The Churuguara Area - Seismic Evidence of Contemporary Activity of the Oca-Ancon System

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Abstract

The Churuguara area is the most active zone in northwestern Venezuela when moderate seismicity is considered, as it presents the highest recurrence of moderate earthquakes in the instrumental record. Several seismic events of magnitude 4 or greater, which have slightly damaged some villages in their respective mesoseismal areas, have occurred in the central region of the State of Falcon in the last three decades (1964, 1966, 1970, 1976, 1980, 1986 and 1990).

In this research, some of these earthquakes have been re-evaluated (i.e. those of 1970, 1986 and 1990). The 1970 earthquake's focal mechanism calculated by Dewey (1972) showed inversion of the T and P axis with respect to the first motions reported in his solution and it was also better adjusted to the regional neotectonic framework. The 1986 main event and its aftershocks were better located because of additional arrival time data provided by the Venezuelan National Network operated by FUNVISIS. This additional data also allowed us to obtain focal mechanism solutions for both the main shock and some aftershocks. However, the 1990 event did not have enough P-wave first motion data to enable the calculation of a focal mechanism solution.

The above-mentioned seismicity can be associated with the major active tectonic feature of northwestern Venezuela: the East-West strike-slip Oca-Ancon fault system. This system has been considered seismically active by many workers (e.g. Dewey, 1972; Soulas, 1987; Audemard, 1991; Bach, 1991; Audemard et al., 1992; Malave, 1992). In the Churuguara area, the Oca-Ancon system is composed of several short (less than 30 km long) subparallel strands that run WNW-ESE (Mendez and Guevara, 1969; Soulas, 1987; Audemard et al., 1992). The frequent moderate seismicity of this area could be due to the large number and the short lengths of those faults.

Two possible focal mechanism solutions can be proposed for the main event of the 1986 seismic sequence; strike slip and reverse. The second solution resembles those proposed by the International Seismological Centre (ISC) (1986) and Malave (1992). However, we believe that the strike-slip solution is better constrained and it fits better with the regional neotectonic information collected by Audemard et al. (1992).

Additionally, a well-constrained focal mechanism can be calculated for the 1986 aftershock sequence. This solution confirms transcurrent movements along the Oca-Ancon fault system or on minor faults associated with it.

It is relevant to mention that all focal mechanisms calculated for the Churuguara earthquakes in this work are in perfect agreement with the present stress tensor of northwestern Venezuela obtained from geological structures (e.g. Giraldo, 1985, 1990; Soulas, 1987; Beltran and Giraldo, 1989) and microtectonic data (e.g. Wozniak & Wozniak, 1979; Audemard, 1991 and Audemard et al., 1992), which is characterized by NNW-SSE maximum horizontal stress.

Introduction

Northern Venezuela lies within the interaction zone between the Caribbean and South American plates. Although it is generally accepted that the Caribbean plate is moving to the east with respect to South America (e.g. Bell, 1972; Malfait and Dinkelman, 1972; Jordan, 1975; Pindell and Dewey, 1982; Sykes et al., 1982; and Wadge and Burke, 1983), this plate boundary is not a simple right-lateral strike-slip type but a broad active deformation zone, resulting from a long-lasting complex oblique-collision process. Nevertheless, a great amount of this dextral relative movement seems to be accommodated along the right-lateral Bocono-San Sebastian-El Pilar fault system (Molnar and Sykes, 1969; Minster and Jordan, 1978; Perez and Aggarwal, 1981; Stephan, 1982; Aggarwal, 1983; Schubert, 1984; Soulas, 1986; Beltran and Giraldo, 1989).

Contemporary seismicity in northern Venezuela is rather moderate in magnitude since the installation of the World Wide Standardized Seismograph Network- WWSSN - (1964 to present). However, if a longer time span is considered, several destructive earthquakes are known from historical chronicles to have occurred since the settlement of Spaniards in the Americas at the beginning of the sixteenth century (Centeno-Grau, 1940; Grases, 1980), which proves that this boundary zone between the Caribbean and South American plates is active. Additionally, northern Venezuela is characterized by a diffuse seismicity which suggests that deformation along this boundary does not occur along a single fault zone even if major historical earthquakes have been related to the Bocono-San Sebastian-El Pilar fault system. Other minor faults exist in this broad zone of active deformation which are responsible for intermittent moderate seismicity.

This work focusses on a particular seismic activity concentrated in the central region of Falcon State, near the town of Churuguara in northwestern Venezuela and far away from the major tectonic features of the plate boundary, where several small to moderate earthquakes have been recorded during the last thirty years (FUNVISIS Earthquake Catalogue). Some of these events have been re-examined inorder to refine their epicentres, to obtain focal mechanism solutions and to establish possible seismotectonic associations.

Location of the study area

The study area lies in northwestern Venezuela, more precisely in the central region of Falcon State and near the border between the states of Falcon and Lara, within the following coordinates: 69° to 70° west and 10° 30' to 11° 15' north.

Seismicity

Northwestern Venezuela is characterized by a scattered and low to moderate instrumental seismicity (FUNVISIS Earthquake Catalogue). However, two regions stand out from the regional seismicity pattern: the Churuguara area and the 1989 Boca de Tocuyo seismic swarm (Figure 1). The latter has been a temporary cluster (FUNVISIS, 1989; Audemard et al., 1990; De Santis et al., 1990; Audemard and De Santis, 1991) while the Churuguara area has been an intermittent but persistent seismic source in northwestern Venezuela throughout both the historical (Centeno-Grau, 1940; Audemard et al., 1992) and the instrumental record (FUNVISIS Earthquake Catalogue).

In this region, no major earthquake has been either recorded since the installation of the WWSSN or reported in the historical record (Audemard et al., 1992) where important Spanish settlements existed since the conquest (beginning of the sixteenth century), although the occurrence of major earthquakes associated with the Oca-Ancon fault system during the Holocene has been revealed by trenching (Cluff and Hansen, 1969; Audemard, 1991). This fact suggests that the recurrence time between successive major earthquakes along this fault system, which crosses northwestern Venezuela from west to east, is much longer than our entire seismic record (close to 500 years of observations and readings) and this has been confirmed by some calculations made by Audemard (1991, 1993). Therefore, we have to keep in mind that any present seismic quiescence cannot automatically be correlated with tectonic inactivity.

As mentioned above, the Churuguara area is the most active seismic zone in northwestern Venezuela as it presents the highest recurrence of small to moderate earthquakes which define a seismic cluster (Figure 1). This area has produced several seismic events of magnitude 4 or greater in the last three decades that have slightly damaged some towns, including Churuguara itself, and several villages (Mapararí, El Cacuro, el Tigrito, among others), in their respective mesoseismal areas (Romero and Malaver, 1980; Chacon and Romero, 1986; Ferioli and Audemard, 1991).

This paper deals with three of those shocks; the 1970, 1986 and 1990 earthquakes. Due to the fact that the FUNVISIS National Network began operations in 1981, we do not possess the original seismic data for the 1970 earthquake which was located by the ISC but we have re-examined the focal mechanism solution proposed by Dewey (1972) and its seismotectonic association. The 1986 earthquake is not just a shock but a sequence of 7 events characterized by a main event of magnitude 5.6 and 6 aftershocks of magnitude ranging between 2.9 and 4.4. This seismic sequence has been re-evaluated since additional seismograms, recorded as well by the National Network operated by FUNVISIS, were considered. Their epicentral locations were refined and additional P-wave first-motion readings obtained directly from the seismograms. The 1990 earthquake was also re-examined in order to propose a focal mechanism solution for this event but P-wave first-motion readings were very similar and therefore they were clustered on the stereonet, and there were even contradictions in some cases.

Neotectonic Setting

As a consequence of lying in the boundary zone between the Caribbean and South American plates, northwestern Venezuela is affected by several active faults, among which the Oca-Ancon fault system stands out (Figure 2). This major dextral fault system strikes roughly east-west for over 600 km and its trace extends eastward from the Colombian Atlantic coast, near Santa Marta, to the village of Boca de Aroa, located on the Caribbean coast of Venezuela and more precisely on the eastern coastlands of Falcon State; crossing the Goajira Peninsula, the outlet of lake Maracaibo at Toas Island (first site where the fault plane and associated deformation were observed by Rod (1956)), the coastal plains of Buchivacoa, the central Falcon range (also called the Falcon anticlinorium) and along the northern margin of the Aroa river valley. The Oca-Ancon system converges with the Boconó-San Sebastian-El Pilar fault system on the Aroa-Golfo Triste depression.

This fault system has been mapped by many geologists since the early beginning of oil exploration in northwestern Venezuela as its fault trace is very conspicuous west of Maracaibo where this tectonic feature sharply truncates the northern end of the Santa Maria block in Colombia and the Perija Range on both sides of the Colombia-Venezuela border. East of Maracaibo, it is amazing that only a few workers have mapped the fault trace in some detail since the fifties (Jaeckli and Erdman, 1952; Mendez and Guevara, 1969; Soulas, 1987; Audemard, 1991; Audemard et al., 1992) where profuse geophysical and geological information has been gathered by oil companies for over 70 years. In fact, this fault system has been sketched frequently across the Falcon anticlinorium following diverse trends and positions in order to connect the well-known western portion (west of Maracaibo) of the Oca-Ancon fault system with the Bocono-San Sebastian-El Pilar fault system on the Aroa-Golfo Triste depression, considered by many authors as the main present boundary between the Caribbeana and South American plates.

Despite spectacular diagnostic geomorphic features of Quaternary activity along this fault system, such as pluri-kilometric fault scarplets in Quaternary alluvial deposits photo-interpreted by Voorwijk (1948) and displaced Holocene beach-strandlines reported by Miller (1960), many authors in recent times have underestimated the seismic potential of

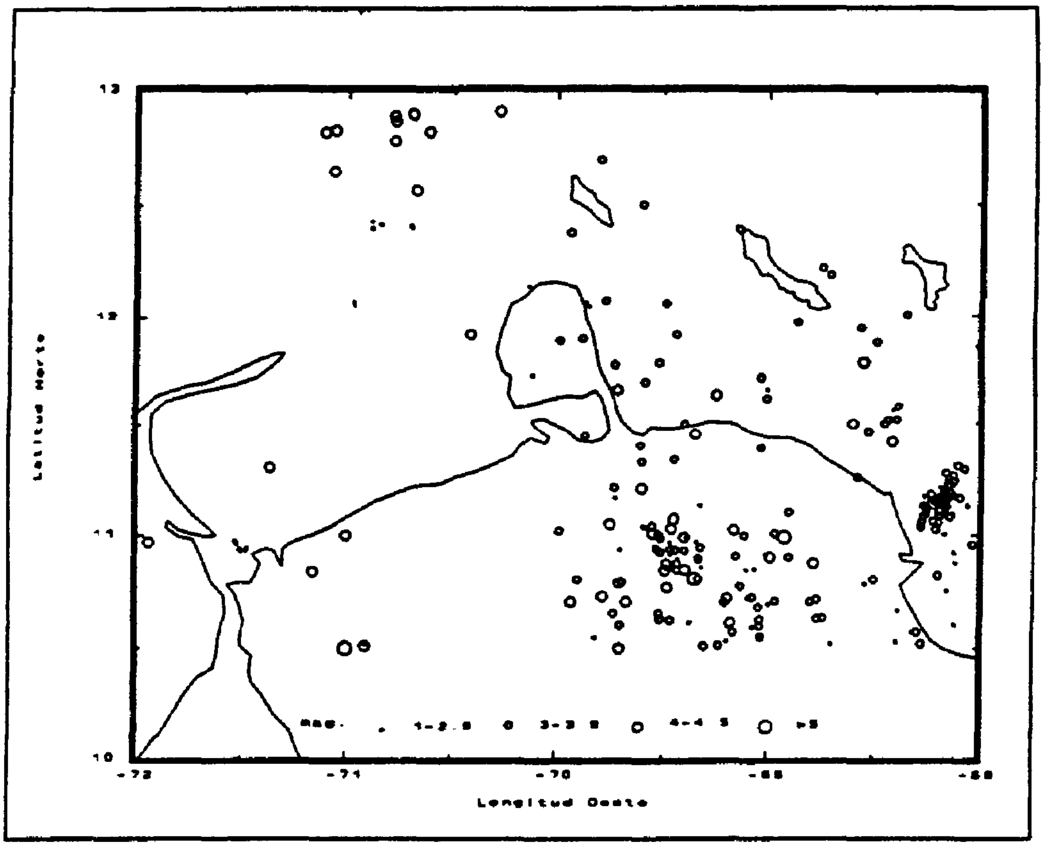

FIGURE 1: Seismicity of northwestern Venezuela (FUNVISIS Seismic Catalog)

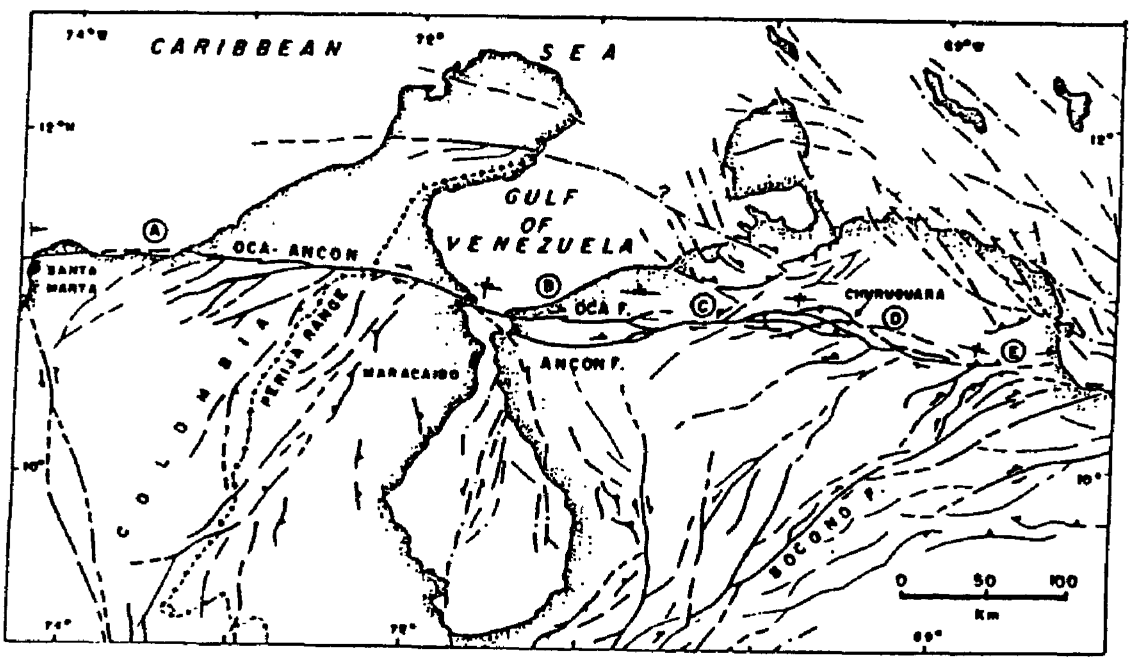

FIGURE 2: Neotectonic map of Northwestern Venezuela and north Colombia. The most relevant tectonic feature of the region is the East-West right-lateral strike-slip Oca-Ancon fault system. Capital letters identify fault segments as referred in the text. Map sources: MILLER (1960); TSCHANZ *et al.* (1969); KELLOGG & BONINI, 1982; SOULAS (1986, 1987); AUDEMARD (1991) and AUDEMARD *et al.* (1992).

this active system and have occasionally considered it inactive. Nevertheless, Cluff and Hansen (1969) proved the occurence of Holocene (< three thousand years old) large earthquakes by trenching Miller's evidence and Audemard (1991) re-inforced that fact through his paleoseismic evaluation of the Oca-Ancon fault system carried out on those scarplets identified by Voorwijk (1948) on the alluvial plains of Buchivacoa, slightly east of Maracaibo city. Moreover, some contemporary seismic activity has been associated with this fault system, such as a pair of moderate earthquakes on October 20, 1969, whose epicentres Dewey (1972) estimates to lie at 10.90° N and 72.40° W approximately. More recently, Soulas (1987), Audemard (1991), Audemard et al. (1992) and Malave (1992) have associated the frequent moderate seismicity of the Churuguara area to the Oca-Ancon fault system.

The detailed mapping of the active trace of the Oca-Ancon fault system allows its subdivision into five different segments (Figure 2). These are from west to east:

a) Between Santa Marta and Toas Island at the outlet of Lake Maracaibo: This segment is fairly simple as it is composed of a main trace that truncates the northern termination of the Perija Range (known as Montes de Oca from where the name of the fault derives). Westward it seems to control the linear northern coast of the Santa Marta block (Sierra Nevada de Santa Marta) where some potentially active minor faults, which are located south of the fault and strike NE-SW, converge with the main trace in a kind of horse tail structure. Further west, it seems to connect to the east-west striking Jordan fault, mapped east of Santa Marta.

b) Between Toas Island and the town of Mene de Mauroa: The fault trace of the system in this segment divides into two subparallel strands: the E-W striking Oca and Ancon faults. Both traces are defined by pluri-kilometric fault scarplets in Quaternary alluvial terraces that were photo-interpreted by Voorwijk (1948) and trenched by Audemard (1991, 1993). Both scarplets face each other and they limit a large area of probable recent subsidence which Audemard (1991, 1993) interpreted as an active pull-apart basin located in the right stepover between the dextral Oca and Ancon faults.

c) Between the towns of Mene de Mauroa and Paraiso: The fault trace is very complex as several strands converge on or diverge from the main lineament which presents itself in an anastomosed character. The eastern portion of this fault segment, between the villages of Camare and Paraiso in central Falcon State, has been interpreted by Jaeckli and Erdman (1952), Audemard (1991) and Audemard et al. (1992) as a flower structure since the inner deformation in the fault zone is of strike-slip type while the outer deformation is characterized by reverse faults affecting Quaternary alluvial ramps on both flanks of the Camare-Paraiso range.

   All the above-mentioned segments strike roughly N90° to N100° (east-west).

d) Between the village of Paraiso and the Aroa Valley: This segment of the fault system is composed of several subparallel fault strands of relatively short length in comparison with other segments of this major tectonic feature (Mendez and Guevara, 1969; Soulas, 1987; Audemard et al., 1992). This section of the Oca-Ancon system strikes WNW-ESE. The fault strands cut across the towns of Churuguara and Mapararí and they run slightly oblique to the Tocuyo river course, till becoming tangent to it.

e) Between the villages of Socremo and Boca de Aroa: The fault system regains its original direction along the northen margin of the Aroa Valley: approximately east-west. The fault in this segment shows geomorphic features of reverse faulting where Quaternary alluvial ramps are tilted and flexured (Audemard et al., 1992).

The seismic activity near Churuguara in central Falcon State, which is characterized by small to moderate but persistent earthquakes, can be clearly associated to the WNW-ESE segment of the Oca-Ancon fault system (Soulas, 1987; Audemard, 1991; Audemard et al., 1992; Malave, 1992). The relatively high frequency of such small to moderate earthquakes could be attributed to the number and short length of the fault strands that compose the system in that region.

Focal mechanism solutions and seismotectonic associations

As a matter of fact, we Three events of the Churuguara seismic cluster have been evaluated in this paper. Those events occurred in May 1970, July-September 1986 and November 1990.

May 19, 1970, Earthquake

This event has been studied by Dewey (1972) using the standard P wave first motion technique. However, Kafka & Weidner (1981) suggested that P wave data alone could yield ambiguous results for such a small event and that it must be supplemented with additional seismic data such as surface wave data to better constrain its focal mechanism and depth.

First of all, we have observed that the focal mechanism solution proposed by Dewey (1972) showed inversion of P and T axes that has misled later interpretations such as the No. 37 focal mechanism of Pennington (1981), although he did interpret the solution correctly and we quote his words: "...is consistent with substantial right-lateral faulting parallel to the zone of epicentres, but does not require such faulting. A component of normal faulting is also present...". This proposed solution was consistent with the supposed trend of the fault system at that time. As a matter of fact, we now know that the system in this region strikes WNW-ESE. Therefore, we have adjusted his solution to the present neotectonic framework by slightly rotating clockwise his E-W nodal plane to a WNW-ESE direction (I in Figure 3). This seismic event could be attributed to one of those fault strands of the Churuguara area since one of the nodal planes is characterized by a WNW-ESE strike and a right-lateral movement. Nevertheless, an inconsistency remains between the south dip of the considered nodal plane and the proposed epicentre which is far to the north with respect to the fault traces if Jaeckli and Erdman (1952)'s intepretation of this segment of the fault system is considered correct since they interpreted the fault strands as representing a graben-like structure. That is, the fault strands dip inward and the epicentre is outside the strip limited by the faults. In any case, the epicentre should be located south of the fault strands if the proposed focal mechanism is considered valid.

If this event is associated with the Oca-Ancon fault system as it seems, this problem remains unresolved. Could this event be located some 20 km southwest of its present epicentre? Using Dewey's JHD89, Malave (1992) relocated this event some 12 km westward of the original location proposed by Dewey. Thus, the epicentre of the 1970 earthquake got closer to the fault strands but it still remained too far north.

Kafka and Weidner (1981), based on surface wave data, proposed a focal mechnism solution which is in perfect contradiction with Dewey's solution, the neotectonic setting and the regional stress field.

The 1986 seismic sequence

Between July and September 1986, the Churuguara area underwent several small to moderate earthquakes. The mainshock occurred on July 18 at 10.802° N and 69.369° W, slightly east of the towns of Churuguara and Mapararí. During the next two months, a sequence of six aftershocks followed the main event. This aftershock sequence presented a main aftershock of magntude (m_b) 4.4 (FUNVISIS, 1986) that occurred on September 12 at 11.040° N and 69.442° W, about 30 km north of Churuguara.

Some events of this sequence have had their epicentral locations re-calculated during this research (Figure 4), since additional seismograms, recorded as well by the FUNVISIS National Network, were evaluated and considered. This allowed us to refine their hypocentral locations, enlarge the amount of P-wave first motion readings and review their quality, thus letting us find new focal mechanism solutions.

The main observations that can be drawn after plotting the sequence epicentres on a neotectonic map (Figure 4) are: (a) the epicentres are clearly associated with the Oca-Ancon fault system and b) this sequence is geographically and temporarily subdivided into two small clusters, which suggests that those events could be from different sources. Taking into account these facts, we have tried to obtain different composite focal mechanism solutions for each of the two different clusters and for the main event combined with its first aftershock which occurred just 7 hours later.

HARVARD, ISC (1986) and Malave (1992) have proposed similar focal mechanism solutions for the main event based on P-wave first motions. Those solutions indicate nodal planes that strike NE-SW with mainly reverse-slip and a small component of strike-slip. We have obtained a similar solution for the cluster containng the main event (from now on named the first cluster), based on P-wave first motions from the FUNVISIS short-period seismograms (III in Figure 3), but slightly rotated as our reverse nodal planes strike approximately east-west.

Any of these solutions could be associated to active north-dipping, reverse faults mapped by Audemard et al. (1992) to the south of Santa Cruz de Bucaral and between the villages of Maparari and el Palmar. Nevertheless, we do not believe them to be the more appropriate solutions since a compressional first motion is in a dilatational quadrant in our solution and the same fact is observed in the proposed solutions of Malave (1992) based on either P-wave first motions from long period seismograms or polarities from the ISC bulletin. Moreover, if we observe the depths of events composing the first cluster, we can deduce that the fault plane, which should contain the mainshock and the afershocks, dips south to southwest. In fact, we propose another focal mechanism much better adjusted to the first motion polarities. This focal mechanism is characteristic of strike-slip tectonic regimes. Two attempts at focal mechanism calculation were caried out: a first composite focal mechanism for the main event and its first aftershock was calculated which had a nodal plane in perfect agreement with the active fault strands of the Oca-Ancon system in the Churuguara area that are characterized by a WNW-ESE orientation and a dextral movement, and also a south dip as suggested by the depth distribution of the four events belonging to the first cluster (II in Figure 3).

The second focal mechanism included the four events of that cluster and the obtained composite focal mechanism solution remained almost the same (IV in Figure 3). Therefore, it is also in perfect agreement with the neotectonic setting of the region.

On the other hand, the second cluster had a well-constrained focal mechanism solution (V in Figure 3). Both nodal planes are characterized by reverse-slip and a certain component of strike-slip. Before any seismotectonic association is advanced, we should mention two facts: in the Churuguara area, no active left-lateral fault has been recognized yet and a complex neotectonic setting exists northwestward of Churuguara as two segments of the Oca-Ancon fault system (segment C and D described in the Neotectonic Setting section), characterized by different tectonic styles, converge on the Paraiso-Araju area. Let us remember that segment C is composed of a positive flower structure which implies the coexistence of strike slip and shortening.

Additional information is brought to light by the depth distribution of the three events composing the second cluster: the fault plane should dip south, as the other nodal plane of the focal mechanism does. The above-mentioned conditions are fulfilled by reverse faults with a certain amount of right-lateral movement mapped along segment C of the Oca-Ancon fault system such as the fault that runs along the northern flank of the Camare-Paraiso range and as far east as the village of Aracua (Figures 2 and 4).

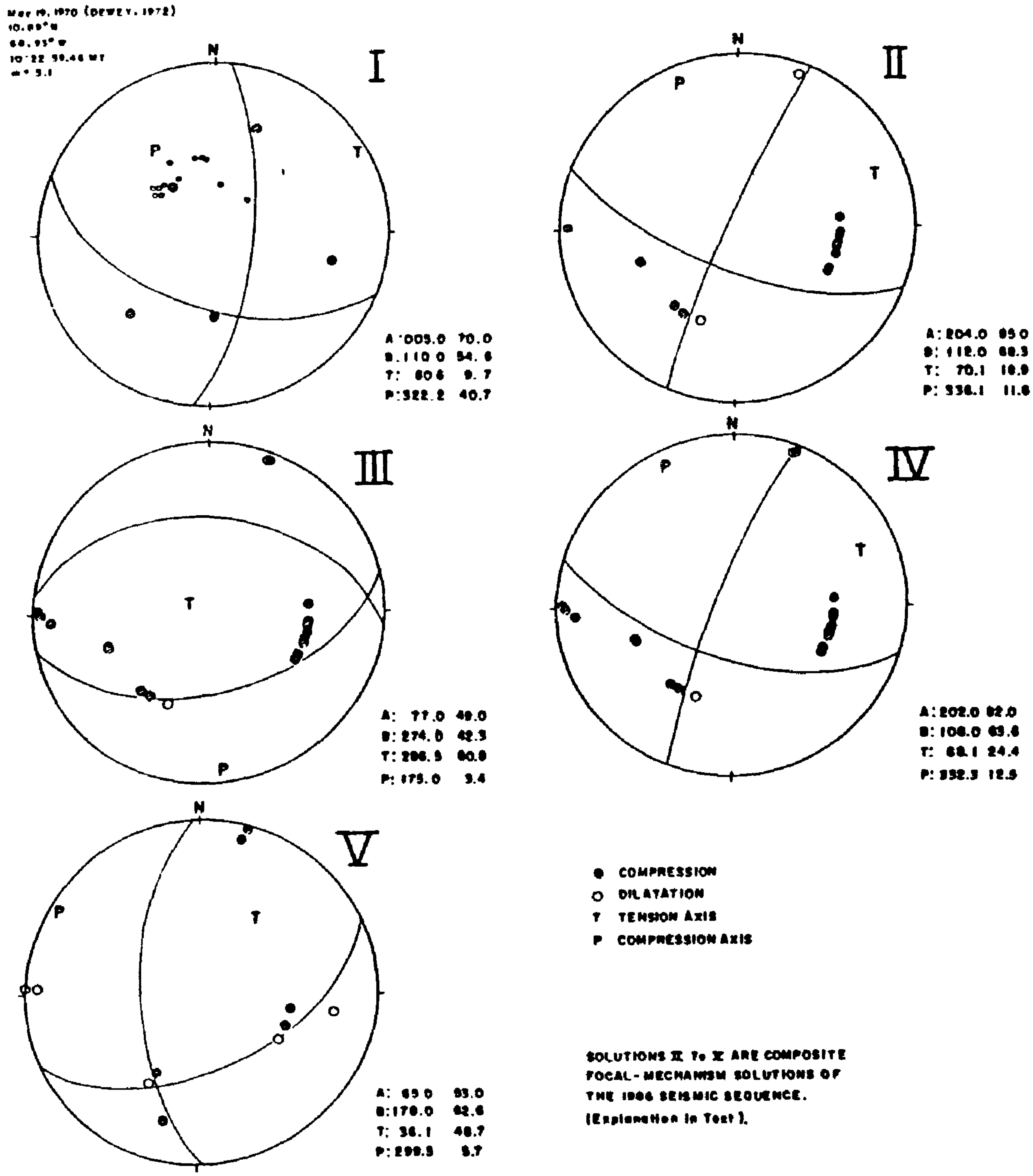

FIGURE 3: Focal mechanism solutions proposed for the 1970 and 1986 Churuguara earthquakes

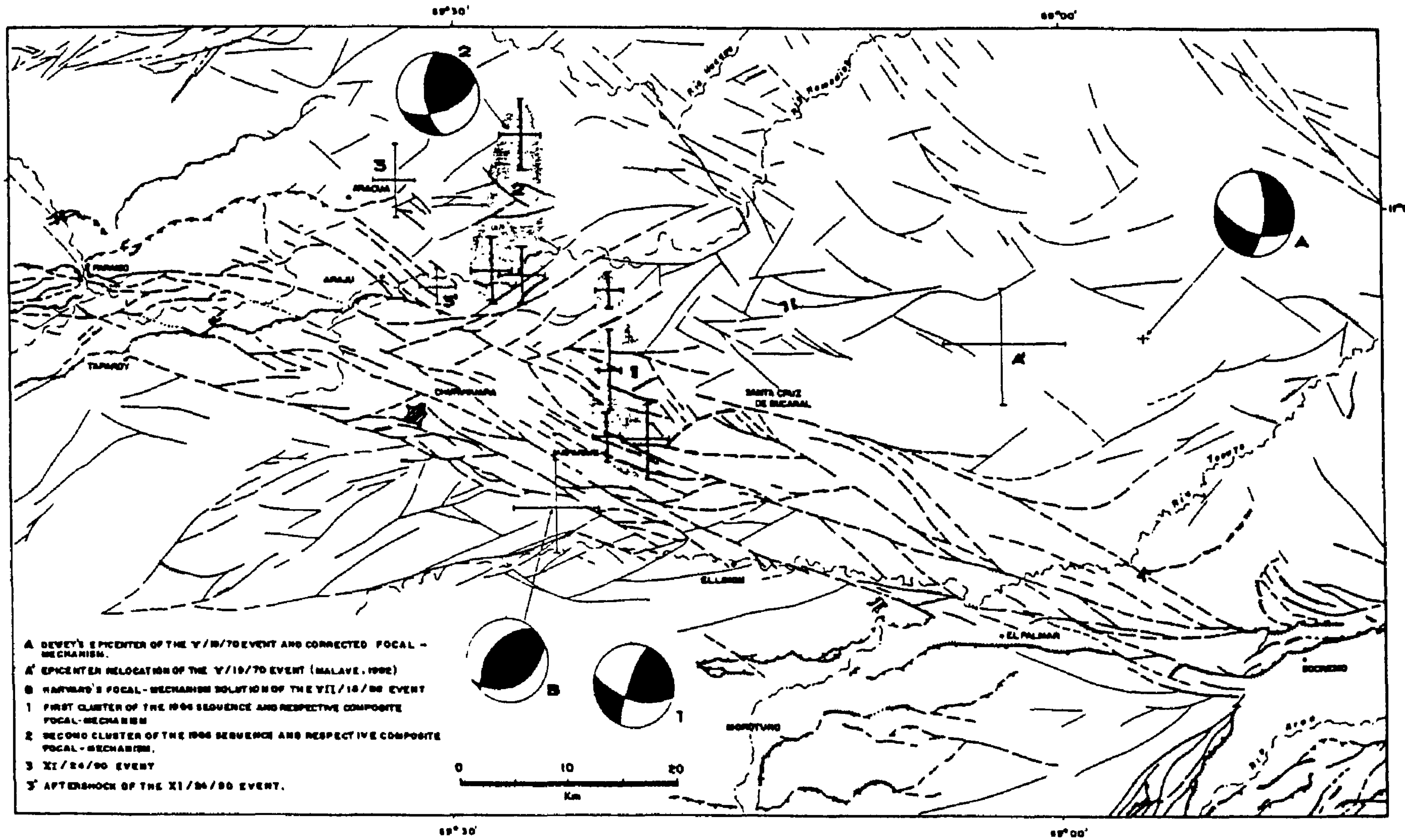

FIGURE 4: Neotectonic map of the Churuguara area and compilation of selected earthquake focal-mechanism solution. Map Source: AUDEMARD *et al.* (1992)

The 1990 earthquake

On November 24, 1990, two small earthquakes of magnitude m_b 4.5 and 3.3 were felt in the Churuguara area. These small earthquakes were located by FUNVISIS (1990) slightly east of the village of Aracua, at 11.006 °N and 69.545 °W and 10.923 °W respectively. Some villages in the Churuguara area (e.g. Churuguara, Mapararí, El Porvenir and Cacuro) were slightly damaged but no life losses were reported (Ferioli and Audemard, 1991). Most of the observed damage corresponded to fissures or wall falls of defective house masonry. They also concluded that a discrepancy existed between the location of the instrumental epicentres and their mesoseismal areas which are some 20 km apart.

Although these earthquakes are additional evidence of the seismic activity on the Oca-Ancon fault system, as they seem to be clearly associated with it, the available seismic data was not sufficient to permit accumulation of a focal mechanism solution for this 1990 earthquake since some P-wave first-motion readings were very similar and there were even contradictions in some cases.

Conclusions

The Churuguara area has been an intermittent but persistent source of seismic activity in northwestern Venezuela through the historical and the instrumental records. This area is characterized by a relatively high recurrence of small to moderate earthquakes.

The seismicity of this area can be clearly associated with the Oca-Ancon fault system and paticularly to the WNW-ESE segment of this feature that runs across the towns of Churuguara and Mapararí, confirming the seismogenic character of this tectonic system.

The large number and short lengths of the fault strands composing this sytem in that particular segment could be responsible for the relatively high frequency of moderate earthquakes in the Churuguara area.

The 1970 earthquake could be attributed to the Oca-Ancon fault system as its focal mechanism solution is almost in perfect agreement with the neotectonic setting except for the discrepancy between the epicentre location, whch is too far north, and the southward dip of the fault plane. This problem remains unresolved.

Focal mechanism solutions proposed for the 1986 seismic sequence are in perfect agreement with the neotectonic setting: a right lateral strike-slip solution for the first cluster matches very well with the kinematics of the WNW-ESE fault strands interpreted from geological data. The oblique-slip (dextral-reverse) solution for the second cluster can be attributed to the Camare-Paraiso segment of the Oca-Ancon fault system where transpressive deformation is taking place, as revealed by reverse faults affecting Quatermary terraces on both flanks of the Camare-Paraiso range.

All focal mechanisms calculated in this work are in perfect agreement with the present stress tensor for the Falcon region obtained from microtectonic data by Wozniak and Wozniak (1970), Audemard (1991) and Audemard et al. (1992), which is characterized by a NNW-SSE maximum horizontal stress.

Acknowledgements

We gratefully acknowledge the financial support from INTEVEP that allowed much of the field work required for mapping the neotectonic features. Ths study also benefitted greatly from the kindness of the Seismological Department of FUNVISIS that permitted us to use their seismograms, seismic data and software.

We also want to thank both the Seismological and Earth Sciences departments of FUNVISIS for encouraging this research. Our thanks to Yris Pane for typing the manuscript and Marina Peña for drafting the figures.

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