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THE TOBOSI FAULT: SOURCE OF THE 2011–2012 TOBOSI EARTHQUAKE SWARM IN CENTRAL COSTA RICA

LA FALLA TOBOSI: FUENTE DEL ENJAMBRE SÍSMICO DE TOBOSI DEL 2011-2012 EN EL CENTRO DE COSTA RICA

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ABSTRACT: The Central Costa Rica Deformed Belt (CCRDB) is an ~100-km broad zone of deformation that marks the boundary between the Caribbean Plate and the Panama Microplate. From December 2011 to February 2012, an earthquake swarm took place in a portion of the CCRDB, near the town of Tobosi, 7 km southwest of the city of Cartago. In this study, data recorded by the National Seismological Network of Costa Rica (RSN: UCR-ICE) is used to relocate the earthquakes and calculate their focal mechanisms. Additionally, the tectonic geomorphology of the region is analyzed. The results show a transtension structure near the town of Tobosi, which comprises at least three faults, named: the Tobosi, Tablon, and Alumbre faults. It was found that the Tobosi fault is an active left-lateral strike-slip fault with a normal component and was the source of the Tobosi earthquake swarm.
Key words: Active fault, earthquake swarm, seismic hazard, Tobosi, Costa Rica, focal mechanisms.

RESUMEN: El Cinturón Deformado del Centro de Costa Rica (CCRDB) es una zona de deformación de ~100 km de ancho que representa el límite entre la Placa Caribe y la Microplaca de Panamá. Entre diciembre 2011 y febrero 2012 ocurrió un enjambre de sismos en un segmento del CCRDB ubicado en las cercanías del poblado de Tobosi, 7 km al suroeste de la ciudad de Cartago. En este estudio se utilizaron los registros de la Red Sismológica Nacional (RSN:UCR-ICE) para relocalizar los sismos y calcular sus mecanismos focales. Asimismo, se realizó un estudio de la geomorfología tectónica de la zona. Los resultados evidencian una estructura de transtensión compuesta por al menos tres fallas, llamadas: Tobosi, Tablón y Alumbre. Este estudio demuestra que la Falla Tobosi es una falla activa la cual presenta un movimiento de tipo sinestral con componente normal y fue el origen del enjambre de sismos de Tobosi.
Palabras clave: Falla activa, enjambre sísmico, amenaza sísmica, Tobosi, Costa Rica, mecanismos focales.

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INTRODUCTION AND TECTONIC SETTING

From December 9th, 2011 to February 28th, 2012, an earthquake swarm took place in Central Costa Rica near the town of Tobosi, ~14 km southeast from San Jose, the capital city of the country. On a regional scale, this earthquake swarm is located on a portion of the Central Costa Rican Deformed Belt (CCRDB), an ~100-km broad zone of deformation that represents the western boundary between the Caribbean Plate and the Panama Microplate (i.e., Marshall et al., 2000; Montero, 2001, Fig. 1A). Regionally, the Cocos Plate subducts underneath both the Caribbean Plate and the Panama Microplate. The CCRDB connects the Middle American Trench on the Pacific side to the North Panama Deformed Belt on the Caribbean (Fig. 1A). The CCRDB includes active faults and folds of diverse geometry, but in general three different domains can be recognized (i.e., Marshall et al., 2000; Montero, 2001). In the western domain, located in the Pacific forearc, faults are mainly of transtensive type striking northeast-southwest. In the central domain, located approximately in the inner volcanic arc, faults are mainly of strike-slip type with right lateral displacement along faults striking northwest-southeast and left lateral displacement along faults striking northeast-southwest. The eastern domain, in the Caribbean back arc, is dominated by transpression faults. The origin of the CCRDB could be related to the collision of the buoyant over-thickened Cocos Ridge, which drives both shortening and lateral scape of crustal blocks over a broad zone (i.e., Lewis et al., 2008; Montero et al., 2013).

In a more local scale, the Tobosi earthquake swarm occurs between two major well-known left-lateral strike-slip fault systems: Aguacaliente and Navarro (i.e., Montero, 2001; Fernández & Montero, 2002, Fig. 1B). Several historical damaging earthquakes have impacted Central Costa Rica, including the magnitude (Ms) 6.1 Cartago (Sta. Monica) earthquake on May 4th, 1910, which has been the most destructive earthquake in the history of Costa Rica (i.e., Montero & Miyamura, 1981, Fig. 1B).

The National Seismological Network of Costa Rica (RSN) is one of the entities that monitors the seismicity of the country. The RSN derives from an agreement between the Seismology and Volcanology Division of the School of Geology at the University of Costa Rica (UCR) and the Seismology Unit of the National Electricity Institute (Instituto Costarricense de Electicidad - ICE). The Seismology Laboratory at the UCR was founded in 1973 with a data catalogue that goes from 1976 to the present. During 2011 and 2012, the RSN ran a network of 62 permanent stations.

This paper describes the Tobosi earthquake swarm in terms of its time and space distribution and determines its tectonic source. These goals are accomplished by relocating earthquakes and calculating focal mechanisms using data recorded by the RSN and by analyzing the tectonic geomorphology of the region. Given the history of destructive earthquakes in central Costa Rica, studies of active faults in this area are relevant for determining seismic hazards for this region, where most of the population lives and most of the economic and industrial activities are concentrated.

METHODOLOGY

Earthquakes were selected from the RSN data catalogue. The earthquake search was performed using the following criteria: earthquakes occurring from December 9th, 2011 to February 28th, 2012 located in the Tobosi region, with at least ten P-wave phases and one S-wave observation, with good seismic station coverage (i.e., GAP < 180), and with a root mean square (RMS) of less than 0.5 s in the initial location. These earthquakes were recorded by 37 RSN stations, including sites from the permanent RSN network as well as temporal stations from ICE (figures 1A and 2A). These stations include both short period (Lennartz 3D Lite) and broadband sensors (Guralp). "La Lucha" (LCR2, Fig. 2A) was the nearest station to the earthquake swarm, located at ~8 km. On the other hand, the farthest station was located at the Rincon de la Vieja volcano (station GPS3), 189 km away from the

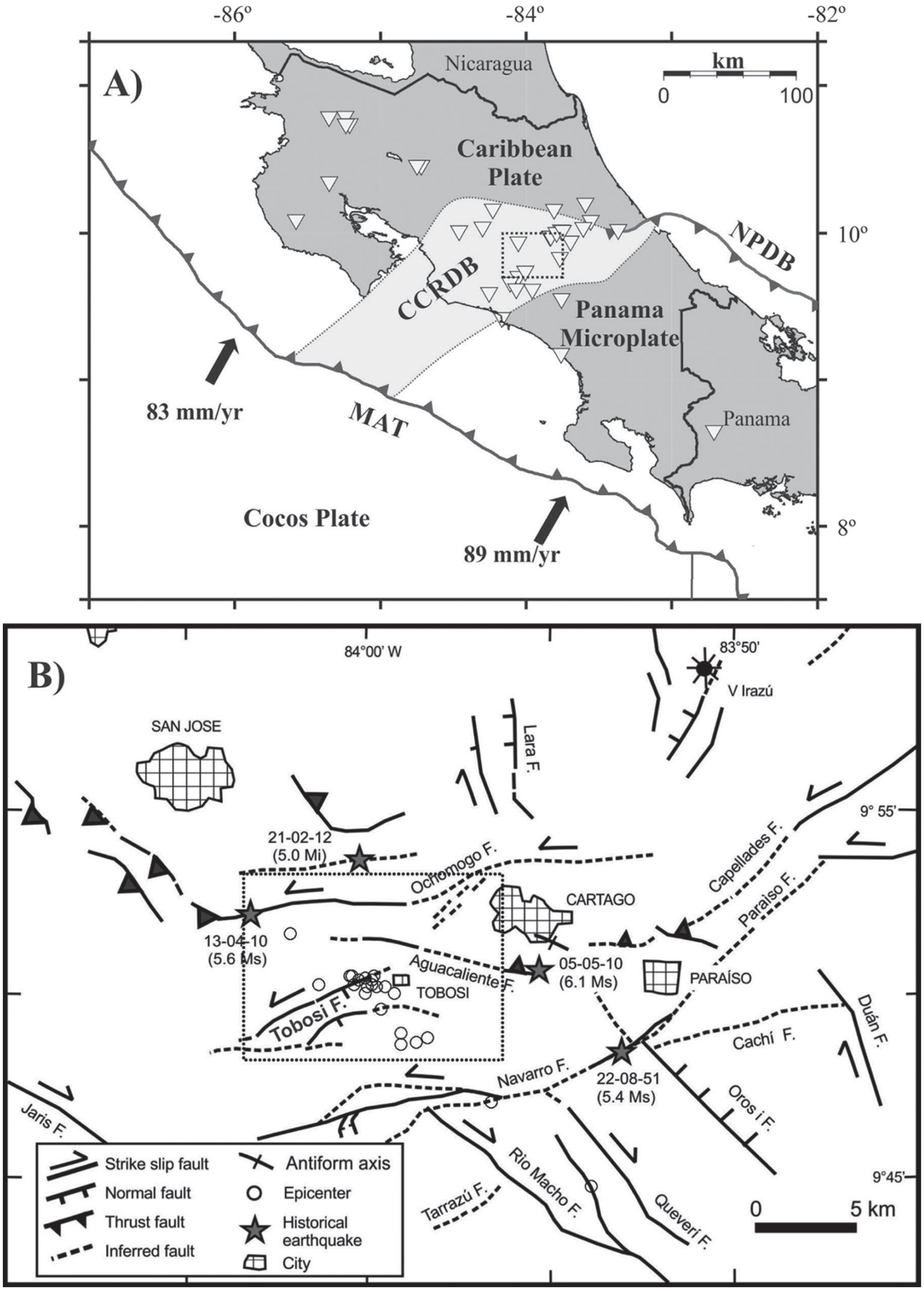

Fig. 1: A) Location and tectonic setting. Dotted line marks the area shown in Fig. 1B. White triangles represent seismic stations used in this study. Light gray area represents the approximate location of the Central Costa Rican Deformed Belt (CCRDB) based on Montero et al. (2013). B) Zoom to the study area. Tobosi swarm epicenters are shown as open circles and historical earthquakes as stars. Historical earthquake magnitudes are taken from Ambraseys & Adams (2001) and from Morales (1985). Ms means surface wave magnitude and Mi means magnitude calculated using intensity data. Dotted line marks the area shown in figures 4 and 7.

epicenters. Earthquakes were clearly recorded at stations located less than 70 km from the source (Fig. 2A).

The software package used for earthquake processing and analysis was SeisAn (Ottemöller et al., 2011), which is an open-source software commonly used in Central American Seismology institutions. The earthquake database managing and picking was performed by using the programs "eev" and "mulplt", respectively, both from the SeisAn package. The time window used for P-wave and S-wave picking was 5 and 10 s, respectively. P-wave arrival was usually very clear for the nearest stations to the source (Fig. 2B). A five-level weighting scheme was used for categorizing the uncertainty of the picks. Level zero corresponds to 100% pick confidence while level four corresponds to 100% pick uncertainty.

Earthquake locations were found using a seven-layer linear 1D model, used for routine locations at RSN, also based on the model proposed by Matumoto et al. (1977). The response files for each of the stations were built with an open-source software called PDCC (Portable Data Control Center) from Casey (2012). Additionally, first motion focal mechanisms were calculated using the FOCMEC (Focal Mechanisms Determinations; Snoke, 1984) program. Finally, field trips were conducted in the region to characterize the local Tectonic Geomorphology and to complement the earthquake analysis.

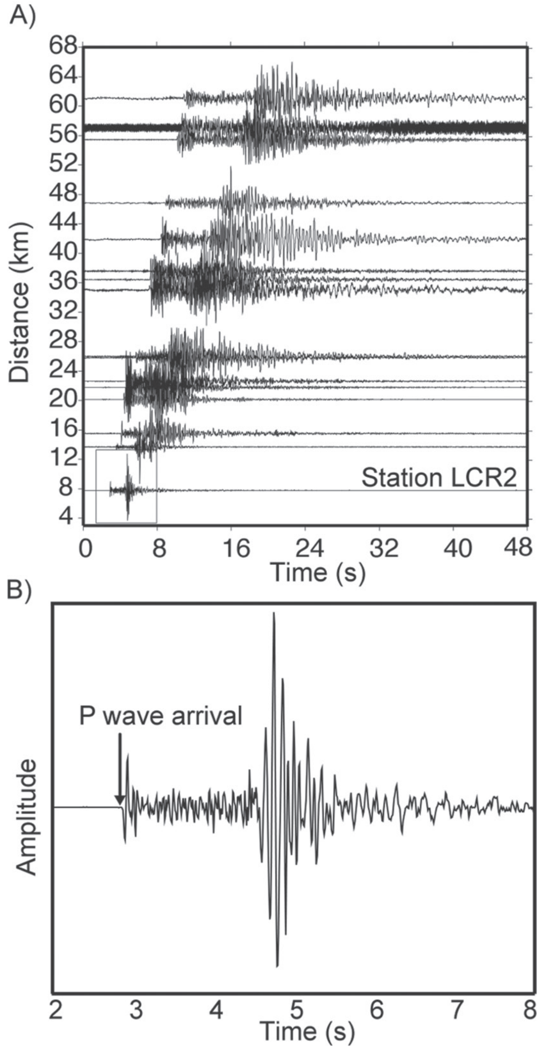

Fig. 2: A) Record section of an earthquake on December 23rd, 2011 (3.3 Mw) registered at stations located less than 70 km from the source. B) Zoom to the P-wave arrival at the nearest station LCR2 located 8 km from the source.

THE TOBOSI SWARM AND HISTORICAL EARTHQUAKES

Examining earthquake spatial and temporal distribution is fundamental to understand the physics of the earthquake source and cycle (i.e. Eneva & Hamburger, 1989). An earthquake swarm is defined as an increment of earthquakes in a limited area within a limited period of time, from several days, weeks or even months, and without connection to a main shock (i.e., Hill, 1977; USGS, 2004).

In the vicinity of the town of Tobosi, 22 earthquakes occurred from December 9th, 2011 to February 28th, 2012. Twenty of these earthquakes occurred within a time frame of 13 days. The swarm initiated in December 9th, 2011 with a 3.3 Mw earthquake and a depth of less than 1 km. Most of the events occurred between December 22nd and 27th, 2011. The dates with most events were December 23rd and 26th, with five and six of them, respectively. The last event occurred on February 28th, 2012 with a magnitude Mw of 3.3 and depth of 5.8 km. This event is not included in the date histogram (Fig. 3A) in order to allow a better visualization of the scale of this histogram.

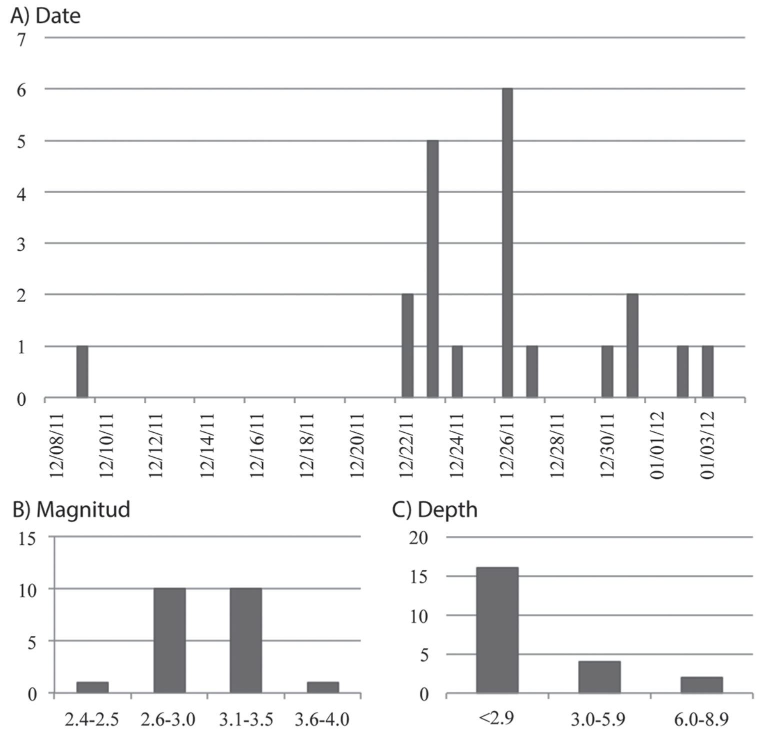

Fig. 3: Histograms of the earthquake swarm showing earthquake distribution in terms of A) Date, B) Magnitude, and C) Depth.

Earthquake moment magnitudes (Mw) for the Tobosi swarm ranged between 2.4 and 3.9, with the strongest earthquake occurring on December 26th, 2011. Most of the earthquakes (20) were between 2.6 and 3.5 Mw (Fig. 3B). Hypocenters ranged between 0.6 and 8.2 km in depth, with an average of 2.4 km (Fig. 3C, Table 1). Most of these earthquakes were felt at Tobosi and the largest ones were felt as far as in the cities of Cartago and San Jose.

There have been several historical earthquakes in the vicinity of the Tobosi swarm (Montero & Miyamura, 1981; Ambraseys & Adams, 2001; Fig. 1B). The closest significant earthquakes have been associated with the Aguacaliente Fault. These took place on April 13th, 1910 at 7:05 UTC (Coordinated Universal Time), with a magnitude of 5.6 (i.e., Peraldo & Montero, 2010), and on May 4th, 1910 at 18:47 UTC south of the city of Cartago (i.e., Montero & Miyamura, 1981) with a magnitude Ms of 6.1. These earthquakes caused significant damage in the central part of Costa Rica, especially the Cartago earthquake, considered the deadliest natural disaster in the history of Costa Rica (Montero & Miyamura, 1981; Montero, 2010). Two other significant earthquakes struck the area; the first one on February 21st, 1912 near the town of Tres Rios, with a magnitude calculated based on intensity data (Mi) of 5.0 (Morales, 1985) and the second one, on August 22nd, 1951, near the city of Paraiso, with a magnitude Ms 5.4 (Ambraseys & Adams, 2001). The latter event might be associated with the Navarro Fault (Montero, 2001).

THE TOBOSI TRANSTENSION

Based on tectonic geomorphology, a transtensional region was found near the town of Tobosi, which is referred to as the Tobosi Transtension (Fig. 4) in this paper. This structure is located between two major left-lateral fault systems mentioned above: the Aguacaliente Fault to the north (Woodward & Clyde, 1993; Montero et al., 2005;

Table 1

Swarm events sorted by date

	Date	Latitud	Longitud	Depth	Mw
1	09/12/2011	9.841	-84.008	0.9	3.3
2	22/12/2011	9.839	-83.998	0.6	3.4
3	22/12/2011	9.746	-83.899	6.2	2.8
4	23/12/2011	9.815	-83.985	2.3	2.9
5	23/12/2011	9.837	-83.998	1.0	3.3
6	23/12/2011	9.810	-83.985	1.3	3.3
7	23/12/2011	9.839	-84.004	1.0	2.9
8	23/12/2011	9.840	-84.001	0.6	2.9
9	24/12/2011	9.826	-84.994	3.0	2.8
10	26/12/2011	9.837	-84.006	5.8	2.6
11	26/12/2011	9.833	-84.001	1.3	3.1
12	26/12/2011	9.836	-84.000	2.4	3.9
13	26/12/2011	9.836	-83.996	2.3	3.1
14	26/12/2011	9.836	-83.992	0.9	3.2
15	26/12/2011	9.860	-84.035	0.7	2.6
16	27/12/2011	9.841	-83.997	1.1	3.0
17	30/12/2011	9.833	-83.988	1.2	2.4
18	31/12/2011	9.841	-84.007	1.0	2.6
19	31/12/2011	9.837	-84.022	4.8	2.7
20	02/01/2012	9.784	-83.994	0.9	3.3
21	03/01/2012	9.811	-83.978	8.2	3.2
22	28/02/2012	9.813	-83.973	5.8	3.3

Montero & Kruse, 2006; Montero et al., 2013; Alonso-Henar et al., 2013) and the Navarro Fault to the south (i.e. Berrangé & Whitaker, 1977; Aguilar, 1984; Geomatrix, 1994; Montero et al., 1998; Linkimer, 2003; figures 4 and 1B). The Aguacaliente Fault is located about 3 km north of the Tobosi earthquake swarm. This active fault is 15-18 km long and is a seismogenic source capable of producing large earthquakes (Mw 6.6–6.9) with an estimated recurrence interval of about 500 years (Alonso-Henar et al., 2013). The Navarro Fault is located 7 km south of the Tobosi earthquake swarm. The accumulative longitude of different segments of the Navarro fault system is about 54 km and it might be capable of generating earthquakes of Mw 6.7 (Linkimer, 2003).

The Tobosi Transtension structure includes three fault traces: Tobosi, Tablon, and Alumbre, each of them displaying a left-lateral strike-slip displacement with a normal component. The Tobosi Fault bounds the Tobosi Transtension structure to the northwest. It strikes ENE-WSW and is about 10 km long. Initially, this fault was named Tablon Fault by Woodward & Clyde (1993) and interpreted by these authors as a potentially active fault. Considering its proximity to the town of Tobosi, it will be called the Tobosi Fault in this study. The fault trace proposed by

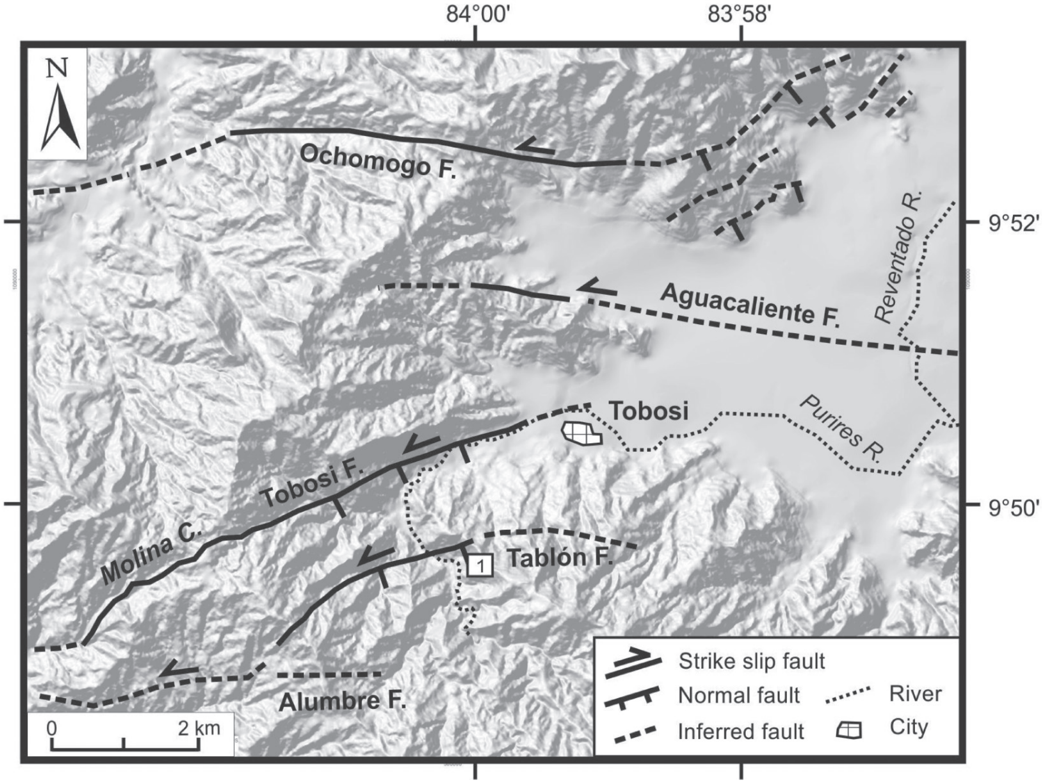

Fig. 4: Morphotectonics of the Tobosi area and the Tobosi transtension structure. Molina C. stands for Molina Creek. The number 1 represents a site discussed in the text.

Woodward & Clyde (1993) was also extended to the southwest, along the linear river valley of the Molina Creek (Fig. 4). To the southwest of Tobosi, this fault displays an east-faceted scarp and the Purires River flows in a parallel direction to it. A left-lateral displacement with a normal component was interpreted for this fault.

The Tablon Fault is the central trace of the Tobosi Transtension structure. This fault is about 8 km long and displays a left-lateral strike-slip displacement along the segment where the fault strikes east-west; and oblique (normal-left lateral) where the fault strikes ENE-WSW. The main geomorphological features of this fault are faceted scarps, linear riverbed valleys and deflected river drains. At the intersection between the Tablon fault and the Purires River (site 1 in Fig. 4), a fault scarp deflects to the left of the river.

The Alumbre Fault (Fig. 4) bounds the Tobosi Transtension structure to the south. It strikes east-west, is about 8 km long and displays a left-lateral strike-slip movement. The geomorphological evidences for this fault include linear riverbed valleys, mountain saddles, faceted scarps on both sides of the fault and deflected hills and mountain divides.

FOCAL MECHANISMS SOLUTIONS AND ORIGIN

First-motion focal mechanisms were calculated for the events with more than seven polarities (Fig. 5). The software used to compute the

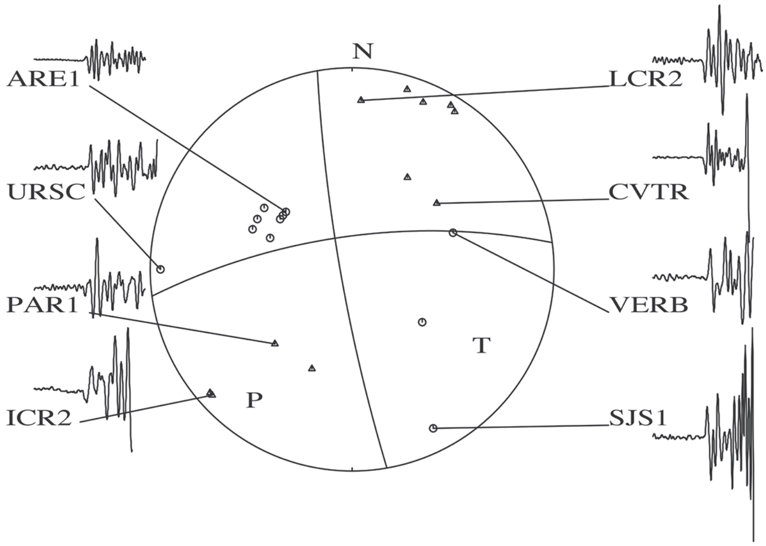

Fig. 5: Example of a high-quality focal mechanism for the 3.9 Mw event on December 26th, 2011. This event corresponds to focal mechanism number 12 in figure 6 and Tables 1 and 2.

focal mechanisms is called FOCMEC (Focal Mechanisms Determinations; Snoke, 1984). The search for nodal planes was performed every five degrees in the focal sphere. The quality of resulting focal mechanisms was categorized in two groups: A and B (Fig. 6). Quality A (QA) corresponds to the best quality and has at least 13 polarities mapped with no polarity errors in the focal sphere and sometimes with only one possible solution (Fig. 5). Quality B (QB) corresponds to focal mechanisms with at least seven polarity observations mapped with no polarity errors in the focal sphere. Fourteen focal mechanisms were computed: seven of QA and seven of QB (Fig. 6, Table 2).

A strong trend on the polarity observations was found for most of the focal mechanisms for both QA and QB. In QB focal mechanisms, the number of polarity observations allowed many possible solutions, so that even when the map of polarity observations in the focal sphere was very similar to those of QA, they could not be considered as high-quality solutions and only QA focal mechanisms were considered for the tectonic interpretation (Fig. 7). The trend of polarity observations noted for QB focal mechanisms suggests that most of them might have similar solutions for most QA. A possible solution for each QB was found in Fig. 6.

QA focal mechanism solutions are mostly strike-slip faults. The polarity observations and nodal plane solutions of six events are nearly identical (events number 1, 2, 5, 7, 12 and 14, Table 2, Fig. 7). These solutions correspond to a left-lateral strike-slip solution (rake angle varies from 3 to 12°) for a nodal plane striking from 254 to 264 and dipping from 71° to 80°, and to a right-lateral strike-slip solution (rake angle varies from 161° to 170°) for a nodal plane striking from 162 to 172 and dipping from 78° to 87°. Pressure and Tension axis for this set of QA focal mechanisms have a strike of 28°-38° and 118°-128°, respectively, and a dip angle of 1°-8° and 15°-19°, respectively (Table 2).

The main cluster of epicenters for the Tobosi swarm is aligned ENE-WSW and covers a region of approximately 3 km long and 1 km wide to the west of the town of Tobosi (Fig. 1B). The epicenters are also located at the eastern portion of the Tobosi Fault, where it has a strike of ENE-WSW. The left-lateral strike-slip solution for nodal planes striking ENE-WSW from the QA focal mechanisms seems to agree very well with the Tectonic Geomorphology observations for the region (Fig. 7). However, a discrepancy was noticed in the dip angle. Based on the Geomorphology, the Tobosi

Table 2

High-Quality focal mechanism solutions

Event	Date	Strike (°)	Dip (°)	Rake (°)	Fault type	Axis				Q	Pol
						P		T			
						Strike	Dip	Strike	Dip		
1	09/12/2011	264	80	12	Str-Left	38	1	128	15	A	15
		172	78	170	Str-Rigt						
2	22/12/2011	254	79	10	Str-Left	28	1	118	15	A	19
		162	80	169	Str-Rigt						
5	23/12/2011	264	80	12	Str-Left	38	1	128	15	A	17
		172	78	170	Str-Rigt						
6	23/12/2011	210	81	-33	Nor-Left	162	30	82	17	A	21
		306	56	-170	Str-Rigt						
7	23/12/2011	258	73	10	Str-Left	33	5	121	19	A	13
		165	80	163	Str-Rigt						
8	23/12/2011	261	75	3	Str-Left	37	9	125	12	B	10
		170	87	165	Str-Rigt						
11	26/12/2011	263	74	12	Str-Left	37	3	126	20	B	12
		170	78	164	Str-Rigt						
12	26/12/2011	262	71	7	Str-Left	38	8	125	18	A	22
		170	83	161	Str-Rigt						
13	26/12/2011	261	60	-19	Str-Left	44	34	129	9	B	13
		1	73	-149	Nor-Rigt						
14	26/12/2011	257	80	3	Str-Left	33	5	122	9	A	15
		166	87	170	Str-Rigt						
16	27/12/2011	257	80	3	Str-Left	33	5	122	9	B	10
		166	87	170	Str-Rigt						
18	31/12/2011	263	80	3	Nor-Left	49	44	132	7	B	11
		172	87	170	Nor-Rigt						
19	31/12/2011	260	80	12	Str-Left	38	4	127	9	B	10
		168	78	170	Str-Rigt						
22	28/02/2012	260	55	-30	Str-Left	34	1	124	16	B	7
		9	66	-141	Str-Rigt						

Str- Left: Left lateral strike slip fault; Str-Rigt: Right lateral strike slip fault; Nor-Rigt: Normal fault with right lateral strike slip component; Nor-Left: Normal fault with left lateral strike slip component; P: Pressure Axis; T: Tension Axis; Q: Quality; Pol: Number of Polarities

Fault may be interpreted as a nearly vertical fault inclined towards the SSE. On the other hand, the nodal plane solutions for focal mechanisms are nearly vertical (average of 77°), but dipping towards the NNW. Uncertainties in the search for nodal planes in the focal sphere for focal mechanisms may explain this disagreement, especially because the dip angle is almost vertical. An outcrop exposing the Tobosi fault plane is needed to more accurately determine the dip direction of this fault.

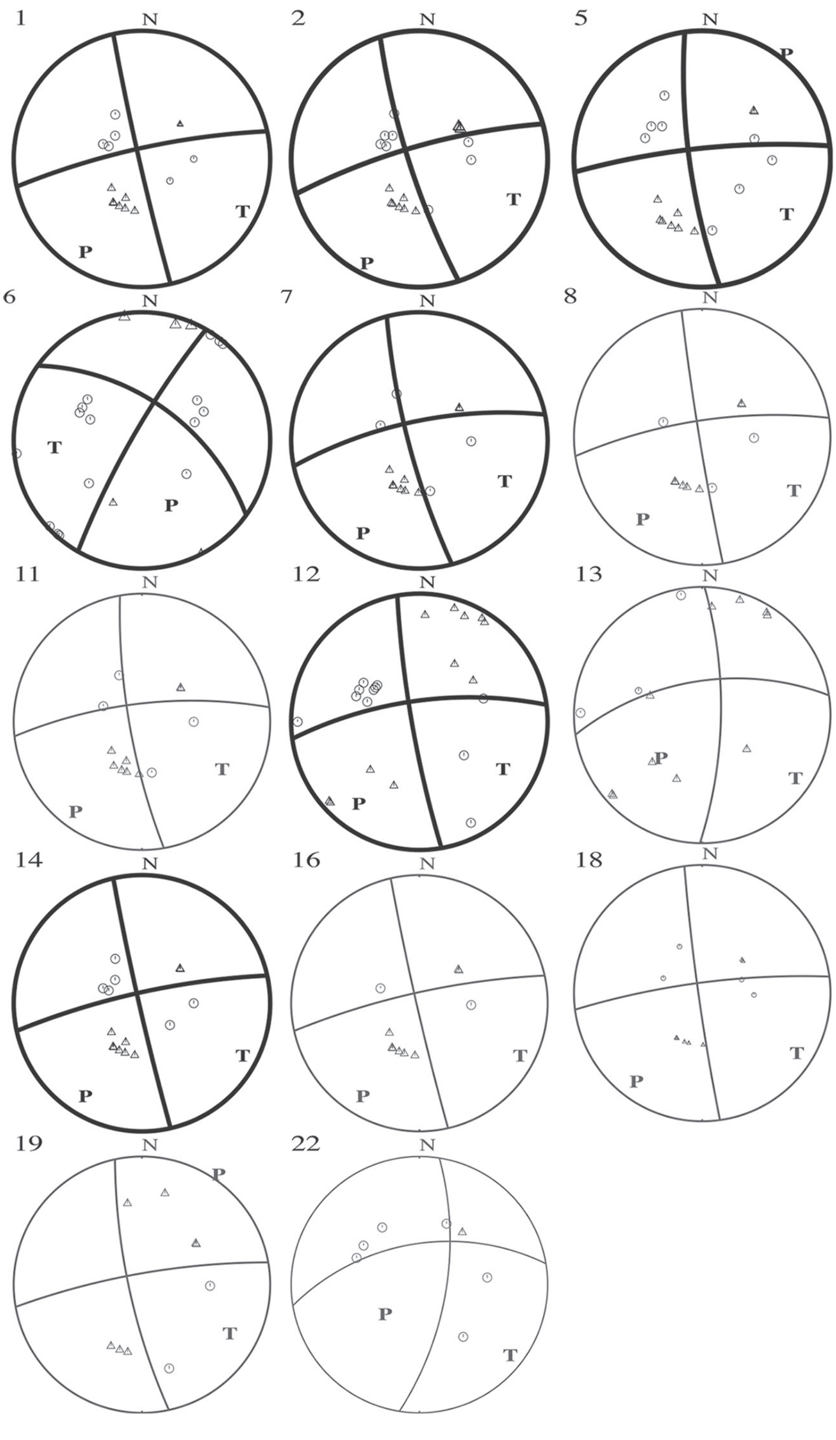

Fig. 6: Focal mechanisms for the Tobosi swarm. Quality-A (best) focal mechanisms are shown as thicker black lines and Quality-B as thinner gray lines. Numbers on each focal mechanism refer to the event number on Tables 1 and 2.

Based on the agreement between the fault trace location and the earthquake swarm locations, and on the left-lateral strike-slip solution for nodal planes striking ENE-WSW from the QA focal mechanisms, it is suggested that the Tobosi Fault was the source of the Tobosi swarm (Fig. 7).

Only one QA focal mechanism displays a different solution compared to the main trend (event number 6 in Table 2). This was the solution for an earthquake that happened in December 23rd, 2011, located to the south of the main cluster of earthquakes (Fig. 7). This event shows a right-lateral strike-slip solution (rake = -170°) on a plane striking 306° and dipping 56° and an oblique (normal-left lateral) solution (rake = -33°) for a nodal plane striking 210° and dipping 81°. This earthquake might have been produced by a different fault. Based on the Geomorphology where this epicenter is located, no clear indication of faulting was found, so it is not possible to determine which nodal plane may correspond to the active fault that originated this particular event. Interestingly, another fault showed seismic activity during the swarm occurring mainly at the north-easternmost portion of the Tobosi Fault.

CONCLUSIONS

In the vicinity of the town of Tobosi, an earthquake swarm of 22 events occurred from December 9th, 2011 to February 28th, 2012. Twenty of these earthquakes occurred on a 13-day time frame. Earthquake magnitudes (Mw) varied between 2.4 and 3.9 and focal depths between 0.6 and 8.2 km. This earthquake swarm occurred on a portion of the CCRDB where faults are mainly of strike-slip type with right-lateral displacement along faults striking northwest-southeast and left-lateral displacement along faults striking northeast-southwest.

Based on Tectonic Geomorphology, a transtensional structure near the town of Tobosi was determined, referred in this study as the Tobosi Transtension. This structure is located between two major left-lateral fault systems: Aguacaliente and Navarro. The Tobosi Transtension structure is composed of three faults, named Tobosi, Tablon, and Alumbre. Each of these faults displays geomorphological features that suggest left-lateral strike-slip displacements with a normal component. Some geomorphological evidences for these faults include linear riverbeds valleys, mountain saddles, and faceted scarps.

A strong trend on the polarity observations for focal mechanisms was found for most earthquakes analyzed. High-quality focal mechanism solutions display mostly strike-slip faults. These solutions correspond to a left-lateral strike-slip displacement on a nodal plane striking 254 to 264 and dipping from 71° to 80°, and to a right-lateral strike-slip displacement on a nodal plane striking 162 to 172 and dipping from 78° to 87°. The main cluster of epicenters occurs to the west of the town of Tobosi, is aligned ENE-WSW, and covers a region of approximately 3 km long and 1 km wide. The epicenters are also located at the northeastern portion of the Tobosi Fault where it strikes ENE-WSW. The left-lateral strike-slip solutions for the high-quality focal mechanisms seem to agree very well with the Tectonic Geomorphology observations for the Tobosi Fault in this region. Based on these observations, it is proposed that the Tobosi Fault was the source of the 2011-2012 earthquake swarm.

There have been at least five historical earthquakes in the vicinity of the Tobosi swarm. The most significant earthquakes have been associated with the Aguacaliente Fault (i.e., Cartago, 1910, Ms 6.1) and the Navarro Fault (Paraiso, 1951, Ms 5.4). Given this history of destructive earthquakes, studies of active faults are important for determining seismic hazards for the densely populated area of Central Costa Rica.

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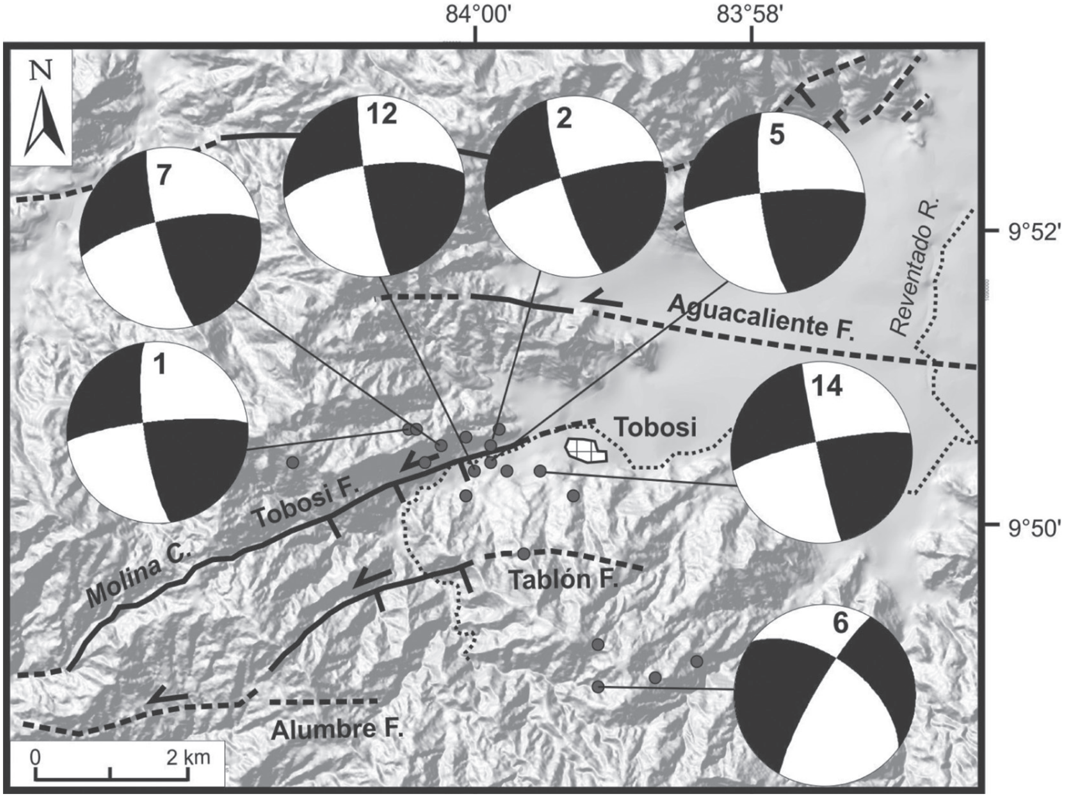

Fig. 7: Earthquake locations (small gray circles) and Quality-A focal mechanisms in the neotectonic context of the Tobosi area. Numbers on each focal mechanism refer to the event number on Tables 1 and 2.

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