on a PC computer running the SEILOG data acquisition program. The station spacing is densest in the study area and in westhern Costa Rica.

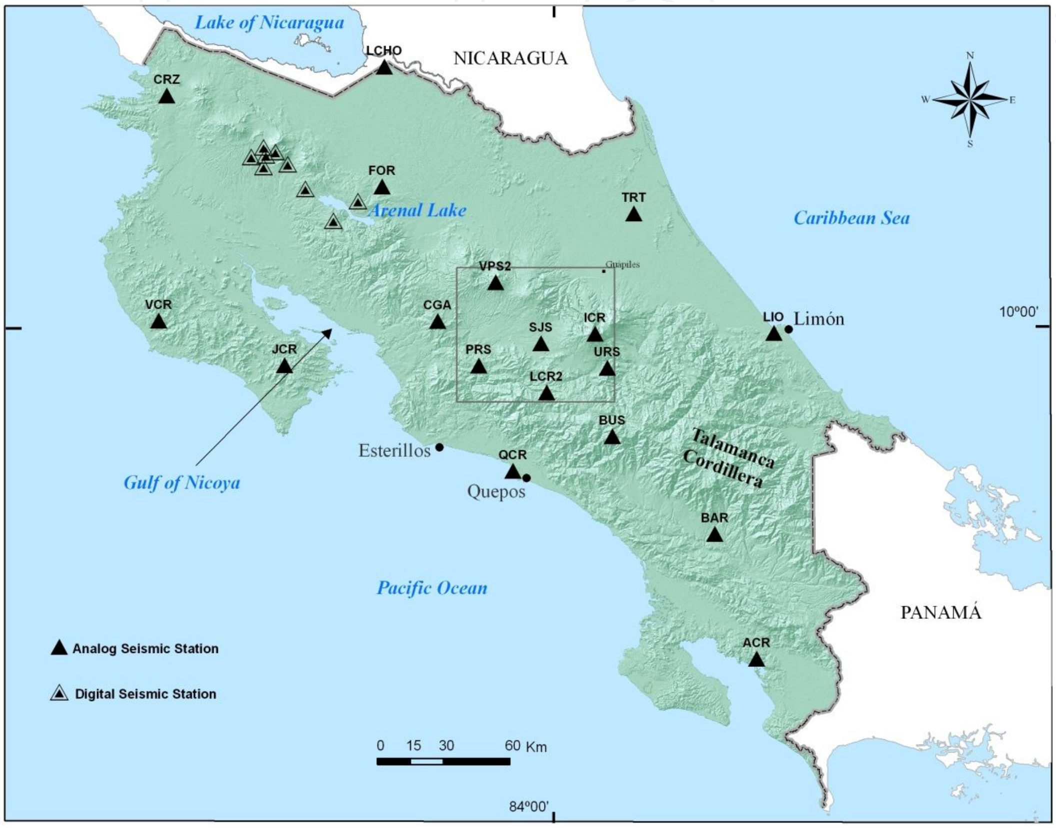

Figure 2. Seismic stations of the Red Sismologica Nacional (RSN: ICE_UCR) shown with triangles. Black triangles are analog stations. The digital stations are indicated by open triangles.

Historical data on earthquakes are from Rojas (1993). The recent seismicity includes shallow earthquakes of depth equal to or smaller than 30 km and intermediate/deep earthquakes with depths larger than 30 km. Both data subsets span from 1992 through 2009 and were extracted from databases of 4845 (shallow) and 7756 (intermediate/deep) events. The range of duration magnitudes is 1.8-6.2 and the average is 2.8.

The subset of 865 high-quality shallow events includes 382 located by Fernández (1995) and 82 more by Fernández (2009). They were located with 5 or more stations (7 average) and 2 readings of S wave. Their average rms residuals and horizontal and vertical errors in location are 0.3 sec, 1.8 and 2.0 km respectively. The average azimuthal gap between stations used in the hypocenter determinations is 149.2° and the average distance to the closest station is 15.3 km.

The subset of intermediate/deep earthquakes includes only those locations showing vertical error smaller than 10 km.The average latitudinal and longitudinal component of the location

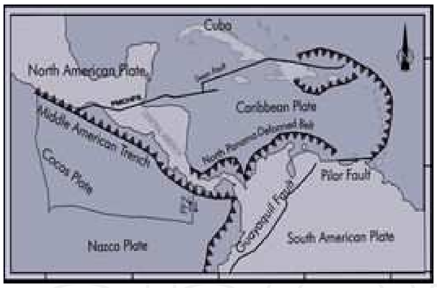

Figure 3. Tectonic Setting. Costa Rica is located on the western extreme of the Caribbean Plate. The border between this plate and the Cocos plate is the Middle American Trench (MAT) located off the Costa Rican Pacific coast. Other tectonic boundaries are the Polochic-Motagua-Chamalecon Fault System (PMCHFS), the Panama Fracture Zone (PFZ) and the North Panama Deformed Belt (NPDB). From Fernandez et al. (2004)

errors for this kind of events are 6.35 and 6.2 km. Their average rms residual is 0.4 sec and the average distance to the closest station is 30.6 km.

Earthquakes were located using P and S wave arrival times and the SEISAN program (Havskov and Ottemøller, 1999) which includes a version of the Hypocenter. A 1-D seismic velocity structure, determined by seismic refraction in northern Costa Rica (Matumoto et al., 1977), is used by the RSN to locate earthquakes in Costa Rica. Fernández (1995) located earthquakes of Central Costa Rica with the 3-D velocity structure of Protti (1994). Fernandez (1995) and Protti et al.(1996) found no significant differencies between earthquake locations obtained with both the 1-D and the 3-D models.

Focal mechanisms for major events in the area were determined by using the first motion of P-waves. The P-wave first motion data were plotted on an equal area projection of the lower hemisphere. The search of fault planes was restricted to events with at least 9 reported first motions. These inversions were performed with the FOCMEC program (Snoke et al., 1984).

3. Tectonic setting and geology

Central America is an active island arc built up by the northeast subduction of Cocos lithosphere beneath Caribbean plate. The junction of these plates forms the Middle American Trench (MAT), the western boundary of the Caribbean plate (Figure 3). The present convergence rate increases along the trench from about 7.3 cm/yr off Mexico and Guatemala to 8.5 cm/yr in western Costa Rica (DeMets 2001). Seismicity suggests that 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 subduction became shallower at the southern terminus of MAT in response to a buoyant submarine ridge (Cocos Ridge) that arrived to the trench ~5 Ma (de Boer et al., 1995), causing a decrease in the volcanic activity. The subduction of the Cocos ridge, which rises almost 2 km above the surrounding seafloor, generates high uplift and significant deformation of the whole arc in front of the present subducting ridge. A major geologic effect produced by the subduction of Cocos plate in southern Costa Rica is the uplift of the Talamanca Cordillera.

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The Talamanca Cordillera is a Miocene plutonic-hypabissal volcanic complex that extends by 180 km from central Costa Rica to western Panama. Major Tertiary volcanic complexes are present in this range but large and young strato-volcanic complexes are absent, a consequence of the significant elevation of the range (de Boer et al., 1995) and the shallow, high-angle subduction in southern Costa Rica [60° according to Arroyo (2001)]. This range is the highest topographic feature of Central America and, therefore, of the Caribbean plate. This elevation is possibly related to the subduction of Cocos Ridge (Kolarsky et al., 1995).

The Central Volcanic Range is a chain of andesitic stratovolcanoes trending northwest, parallel to the MAT. The CVR Consists of five massifs-Platanar, Poas, Barva, Irazú, Turrialba--and several pyroclastic cones associated to the main volcanoes. This cordillera covers an area of 5150 m^2 and its maximum topographic feature is Irazu volcano (elevation 3400 m). The volcanic activity at the present-day edifices commenced in the Late Cenozoic and has continued throughout the range until the present. The current activity consists of fumarolic emissions and hot intra-crater lakes. Barva and Platanar are dorman volcanoes of this range.

The Central Valley is a narrow trough (15 km wide, 70 km long) between the Central Volcanic and Talamanca ranges. Late Tertiary and Quaternary volcanic rocks, believed to be part of the current volcanic edifices forming the Central Volcanic Cordillera, are present in this valley as well as some Miocene sedimentary sequences.

4. Faulting

Previous works, field investigations and assessments of neotectonic features via airphotos indicate that deformation of central Costa Rica occurs in three geographical areas: the Central Volcanic Range, the Central Valley and the northern flank of the Talamanca Cordillera (Figure 4).

The Central Volcanic Range faulting is divided into three sub-zones: Irazu Volcano, Bajo de la Hondura, and Poas Volcano. Irazu is a zone of northwest-trending, short length (< 20 Km), normal faults and some northeast faults whose displacement is also normal (Figure 4). Within the Bajo de la Hondura zone, in the low between Irazu and Barba volcanoes, are the south-north trending Hondura and Patria normal faults and the strike-slip Lara fault. At Poas, in the northwest extreme of the Central Volcanic Range, the southeast- northwest-striking Viejo, Carbonera and Angel faults border the volcano.

Over decades Costa Rican geologists have considered faulting absent in the Central Valley of Costa Rica. Geologic maps show several faults in the borders of the valley but only few within it (MIEM, 1982, MINAE, 1997, Tournon & Alvarado, 1997, Denyer et al., 1993). Such faults probably exist but are difficult to recognize because of the volcanic and concrete surface cover. Among the better known faults of this area are the Alajuela and Escazu. Alajuela is a 28-km long east-west reverse fault and Escazú seems to have reverse and strike-slip component (Fernández and Montero, 2002). In the last decade additional high-quality seismic data have begun to illuminate important structures within the valley. Fernandez and Montero (2002) mapped three more faults in the valley (Cipreses and Río Azul). An interesting finding is the

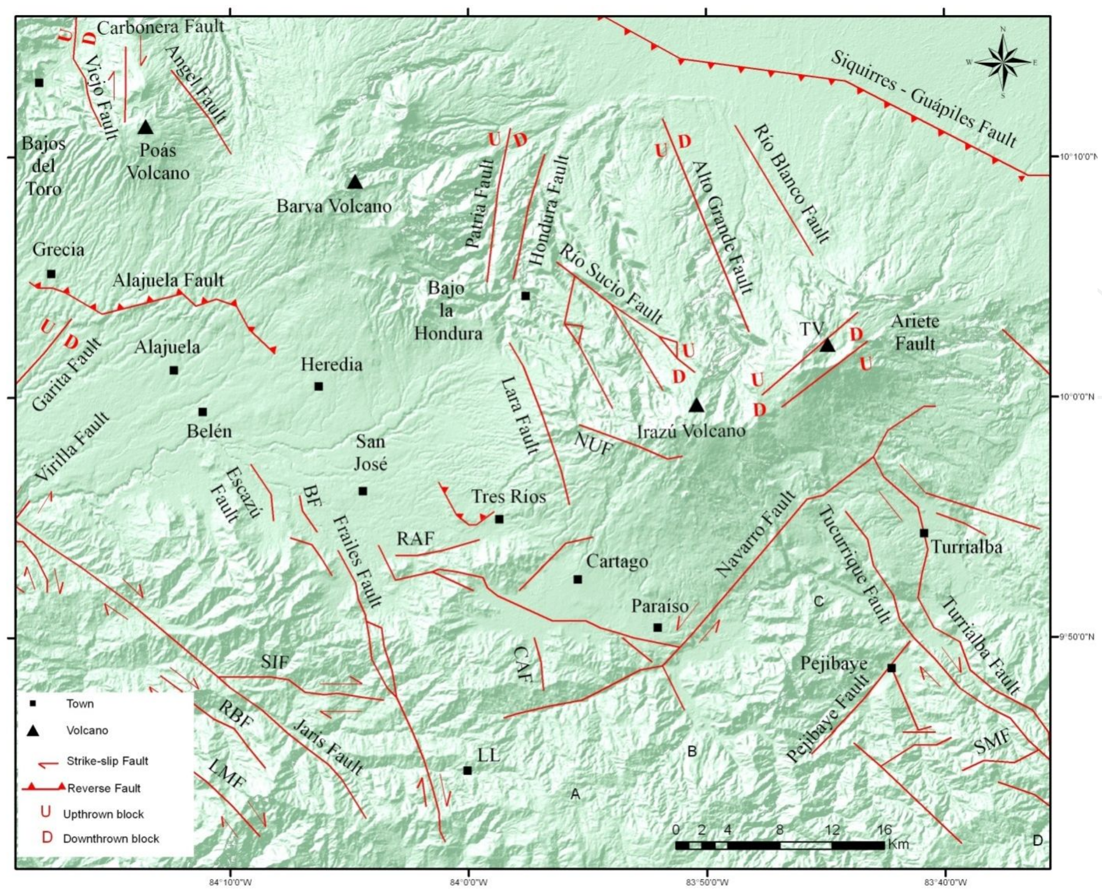

Figure 4. Faults mapped in Central Costa Rica. Triangles mark volcanoes; squares show cities or towns. The aligned volcanoes mark the longitudinal axis of the Central Volcanic Range. The cities of Cartago, San José, Heredia and Alajuela are located in the Central Valley of Costa Rica. The Escazú and Aguacaliente (AF) faults define the southern boundary of the Central Valley. Faults located southeast of the Navarro fault belong to the Talamanca Cordillera. PF: Picagres Fault, BF: Belohorizonte Fault, RAF: Río Azul Fault, SIF: San Ignacio Fault, RBF: Resbalon Fault, LMF: La Mesa Fault, CIF: Cipreses Fault, NUF: Nubes Fault, CAF: Cangreja Fault, SMF: Simari Fault, ATF: Atirro Fault, PCF: Pacuare Fault, LL: La Lucha, SP: Santiago de Puriscal, U/D: normal faults howing relative motion: U, upthrown block; D, downthrown block. Sawteeth along solid lines indicate thrust fault. Strike-slip arrows represent strike-slip faults.

extension of the Aguacaliente and probably Rio Azul faults under the surface of San Jose, the capital of Costa Rica, which represent a significant hazard for that city.

At the Talamanca Cordillera faults trend predominantly northwest with varying fault lengths and slip directions. The most important faults in this area are Atirro, Navarro, Aguacaliente, Frailes-Escazu, and Jaris. In the east, the dextral Atirro Fault is the major structure, and it splits into two branches (the Tucurrique and Turrialba faults). At the northern rim of the range, the Aguacaliente Fault marks the boundary between the range and the Central Valley. Trench excavations across the Navarro, Aguacaliente, and Orosi faults have been conducted in order to date the most recent ruptures and to identify periods of dormancy (Woodward-Clyde, 1993). Soil development along faulted surfaces and scarp morphometry was used to determine the relative deformation rates across the segments. At the Navarro fault, the trench shows evidence of faulting within the unconsolidated sediment section, where sediment deformation features are present. These features include lineaments such as small strike-slip and reverse faults, along fault line locations mapped during field studies. Results suggest that faulting has occurred during the Holocene, but movement is likely disseminated over a broad zone (100 m) instead of being concentrated along any single fault plane. At Aguacaliente, one trench intersected a trace that offset the soil horizon by approximately 30-35 cm (Woodward-Clyde, 1993). The apparent displacement was normal and a dated carbonizad log suggested that the last movement on this fault occurred less than 3700 years ago. On a trench across the Orosi fault in Cartago, Costa Rica, the most significant finding was a set of fractures cutting all the soil units and suggesting normal dip slip, down to the east. The fractures coincide with the steepened facet of the break in slope on the colluvial fan (Woodward-Clyde, 1993).

The NW-striking Frailes-Belohorizonte-Escazu fault zone extends 30 km. The fault zone is marked by scarps, slope changes, and offsets of aligned stream channels and divides. According to Fernandez and Montero (2002) this fault system combines dextral and uplift movement and consists of discontinuous fault traces.

The Guapiles-Siquirres fault runs along the base of the Central Volcanic Range, and therefore, marks the boundary between that range and the Caribbean plain. It is a combination of two continuous reverse faults, Guapiles in the North and Siquirres-Matina in the South (Denyer et al., 2003). Soulas (1989) proposed that the Siquirres-Matina fault is the prolongation of the North Panama Deformed Belt within the territory of Costa Rica. The Guapiles-Siquirres fault is characterized by high topographic relief with uplifted terraces and deep-narrow river valleys over much of its length (Soulas, 1989). Linkimer (2003) extends this large fault to Aguas Zarcas de San Carlos (not shown) for a total distance of 150 km.

Neither the strike-slip fault proposed by Astorga et al. (1989) nor the set of subparalel strike-slip faults suggested by Fan et al. (1993) were found in the studied area. The trace of the strike-slip tectonic boundary suggested by Jacob et al. (1991), Fisher et al. (1994) and Marshall et al. (2000) neither was found within the Central Valley of Costa Rica. The most important east-west faults, the faults required by the hypothetical strike-slip tectonic boundary, of the Central Valley are Aguacaliente and Alajuela. The first one shows a component of normal slip and the second is a tipical reverse fault that connects with the Garita fault whose slip is normal.

5. Seismicity

5.1. Historical seismicity

Well-documented historical earthquakes data from 1700 to 2006 have been analyzed in this work to understand the seismicity of central Costa Rica. Our catalog contains 15 events (Table 1), 7 of which occurred in the Poas Volcano seismic zone, one near Irazu volcano, one west of the city of Heredia and 6 south of the Central Valley. Figure 5 shows a well-defined cluster at the western end of the Central Volcanic Range (Poás volcano area) and another at the northern flank of the Talamanca Range (south of the Central Valley).

No.	Name	Latitude	Longitude	Year	Magnitude	Seismic Zone
1	Barva earthquake	10.1000	-84.2000	1772	5.6	Poás
2	Cartago earthquake	09.8250	-83.9300	1834	5.2	South of Central Valley
3	Alajuela earthquake	09.9500	-84.2670	1835	5.8	Puriscal
4	Cartago earthquake	09.8416	-83.9100	1841	5.8	South of Central Valley
5	Alajuelita earthquake	09.8300	-84.1000	1842	5.4	South of Central Valley
6	Fraijanes earthquake	10.1380	-84.1840	1851	5.5	Poás
7	Fraijanes earthquake	10.1380	-84.1830	1888	5.8	Poás
8	Tablazo earthquake	09.8166	-84.0333	1910	5.2	South of Central Valley
9	Cartago earthquake	09.8416	-83.9100	1910	6.4	South of Central Valley
10	Toro Amarillo earthquake	10.2333	-84.3000	1911	6.1	Poás
11	Sarchí earthquake	10.1916	-84.2750	1912	6.2	Poás
12	Tres Ríos earthquake	09.8666	-84.0000	1912	5.2	South of Central Valley
13	Paraíso earthquake	09.8083	-83.8800	1951	5.2	South of Central Valley
14	Patillos earthquake	10.0250	-83.9083	1952	5.5	Irazú
15	Toro Amarillo earthquake	10.2333	-84.3166	1955	5.8	Poás

Table 1. Historical earthquakes in Central Costa Rica (Rojas, 1993)

The historical seismic data correlate well with previously identified faulting. For instance, at the Poas seismic zone 5 earthquakes are located along the northwest-trending faults that border the volcano from south to west (Figure 5). It is quite probable that the Carbonera and Viejo faults were responsible for the Bajos del Toro (1911, 1955) and Sarchi (1912) earthquakes. The damage zones described for the Fraijanes earthquakes (6 and 7 on Figure 5) suggest that the source could be the Angel fault. To the southeast, the epicenters of historical earthquakes are located on the periphery of the Talamanca Cordillera, where most form an alignment along the Aguacaliente fault (the Cartago earthquakes of 1834, 1841 and 1910 and the Tres Rios earthquake of 1912). The 6.4 Ms Cartago earthquake (1910) and the 5.2 Ms Tres Rios earthquake (1912) appear to be in the same seismogenic context; the 1910 event possibly strained the northwest segment of the Aguacaliente fault and, two years later the accumulated strain was released originating the Tres Rios earthquake. A similar situation could have happened at Poas when Sarchi earthquake followed the 1911 Bajos del Toro earthquake.

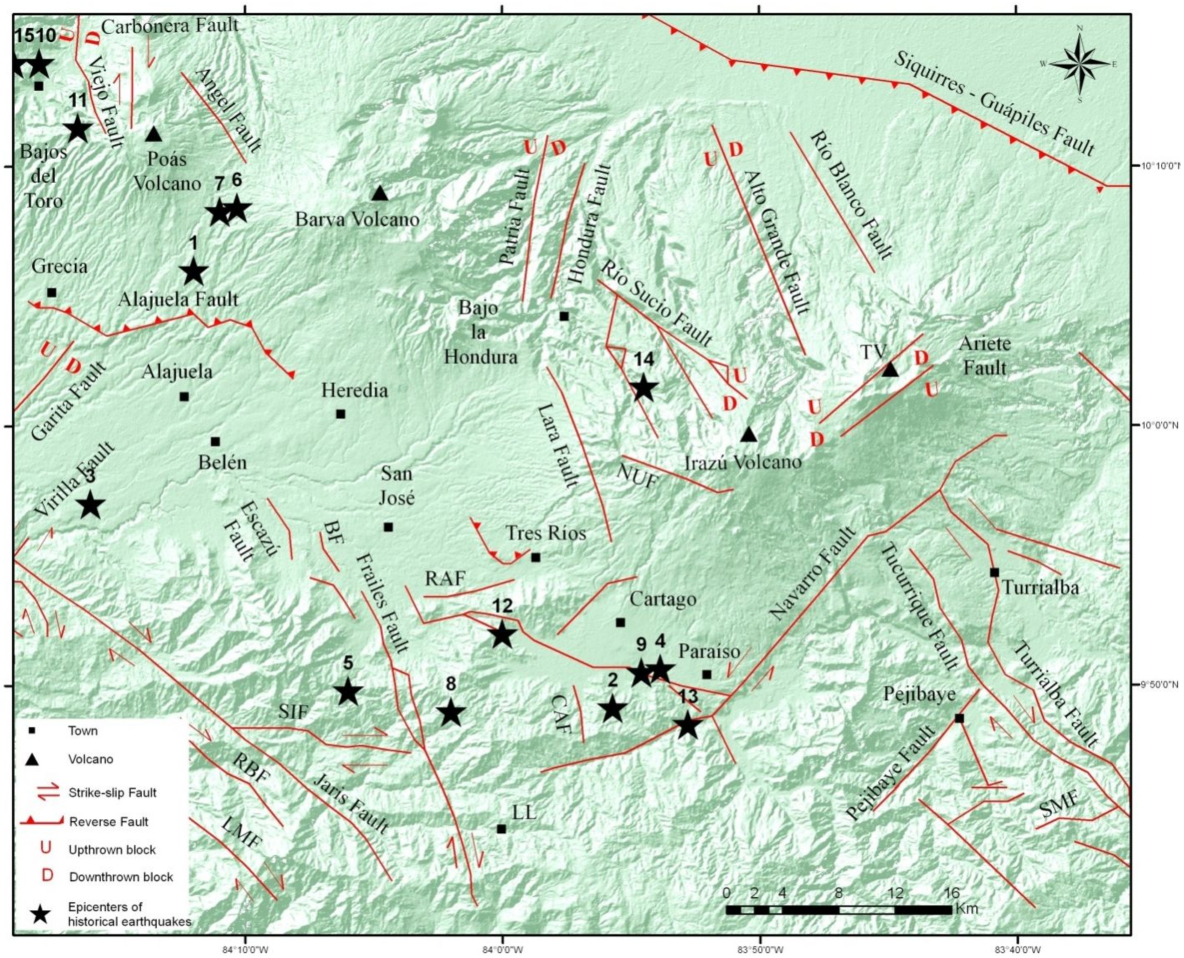

Figure 5. Map showing the historical earthquakes in Central Costa Rica. Stars mark the epicenters of historical earthquakes of the last two centuries. The number near each star is the number of the event in Table 1.Earthquakes 4 and 9 and 6 and 7 share the same epicentral area, respectively. Triangles indicate volcanoes. AF: Aguacaliente Fault, PF: Picagres Fault, BF: Belohorizonte Fault, RAF: Río Azul Fault, SIF: San Ignacio Fault, RBF: Resbalon Fault, LMF: La Mesa Fault, CIF: Cipreses Fault, NUF: Nubes Fault, CAF: Cangreja Fault, SMF: Simari Fault, ATF: Atirro Fault, PCF: Pacuare Fault, LL: La Lucha, SP: Santiago de Puriscal.

Additional strong evidence for the correlation between historical earthquakes and faulting comes from isoseismal maps. Montero & Morales (1988) found elongated intensity contours that clearly surround the known source of these events. For the Cartago, Tres Rios and Fraijanes earthquakes, the contoured intensity distributions relate the earthquakes to northwest-trending faults, suggesting that the Angel and Aguacaliente faults participated in the generation of those events. Bajos del Toro, Sarchi and Patillos events have northeast-trending damage areas that disagree with the fault orientation; in these cases the lack of reports northward the source could affect the geometry of the isoseismal map.

This historical seismicity is considered upper-crustal seismicity by White (1991) and White & Harlow (1993). The later authors pointed out that upper-crustal earthquakes are spatially distributed along the volcanic front of the whole of Central America; they appropriately called them volcanic-front earthquakes and stated that these earthquakes pose the greatest hazards for the population.

A final remark about this seismicty deals with its connection with large Costa Rican earthquakes. Upper-crustal destructive earthquakes of central Costa Rica in the last one hundred years coincided with large earthquakes that took place in the country. In 1904, a 7.2 Ms magnitude subduction earthquake happened in southern Costa Rica and also 6.8 Ms event southwest of the Central Valley, and five years later the Cartago (1910), Tablazo (1910), Bajos del Toro (1911) and Sarchi (1912) earthquakes occurred in Central Costa Rica. Similarly, in 1950 the largest earthquake reported in Costa Rica occurred, a 7.7 Ms magnitude subduction event that was followed by the Paraiso (1951), Patillos (1952) and Bajos del Toro (1955) earthquakes. These data suggest that destructive events of central Costa Rica may represent seismicity triggered by large subduction events.

All of this evidence suggests that historical earthquakes did not occur randomly, and moreover, they did not form any lineament in an east-west direction that supports the existence of a tectonic boundary with that orientation in central Costa Rica. Those events are clearly associated with faults that have been recently mapped.

5.2. Instrumental seismicity

The epicentral distribution of 865 shallow earthquakes (0-30 km) recorded by RSN during the period 1992-2009 is plotted in Figure 6. This shallow seismicity is not uniformly distributed over the study area, that is, there are seismic clusters separated by zones of low level seismicity. On a rough scale, the seismicity of Talamanca is higher than the seismicity of the Central Volcanic Range. In the Central Valley the seismicity has the lowest rate for the whole area.

The volcán Irazu is a zone of seismic swarms that resemble volcano/tectonic. According to Fernández et al. (1998) there have been seismic swarms at Irazu in 1982, 1991, and 2007. The pattern of these swarms is a large number of very small earthquakes with few moderate events of magnitude 4 or so, but no clear mainshock larger than the other events. They have occurred on short fault of the zone, especificaly on Elia, Ariete and Nubes.

At the Bajo de la Hondura, a trough between the Irazu and Barva volcanoes, scarce but permanent seismicity has been recognized. It is a seismicity of magnitude smaller than 5. One of the recent major events was the magnitude 4.4 earthquake that occurred there on August 21,1990, at 13 km depth. The main sources of this activity are the Hondura, Patria and Lara faults.

The seismic activity at Poas is mainly composedd of swarms and sporadic strong earthquakes. The swarm activity consists, like the Irazu activity, of a hundred of small earthquakes generated during one or two months. Fernandez et al. (in prep.) have recognized seismic swarms at Poas in 1980, 1990 and 1999 According to their location, the last swarms at this area was generated by Carbonera and Angel faults. A strong 6.2 Mw magnitude earthquake hit the zone on January 8, 2009 killing 25 people and destroying many houses, several bridges and the route to Cinchona. In adition, the earthquake triggered many landslides in the epicentral area. As a consequence of such earthquake the village of Cinchona (Figure 7) had to be reubicated. The economic losses from the destructive earthquake are estimated in $492 million (Laurent,

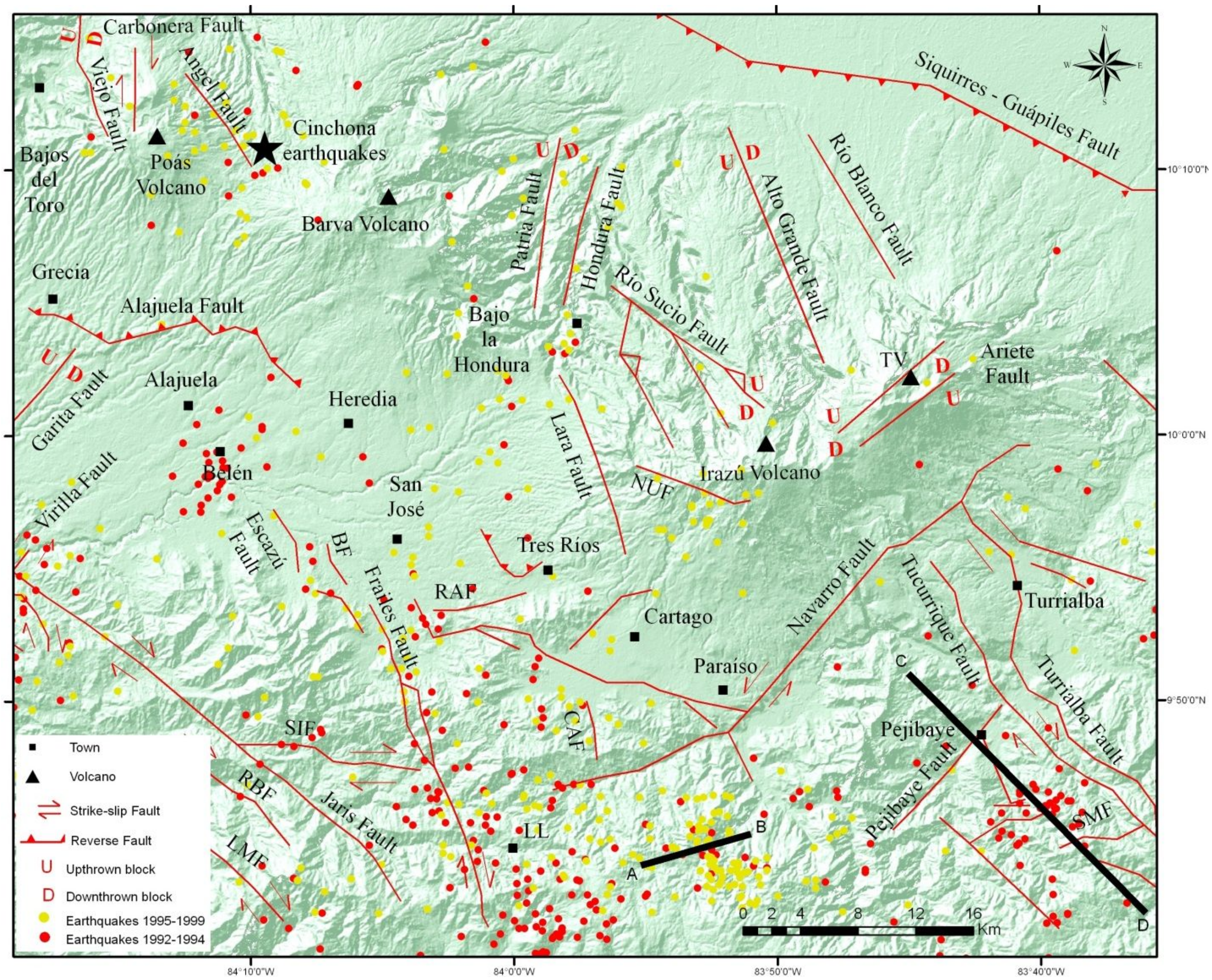

Figure 6. Shallow (0-30 km) seismicity of Central Costa Rica from 1992 through 2009. Several clusters represent the most important seismic zones in the studied area. Crosses are seismic event for the 1995-2009 period. Diamonds are earthquakes located by Fernandez (1995) and black circles represent earthquakes located by Fernandez (2009). Lines A-B and C-D indicate traces of cross sections. AF: Aguacaliente Fault, PF: Picagres Fault, BF: Belohorizonte Fault, RAF: Río Azul Fault, SIF: San Ignacio Fault, RBF: Resbalon Fault, LMF: La Mesa Fault, CIF: Cipreses Fault, NUF: Nubes Fault, CAF: Cangreja Fault, SMF: Simari Fault, ATF: Atirro Fault, PCF: Pacuare Fault, LL: La Lucha, SP: Santiago de Puriscal.

2009). The event was located in the eastern flank of the volcano at 4 km deep and was generated by the Angel fault.

In the Talamanca Cordillera the seismicity is spread all over the area but there are also dense clusters at Pejibaye, south of Cartago and Santiago de Puriscal (Figure 6). Two of these clusters correspond with isolated seismic sequences (Pejibaye and Puriscal) and the other one with a zone of permanent seismicity (La Lucha).

The Pejibaye July 10 1993 (Mc = 5.3) earthquake, together with the Mc = 4.9 July 8 foreshock two days before and the Mc = 4.8 aftershock three days later represent the most extensive and well-recorded seismic sequence in the eastern part of central Costa Rica (Fernandez, 2009). These earthquakes and many aftershocks occurred within a small area of northwest and northeast-trending faults. The event's depths are relatively shallow and can be associated with Simari fault which, according to focal mechanisms, is strike/slip with a high normal component.

Figure 7. The village of Cinchona after the 2009 Cinchona Earthquake. The earthquake changed the geography of the area. Courtesy of Joanna Mendez.

Puriscal was a quiet seismic zone before 1990 but in that year there began one of the highest concentrations of seismic activity of Costa Rica in recent decades. This activity was triggered by a large earthquake from the Pacific Coast. Thousands of micro earthquakes were generated in Puriscal in the December 1990-June 1991 period, almost 30 events of Mc > 4.0 and the main event of Mc = 5.7, the Piedras Negras earthquake.

La Lucha is the most seismically active zone in central Costa Rica, however a large percentage of its present-day seismicty is microearthquake activity (Mc < 3.0). Although the epicentral distribution is diffuse, a northwest trend can be recognized, and this trend is in good agreement with that of the Frailes Fault. The main structural features associated with La Lucha seismicity are Frailes and Navarro faults.

While the Central Volcanic and Talamanca Ranges have significant seismicity (Fernandez, 1995; Fernandez et al., 1998) the number of recorded earthquakes and their magnitudes reflect very little activity within the Central Valley. During more than 20 year of records, the background microseismicity of this valley is represented as scattered low-level activity (Fernandez, 1995). The best known and well- defined concentration of earthquakes in the valley is in Belen and seems to be associated with the Escazu fault. A more recent manifestation of seismicity has been observed in the metropolitan area of San Jose in the last 5 years; it consists of 2 < Mc < 4 earthquakes whose epicenters appear to define a NW-striking lineation that coincides with the northwest end of the Rio Azul and Aguacaliente faults. In the southern border of the central valley there are seismic sources with relatively high rates of seismicity such as the Escazu and Aserri faults, both related to the Frailes-Belohorizonte Escazu fault system. The Aguacaliente fault, responsible for the 1841 and 1910 Cartago earthquakes, has had little activity in the last three decades.

In an effort to see if earthquakes define faults, seismicity cross-sections were carried out in the studied area. Due the low number of earthquakes in some cases and the nearness between faults in other cases only two seismic cross sections were calculated, one at the Pejibaye seismic zone and other eastward of La Lucha. In the cross section A-B (Figure 8a) the hypocenters seem to define a inclined plane that dips 75° northeast, which suggests that a high-angle fault is the responsible for this seismic activity. The cross section C-D (Figure 8b) reveals that the dense seismicity cluster along the Pejibaye seismic zone is generated by an almost vertical fault. Fernandez (2009) reported a fault dipping 76° northwest as the cause of this seismicity.

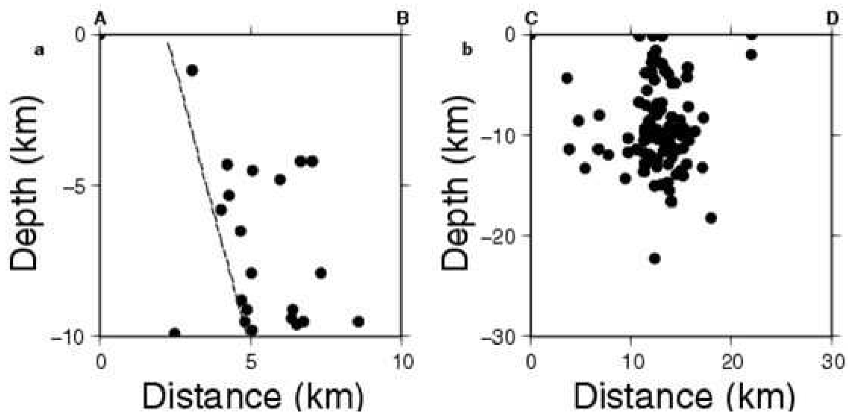

Figure 8. Seismic cross sections A-B and C-D outlined in Figure 6.

5.3. The seismic anomaly of Central Costa Rica

Recent earthquake epicenters from 1992 through 2009 were plotted on a map of Costa Rica in order to show the characteristic local pattern of seismicity that is possibly associated with tectonic features. The plot displays a wide zone of high subduction and crustal seismic activity in Central Costa Rica which coincides with a diffuse zone rather than with a narrow longitudinal area (Fernández et al., 2007). The seismicity forms an anomalous big cluster composed of smaller clusters (Figure 9) but despite the considerable concentration of earthquakes, epicenters of either the big or smaller clusters fail to delineate any large and single NE or EW fault plane.

To know whether or not the seismicity pattern is related to a hypothetical strike-slip tectonic boundary, we examined the depths of the earthquake clusters. We would expect shallow seismogenic source locations for a strike-slip tectonic boundary but deep (greater than 30 km)

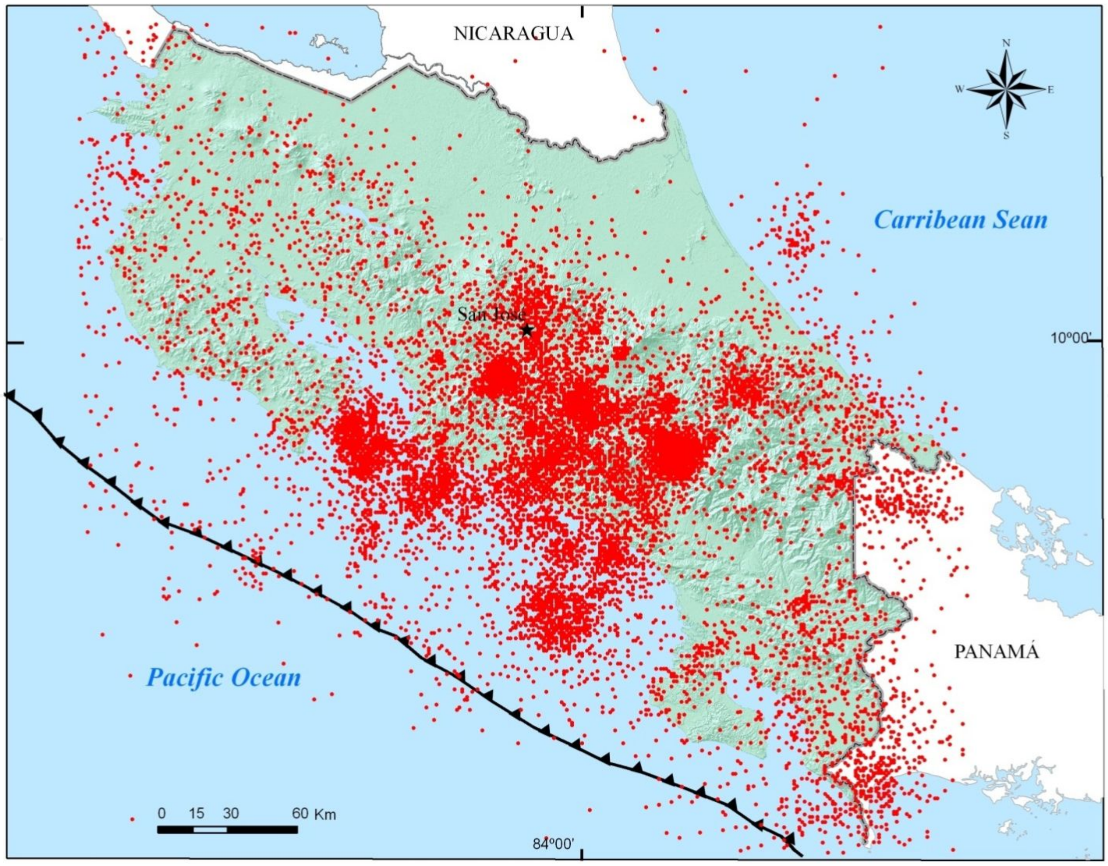

Figure 9. Background seismicity in Costa Rica from 1992 through 2009. Circles are earthquakes. Several clusters represent the most important seismic zones of Costa Rica. The sum of these clusters generates a zone of concentrated seismicity in Central Costa Rica. MAT: Middle American Trench.

source locations for subduction zone earthquakes. Because 80% of the present-day seismicity of Central Costa Rica is shallow, we expect earthquake concentrations to be above a subduction decollement.

To test whether the seismic origin is in the subduction zone or from a much shallower transform fault earthquakes with depths in the range of 30–90 km were plotted at intervals of 10 km (Figure 10). Costa Rican earthquakes are distributed over all depths with deeper clusters to the northeast. The cluster in figure 8a approximately coincide with the results of DeShon et al. (2003) who found that earthquakes occur above 30 km depth, 95 km from the trench offshore Central Costa Rica. Our results suggest a source for the anomaly related to the subduction process, perhaps subducted seamounts on the Cocos plate that generate larger stress fields than nearby smooth subducted areas of the same plate, causing the high intraplate and interplate seismicity in central Costa Rica. Bilek et al. (2003) stated that shallow, smaller-magnitude seismicity is more common in regions of seamounts subduction than in the smoother region subducting off northern Costa Rica, suggesting that subduction of topographic highs localizes seismicity. Von Huene et al. (2004) indicate that subducted seamounts appear to remain attached to the underthrust plate more than 100 km landward of the trench axis as indicated by clustered earthquakes beneath the shelf and local uplift along the coast.

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This is in excellent agreement with our results, which support the seamount domain of Central Costa Rica as the cause of the seismic anomaly.

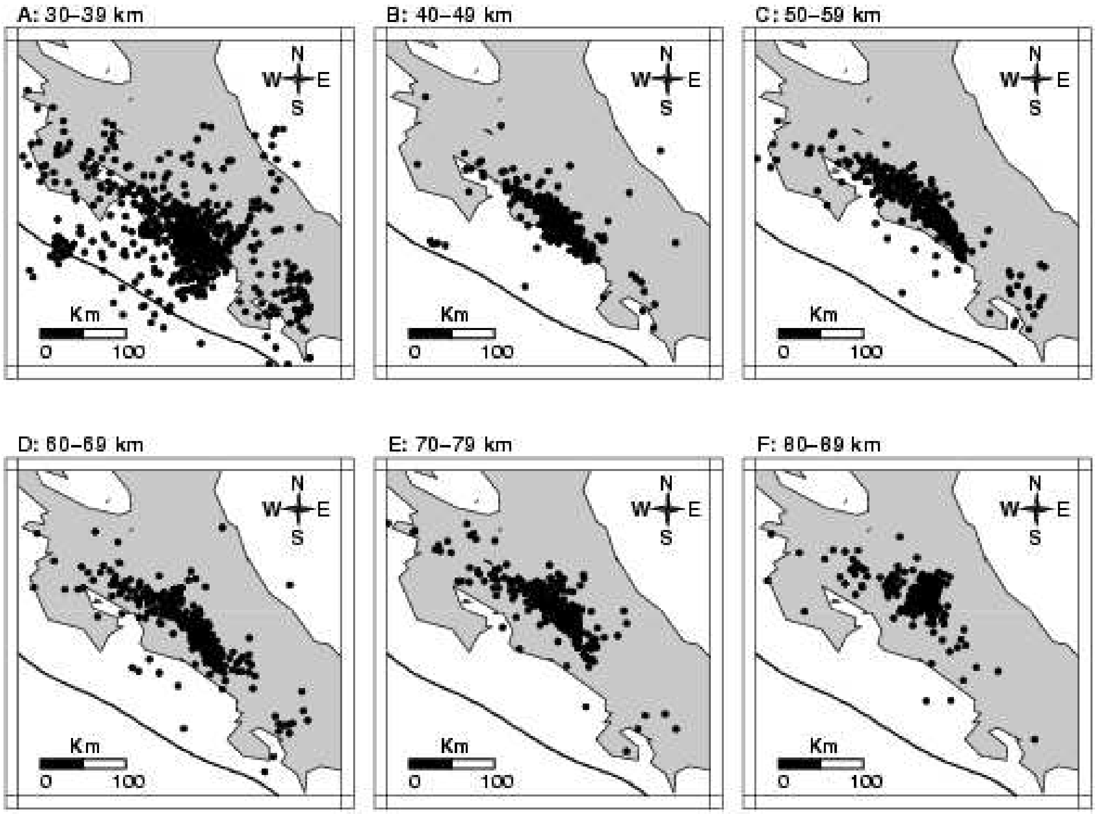

Figure 10. Cumulative numbers of located earthquakes, separated into six depth ranges, within or near the Costa Rican territory. These graphs plot earthquakes detected and located by the Red Sismologica Nacional (RSN: ICE-UCR) from 1992 to 2009. Depth ranges are in km.

Figure 11 shows a set of seamounts on the Cocos plate between the Fisher mounts and the Quepos plateau. The seamounts form a subducting rough zone that collides with the Caribbean plate generating stress, deformation and weakening of the continental crust. Onshore, in front of this zone is the seismic anomaly of Central Costa Rica. The ocean bottom in the Cocos plate between Quepos plateau and Cocos Ridge is almost flat and the seismic level in front of this rectangular area is relatively low (Figures 11). These facts also suggest that sea mounts play an important role in generating seismicity in Costa Rica. They apparently increase intraplate and interplate earthquakes onshore and therefore, in absence of them the seismic activity in Central Costa Rica would probably be lower than the current activity.

6. Focal mechanisms

P-wave first motion is used to determine focal mechanism solutions. However, first-motion observations will frequently be in the wrong quadrant because of incorrect first-motion

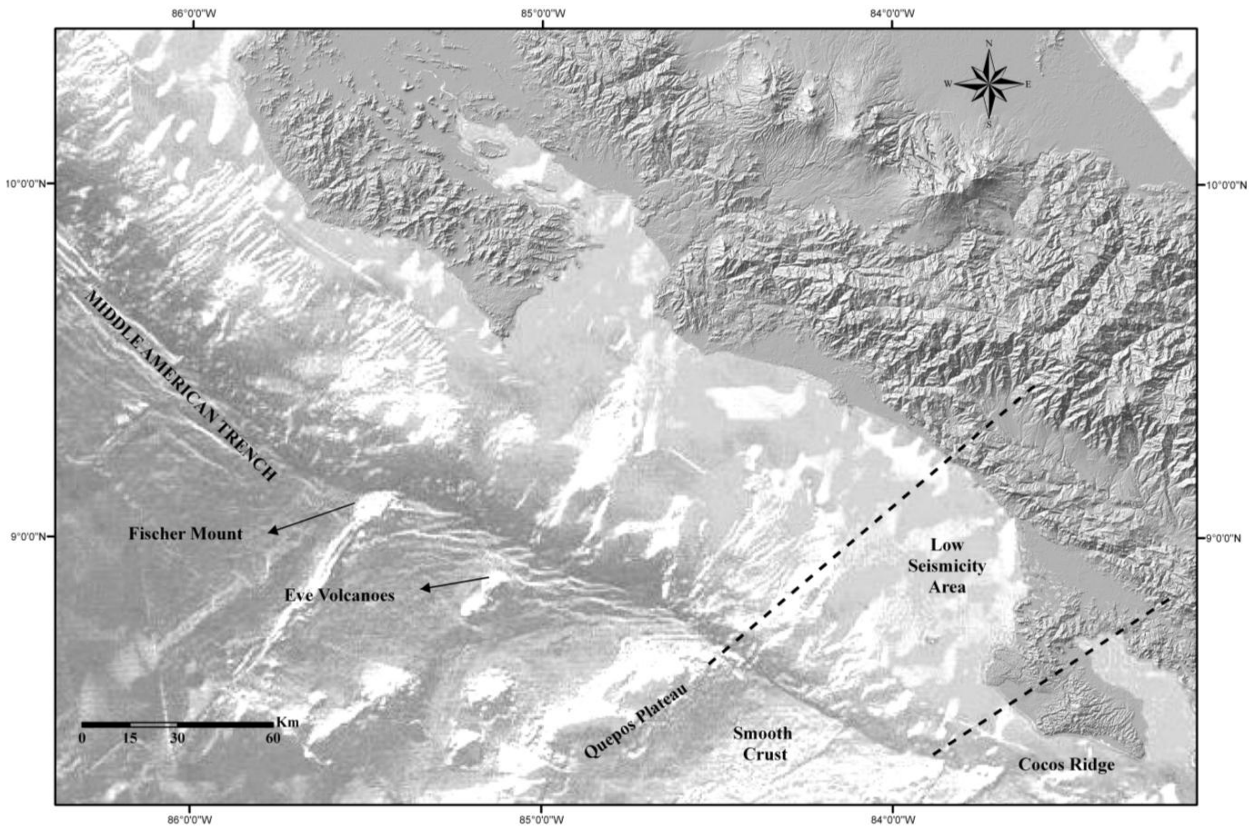

Figure 11. The Cocos-Caribbean tectonic boundary in front of the Costa Rican Pacific coast is the Middle American Trench. Large seamounts (Fisher Mount, Eve volcanoes, Quepos plateau) are being subducted under the Caribbean plate just in Central Costa Rica. This process causes high stress and seismicity. From Ranero and von Huene, 2000.

direction, inappropriate earthquake velocity model, station polarity reversals and incorrect direct P-arrival picks due to low signal-to-noise ratios. The method requires enough data to ideally determine fault-plane solutions. Few data or incorrect first motion observations may generate more than one or many focal mechanism solutions and changes in the earthquake location or in the seismic velocity model can significantly affect the distribution of observations on the focal sphere, changing the best-fitting focal mechanism solution. Low magnitude earthquake and seismometers locates near the nodal planes between the compressional and dilatational quadrants of an earthquake do not produce strong first motions which made difficult to determine focal mechanisms.

Because the studied area is characterized by microseismicity and truly few intermediate-magnitude earthquakes, it is really difficult to obtain a large number of reliable focal-plane solutions in central Costa Rica. After a strict selection of seismic events of the last 18 years, we only found 16 reliable focal mechanisms (Table 2, Figures 12 and 13). They show considerable variation in the sense of motion which probably reflects movement on preexisting planes of weakness that are geometrically favorable for slip but not necessarily aligned with a plane of maximum shear stress. The events exhibit reverse, normal and strike-slip faulting.

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Number	Date	Latitude	Longitude	Mag	Depth	RMS	EH	EZ	AZ	Dip	Rake
1	90/12/22	09.883	-84.334	5.7	14.6	0.28	0.7	1.7	252.5	63.0	30.7
2	92/11/02	09.887	-83.766	3.4	06.2	0.21	0.4	0.7	060.3	72.8	-58.4
3	92/11/03	09.921	-84.138	4.1	06.5	0.30	0.6	0.9	269.0	40.0	58.0
4	92/11/12	09.745	-84.013	3.5	16.8	0.27	0.7	2.1	097.6	51.1	145.6
5	93/01/20	09.979	-84.183	3.7	11.6	0.35	0.8	2.0	230.0	90.0	45.0
6	93/05/07	09.705	-83.767	3.7	03.8	0.28	0.6	0.8	236.9	56.4	-10.3
7	93/07/09	09.756	-83.615	4.3	12.6	0.30	3.2	4.8	239.6	68.5	-57.5
8	93/07/10	09.776	-83.686	5.3	12.8	0.31	2.2	3.2	262.37	75.9	-32.4
9	93/07/13	9.735	-83.615	4.9	12.4	0.22	3.0	2.9	240.5	43.9	-22.2
10	93/07/14	09.701	-83.809	3.9	06.7	0.59	0.8	2.0	224.9	45.9	-76.0
11	94/01/11	09.812	-84.142	3.5	16.8	0.21	0.6	1.1	110.4	65.4	79.0
12	94/10/29	09.867	-84.064	3.3	06.6	0.30	0.7	0.5	253.0	84.0	-40.0
13	96/05/23	09.850	-83.988	3.1	11.4	0.36	0.7	2.0	097.0	74.0	-53.0
14	96/05/26	10.090	-83.660	4.0	14.9	0.40	2.2	3.6	210.0	50.0	-90.0
15	99/07/18	10.206	-84.228	3.2	04.8	0.31	1.0	0.5	359.0	66.1	-26.3
16	09/01/08	10.194	-84.177	6.2	03.6	0.60	2.6	2.6	025.0	47.5	-37.0

Note. Mag.: Magnitude, RMS: root-mean-square, EH: horizontal error, EZ: vertical error, AZ: Azimuth.

Table 2. Parameters of focal mechanisms.

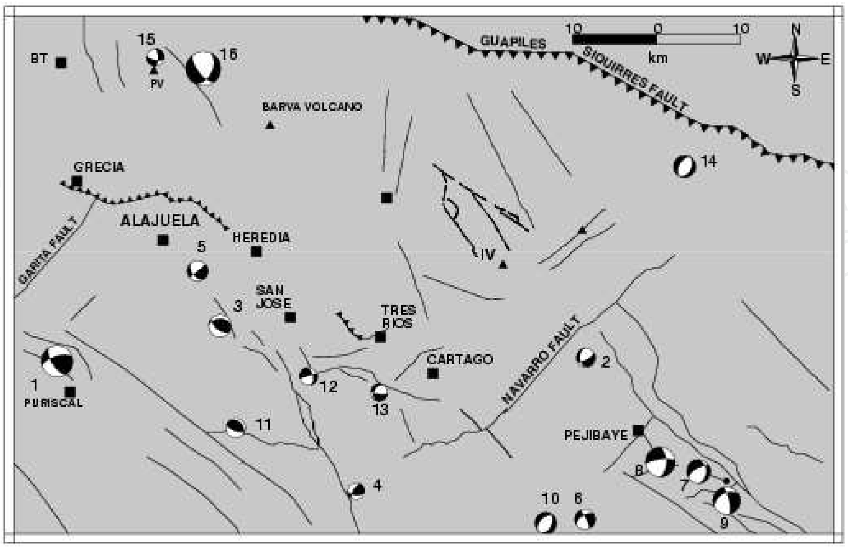

Figure 12. Faulting and focal mechanisms. Small lettered stereo projections are fault-plane solutions for 16 carefully selected earthquakes. BT: Bajos del Toro, PV: Poas Volcano, IV: Irazu Volcano.

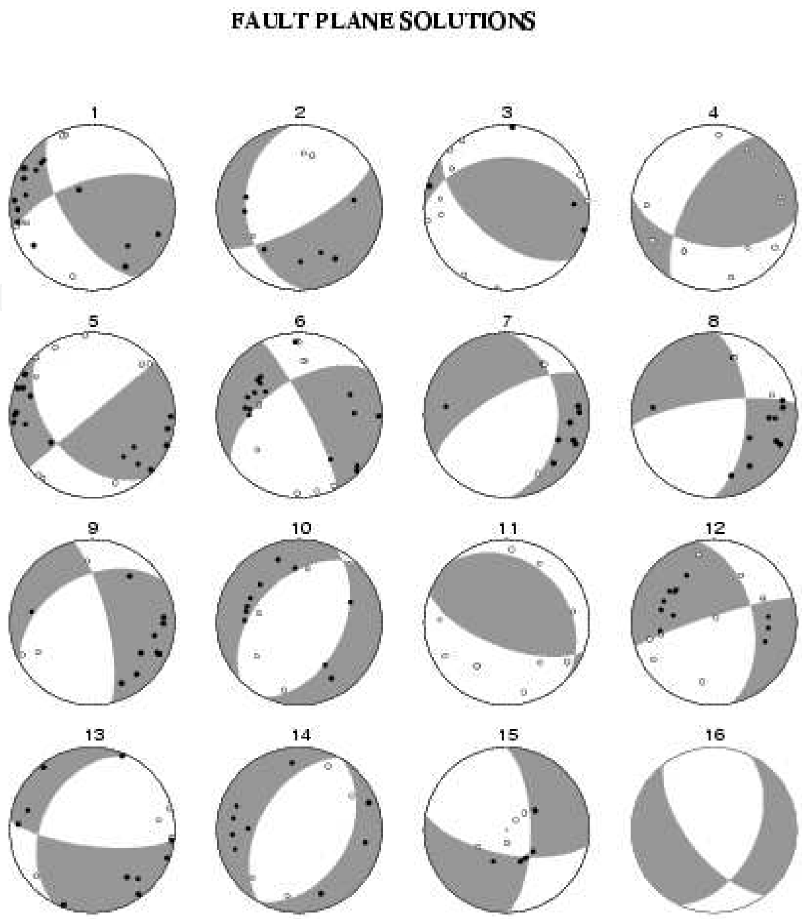

Figure 13. P-wave first motion focal mechanisms, determined using pspolar routine of GMT (Graphic Mapping Tools). In all cases more than 9 P-wave polarities were used. Open circles represent downward first motions, black circles represent upward first motion.

Focal mechanisms near Pejibaye (6, 7, 8, 9, and 10) show nearly normal-slip along planes striking northeast, suggesting a possible association with a northeast-trending faults. At Puriscal, the fault-plane solution (1) is strike-slip with reverse component. That solution indicates right-lateral motion along the northeast striking nodal plane. Based on the destruction near Alajuela associated to the correspondent earthquake Montero (2001) chose that plane as the fault plane and proposed the Virilla fault as the responsible for the earthquake. However, the strike of the selected nodal plane is close to the orientation of the Picagres fault.

Fault-plane solutions for events from Frailes-Escazú faults (3, 4, 5, 11, 12) show thrust and strike-slip motion with a strong reverse component (3, 4, 11). These solutions suggest northwest striking faulting, in good agreement with the strike of the mapped faults. Event 13 suggests a high normal component along the Aguacaliente fault. When resolvable, the focal mechanisms of small to moderate sized earthquakes (M< 4.5) in the Poas area show predominantly strike-slip motion (15, 16). The fault-plane solution for the 2009 Cinchona earthquake (16) is oblique with high normal component (Rojas et al., 2009).

Another important limitation to obtain more and better focal mechanisms in Central Costa Rica is the instrumentation used to detect them. We are still using short period, one component seismic sensors to detect and locate the seismicity. Due to this, the resolution of the strike for the occurring mechanisms depends on the readings at only few stations in many cases. In the future it would be more appropriate to compute the focal mechanisms using waveform inversion (Dreger & Helmberger, 1993; Zhu & Helmberger, 1996; Herrmann et al., 2008; D ´Amico et al., 2010; D´Amico et al., 2011).

7. Discussion

The faulting, high seismicity and strike-slip focal mechanisms do not define a consistent east-west shear zone in central Costa Rica. Strike-slip deformation in central Costa Rica is interpreted as a result of the elastic strain accumulation in the upper plate due to the subduction of seamount domain and Cocos Ridge under the Caribbean Plate. The fault orientation may reflect the northeast movement of Cocos plate, stresses caused by the subduction of sea mounts, and the compression of the Cocos Ridge in southern Costa Rica, where the rate of convergence between Cocos and Caribbean plates is maximum (DeMets, 2001). This high rate and the south-north sliding of the Cocos plate along the Panamá Fracture Zone could be creating a favorable environment to form northwest lateral tears (as Frailes, for instance).

White & Harlow (1993) studied the destructive shallow earthquakes in Central America and found a concentrated seismicity in the volcanic front. According to them, this volcanic front is a zone of dextral strike-slip driven by oblique subduction. Large earthquakes as that of Managua in 1972 and Tilarán in northern Costa Rica in 1973 were strike-slip earthquakes. These data indicate that strike-slip motion within the Caribbean Plate is not concentrated in Costa Rica but it is present all over Central America (Quintero & Guendell, 2000)

Fan et al. (1993) proposed that left-lateral strike-slip motion in central Costa Rica occurs on various sub-parallel strike-slip faults that comprise a diffuse northeast-southwest strike-slip fault zone. This is inconsistent with Astorga et al. (1989, 1991) who proposed an east-west trend for the fault system of Central Costa Rica. But the proposal of Astorga et al (1989, 1991) is not supported by the data described here.

Fischer et al. (1994) stated that the seismicity after Cóbano (1990) and Limón (1991) earthquakes are constrained in a diffuse zone of faulting oriented west-east along the Central Valley of Costa Rica and that the variety of faults may reflect an early stage of a developing shear zone. In this work all currently mapped faults and lineaments are included and we find the same faulting pattern that Arias & Denyer (1991) attribute to a north-south compression that affects Costa Rica since late Miocene-Pliocene. The distribution of earthquakes and focal mechanisms indicate that seismic activity occurs on both northeast and northwest trending faults. Therefore, the seismicity mentioned by Fisher et al. (1994) is not likely to be due to incipient faulting but to preexistent faulting reactivated by the collision of Cocos Ridge with the Caribbean Plate (Denyer & Arias, 1991) and by faults reactivated after large earthquakes.

Strike-slip deformation along plate boundaries is often distributed among several parallel faults (Brink et al, 1996) and shear zones are overprinted by numerous foliation-parallel brittle faults (Cunningham, 1996). Offset strike-slip faults may be connected by intervening pull apart basins but this geometric pattern is not well defined in Central Costa Rica. There are parallel faults but they do not follow a preferential direction and not all of the parallel faults are strike-slip in type. Observing the fault distribution and orientation near the Central Valley of Costa Rica, we see parallelism between the most important: Alajuela, Aguacaliente and Frailes-Escazu faults (northwest extreme). But the Alajuela Fault is a very well-known reverse fault and the Frailes-Escazu also seems to have a strong reverse component according to Denyer et al. (1993), Fernández & Montero (2002) and our results in this work. Focal mechanisms and an excaved trench suggest that in contrast the Aguacaliente fault has a significant normal component. If this is so, the central Valley of Costa Rica would not be a pull apart basin unless it represents a developed strike-slip fault system where strike-slip faults have gradually evolved into oblique thrusts or thrusts (Fuh et al., 1997).

Marshall et al. (2000) attributed the deformation of Central Costa Rica to the subduction of Cocos Ridge and the seamount domain and proposed an E-W deformation front that propagates northward into the overriding volcanic arc, as the tectonic boundary between the Caribbean plate and the Panama block. But even this deformed belt requires a set of EW strike-slip faults along its northern edge, located in the Central Valley of Costa Rica. However, the EW strike-slip faults, and therefore the EW strike-slip motion, are absent in the studied area and most active faults of that area are northwest. DeMets (2001) and Norabuena et al. (2004) estimated trench-paralell motion of the Costa Rican forearc to northwest at a rate of 7 and 8 mm/yr respectively. They suggest interseismic and post-seismic effects from forearc faults and the subduction interface, diffuse extension at the trailing edge of the forearc sliver, partitioning of slip between multiple forearc faults, northwest striking right-lateral strike-slip faults and vertical axis rotation of smaller blocks defined by short, northeast striking, left-lateral "book-shelf" faults as the multiple cause of the observed motion. In the same way, northeast motion could have multiple explanations.

Von Huene et al., (2003) assure that subducted seamounts are causing deformation and weakened of the upper plate which steepness the slope above them, generating great potential for tsunamigenic landslides. The sea mounts destroy the frontal prism and uplifts the continental crust. Since this result it is clear that subducted seamount play an important role in the deforming the upper plate in central Costa Rica.

8. Conclusion

There is a seamount domain off central Costa Rica and intense crustal deformation and high seismicity onshore, in front of this seamount domain. The deformation includes an x-pattern faulting in which both northeast and northwest faults are active and have high seismicity. Focal mechanisms of small-magnitude earthquakes show normal, reverse and strike-slip motion along some faults of the studied area. Most of the historical earthquakes, the largest earth-

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quakes of the zone, suggest northwest motion along the Viejo, Carbonera, Angel, Frailes and Aguacaliente faults.

The strike-slip fault of Costa Rica proposed by Astorga et al (1989) and the set of subparalel strike-slip faults suggested by Fan et al. (1993) were not found in the studied area. Neither the trace of the hypothetical strike-slip tectonic boundary, which according to Jacob et al. (1991), Fisher et al. (1994) and Marshall et al. (2000) cut the Central Valley of Costa Rica, was not found in that valley.

According to our data, there is no a clear and well defined east-west strike-slip fault system in Central Costa Rica that might represent a tectonic boundary. The anomalous deformation and seismicity of central Costa Rica is more related to the subduction of sea mounts than to the proposed hypothetical strike-slip tectonic boundary for Central Costa Rica.

9. Data and resources section

- Earthquake data were provided by the Red Sismologica Nacional (RSN) operated by the Costa Rican Electricity Company and the University of Costa Rica. They cannot be released to the public.
- Some plots were made using the Generic Mapping Tools version 4.2.1 (www.soest.hawaii.edu/gmt; Wessel and Smith, 1998).

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