

Relocation and seismotectonic interpretation of the seismic swarm of August – December of 2012 in the Linares area, northeastern Mexico

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Resumen

En este trabajo relocalizamos 52 sismos en el rango de $2.5 \leq M_c \leq 3.6$ de una secuencia sísmica de más de 250 eventos que ocurrió al suroeste de la ciudad de Linares, N.L., durante los meses de julio – diciembre de 2012, en el noreste de México. Para estudiar este enjambre se instalaron cuatro estaciones sismológicas en la región de interés, las cuales operaron durante diferentes periodos entre septiembre y diciembre. La relocalización de la secuencia demostró que las profundidades hipocentrales fueron de $8 (\pm 5)$ km, y los residuales de los tiempos de arribo tuvieron valores ≤ 0.38 s. Se generaron soluciones del plano de falla para sismos individuales, así como a través de la técnica de mecanismos compuestos. La solución de los mecanismos focales encontrada corresponde con fallamiento inverso con rumbo NNW-SSE y buzamiento hacia el SW para el plano nodal inferido (rumbo $\sim 150^\circ$, buzamiento $\sim 50^\circ$ y ángulo de deslizamiento $\sim 67^\circ$), el cual revela que el esfuerzo horizontal máximo predomina en el área de estudio ($S_{Hmax} > S_{Hmin} > S_v$).

Palabras clave: Esfuerzo horizontal máximo, estado de fuerza actual, mecanismo focal, Sierra Madre Oriental, sismicidad intraplaca.

Abstract

We relocated 52 events of $2.5 \leq M_c \leq 3.6$ from a seismic sequence of over 250 events that occurred during July-December 2012 southwest of the Linares area, northeastern Mexico. To examine this swarm four seismic stations were installed in the region and operated during different time periods from September to December. Relocation of the swarm showed that the earthquake hypocentral depths were at $8 (\pm 5)$ km, and the time residuals had values ≤ 0.38 s. The fault plane solutions were generated for individual earthquakes and through the use of the composite mechanism technique. The focal mechanism solutions show pure reverse faulting; the SW dipping NNW – SSE trending nodal plane is the inferred fault plane (strike $\sim 150^\circ$, dip $\sim 50^\circ$ and rake $\sim 67^\circ$), which reveals that maximum horizontal stress ($S_{Hmax} > S_{Hmin} > S_v$) predominates in the area.

Palabras clave: Maximum horizontal stress, current stress field, focal mechanism, Sierra Madre Oriental, intraplate seismicity.

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Introduction

In recent years, the increase of temporary and permanent seismic networks in the interior of continents has allowed the study of the deformation processes in stable continental regions. The recording data have been used to improve the accuracy in location, obtain focal mechanism, and determine the current stress fields. According to Zoback and Zoback (1980) knowing the pattern of the stress field and its variations are useful to understanding the tectonics of a region. Northeastern Mexico has had a complex geological history characterized by several tectonic events. These have produced the irregular morphology of the crust that has been revealed through gravity data (e.g., Mickus and Montana, 1999; Bartolini and Mickus, 2001). Intraplate seismicity can be correlated with pre-existing faults (e.g., associated with ancient suture zones) which are optimally-oriented for reactivation in the current stress field (Hurd and Zoback, 2012; Ramos-Zuñiga *et al.*, 2012a). Although large intraplate earthquakes are rare, these infrequent events can be extremely devastating because the cities in stable continental region are seismically poorly prepared. These earthquakes can also cause widespread damage because the attenuation of seismic energy is relatively low in plate interiors (Hanks and Johnston, 1992; Crone *et al.*, 2003; Montalvo-Arrieta *et al.*, 2015).

A seismic sequence occurred from July through December 2012, southwest of the city of Linares. This is the first sequence reported in northeastern Mexico since the installation of two permanent broadband seismological stations (LNIG in 2006; and MNIG in 2012) in the region by the Mexican National Seismological Service (Servicio Sismológico Nacional, SSN) in collaboration with the Facultad de Ciencias de la Tierra (FCT) of the Universidad Autónoma de Nuevo León (UANL). The SSN reported 85 earthquakes with $2.9 \leq M_c \leq 3.6$ during this time period. Some of these events were felt by inhabitants of small communities near the epicentral area. In this work we present an analysis of the earthquake sequence that occurred southwest of the Linares area, using a temporal broadband seismic network. This allowed us to relocate the seismic activity, obtain focal mechanisms, and provide a seismotectonic interpretation of the seismic clustering.

Tectonic setting

The morpho-tectonic features located in northeastern Mexico have been generated

by the results of several geological processes that occurred in the past. Moreover, the main tectonic events that have affected this area have been related to: (a) the separation of supercontinent Rodinia in Neoproterozoic-early Paleozoic (Torsvik, 2003) that generated the Iapetus Ocean in the southeast continental margin of North America (Stewart, 1988). (b) The collision of the Gondwana and Laurasia landmasses during the Paleozoic that shaped the Pangea Supercontinent (Sedlock *et al.*, 1993). (c) The split of Pangea that was initiated in late Triassic in Northeast Mexico (Goldhammer, 1999; Padilla y Sánchez, 1985). This was the starting point for the rifting process which formed the Gulf of Mexico (Padilla y Sánchez, 1982; Goldhammer *et al.*, 1991; Goldhammer, 1999). (d) The beginning of the Laramide Orogeny in the Late Cretaceous and Early Tertiary with the development of the detachment of the Mesozoic sedimentary sequence. This created the Sierra Madre Oriental (SMOr; Padilla and Sánchez, 1982; 1985; Eguiluz de Antuñano *et al.*, 2000). (e) The Cenozoic is represented by extensive deformation along normal faults, which are part of Llanura Costera del Golfo Norte de Mexico (LICGNM) (Echánove, 1986; Ortiz Ubilla and Tolson, 2004). As Mickus and Montana (1999) mentioned, the geologic and tectonic framework of northeastern Mexico is known from numerous geological studies and compilations. The region's general crustal structure, particularly the deeper crustal structure, remains relatively unknown due to the lack of published deep drill holes and geophysical studies. These authors determined a general crustal structure of the region by processing gravity data and correlating it to the regional geological and tectonic information of northeastern Mexico.

Historic seismicity

Northeastern Mexico has been considered a tectonically stable region, characterized by low seismicity (Galván-Ramírez and Montalvo-Arrieta, 2008), that according to Johnston *et al.* (1994) represents the southern limit of Eastern North America (ENA). Recent studies show that seismic activity has existed in the area (García Acosta and Suárez Reynoso, 1996; Casasús, 2003). Galván-Ramírez and Montalvo-Arrieta (2008) compiled a catalog of 144 earthquakes for the region from 1787 to 2006 (Figure 1) with magnitudes ranging from 2.3 to 4.8, and three major earthquakes: (1) Parral, Chihuahua in 1928, (M_w 6.5, Doser and Rodríguez, 1993), (2) Valentine, Texas in 1931 (M_w 6.4, Doser, 1987), and (3) Alpine, Texas 1995 (M_w 5.7, Xie, 1998; Frohlich and Davis, 2002). On the

other hand, Rodríguez-Cabo (1946) studied a "swarm" of small earthquakes which took place in August 1944, and which was felt within a 10 km radius from General Terán township, approximately 50 km north of city of Linares. This author proposed that the seismic swarm was originated by the collapse of caverns in the subsoil. It is noteworthy that the conclusions obtained by Rodríguez-Cabo (1946) were not based on seismic stations, but were obtained from what people felt. This can be taken as the first reported evidence of seismic sequences within this region. With the installation of seismological station LNIG in the Linares area (Montalvo-Arrieta *et al.*, 2006; Ramos-Zuñiga *et al.*, 2012b), the recording of seismic activity has increased drastically in northeastern Mexico, increasing from 13 earthquakes reported in the 1981 – 2005 period, to more than 104 quakes in the last six years (2006 – 2012). Approximately 85% of this seismicity took place during a seismic swarm from July to December 2012. Some of these earthquakes have caused minor structural damage near the epicenters in some localities of the state of

Nuevo León, see Ramos-Zuñiga *et al.* (2012a, b) for more details.

Seismic sequence July – December 2012

During July - December 2006, a sequence of small earthquakes ($M_c \leq 3.6$) occurred near the Linares area. Most of the earthquake activity was recorded by the permanent station LNIG of the SSN. The preliminary location of events in the seismicity cluster showed a diffuse image of the seismicity distribution (Figure 2). Several low magnitude earthquakes were felt southwest of city of Linares. Minor damage in houses was reported from some villages near the epicentral area, as well as extensive concern among the population in the region. Small landslides and rockfalls in the SMOr mountain range southwest of Linares were reported. Some preliminary epicentral locations by SSN with the LNIG station suggested the earthquakes occurred northeast of LNIG (Figure 2) but it was necessary to obtain more data to verify the locations of these events.

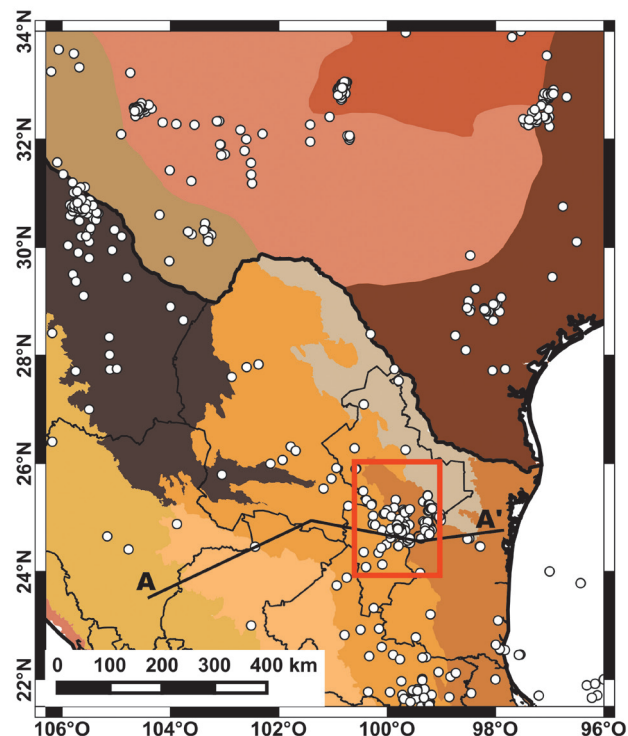
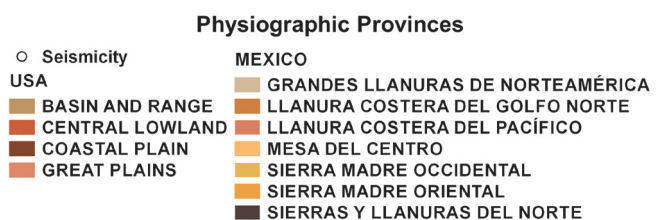


Figure 1. Distribution of seismicity for the 1847–2012 period for the northeastern Mexico and southern Texas. The physiographic provinces of central USA and northern Mexico are indicated by the different colors. The red rectangle is the study area. The solid line A - A' corresponds to the profile of the gravity model proposed by Bartolini and Mickus (2001) used in Figure 10.



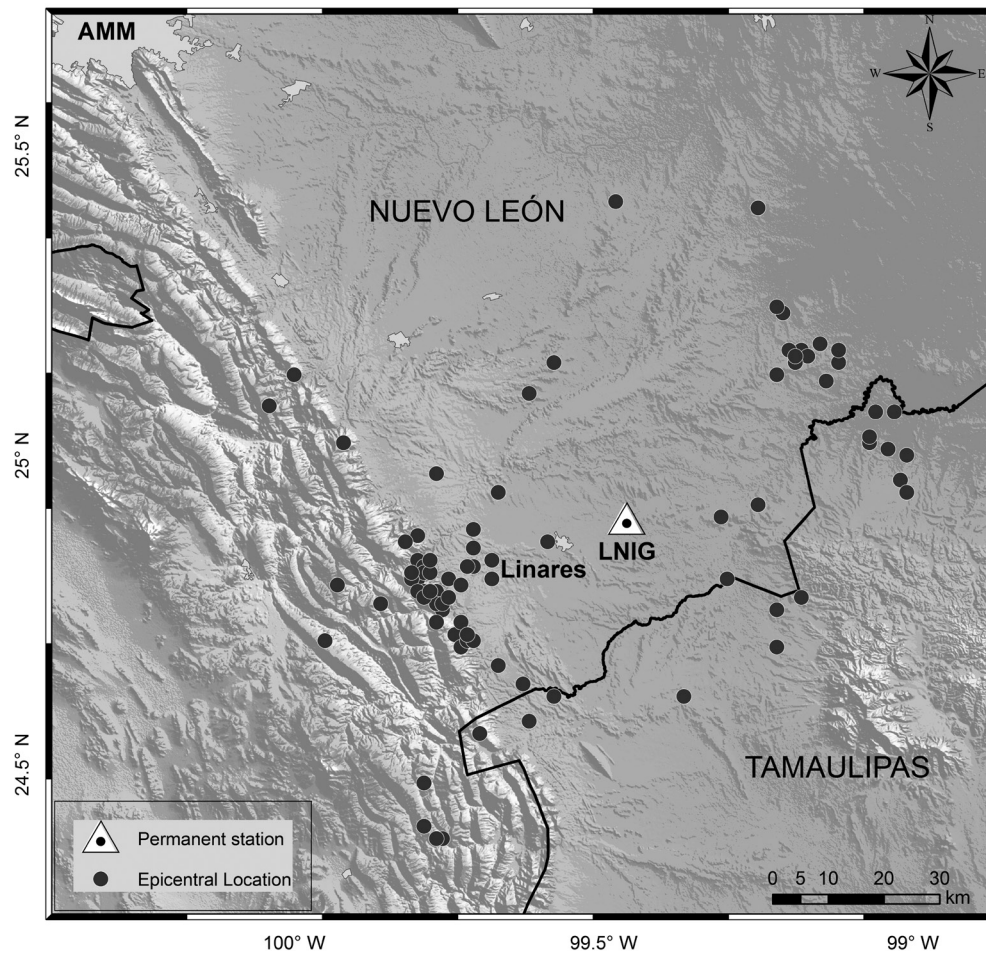


Figure 2. Preliminary epicentral locations obtained using a single station method (LNIG station) for the seismic sequence of July-December 2012 in the state of Nuevo Leon.

Permanent and temporal seismic network

In order to obtain more accurate data for the location of the seismic swarm, the FCT-UANL and the Geophysical Institute, UNAM, installed two temporary seismic stations TAU and BB3 during September-December 2012. The temporary stations were located southwest of the city of Linares near the epicentral area. The permanent LNIG station consists of a STS-2 seismometer, an FBA-23 accelerometer, and a 24 bit Quanterra digitizer. The MNIG stations consist of a Guralp CMG-40T seismometer, a FBA-23 accelerometer and a Reftek digitizer. The temporary stations had a 120 s triaxial Trillium sensor and a 24 bit Taurus digital seismograph. Although these stations were installed during September-December, for various reasons the four stations only recorded simultaneously during November. Otherwise,

in the months of September, October, and December only three seismic stations were simultaneously working.

Relocation

The locations of local earthquakes have been recorded since 2006 by SSN in Northeast Mexico. The data have been obtained from a single 3-component station (one station method, e.g. Alessandrini *et al.*, 1994; Agius and Galea, 2011). This location method has been proved reliable in the absence of more than one seismic station (Frohlich and Pulliam, 1999). With the installation of MNIG, along with two temporary broadband seismic stations, we performed the relocation of 49 events previously reported by the SSN and the location of 3 events not reported previously.

Processing

Earthquake location

Manual picking of *P*- and *S*-wave arrival times and measurements of signal duration were performed for events recorded by one or all stations (Figure 3). The velocity model (Table 1) employed by the SSN was used for location. This model is composed of six layers, where the first layer is 16 km thick with $V_p = 6$ km/s, and the V_p/V_s ratio is assumed to be 1.78. We relocated the earthquakes with the program Hypocenter (Lienert and Havskov, 1995) from the Seisan software package (Otemöller *et al.*, 2013). We compared epicenters relocated using the one-station and multiple-station methods. For some locations there was a change in the azimuth direction (of $\sim 45^\circ$ to $\sim 240^\circ$) of the epicenters related to station LNIG as compared to preliminary locations by SSN. This can be attributed to a better station coverage. The epicenters are now located to the west of the

network instead of to the east, although their distance from station LNIG has not changed. Additionally, this work allowed us to show that the difference of one second in the arrival of the phases can create an error in location of 10 km due to the geological structure of the region. The relocated epicenters (Figure 4) show good correspondence with the area of maximum shaking intensity. Many people in the epicentral area reported having heard underground noise previous to feeling the ground shake.

The spatial distribution of stations TAU and BB3 around the cluster helps improve the quality of epicentral locations. The relocation process collapsed the event locations in a northwest-southeast trending cluster along the SMOr mountain range front. The root mean square (*rms*) travel time error values obtained were less than 0.38 s (Figure 5). MNIG was the farthest station, and a distance-based weight was applied to take account of the lower amplitudes of arrivals observed at this station.

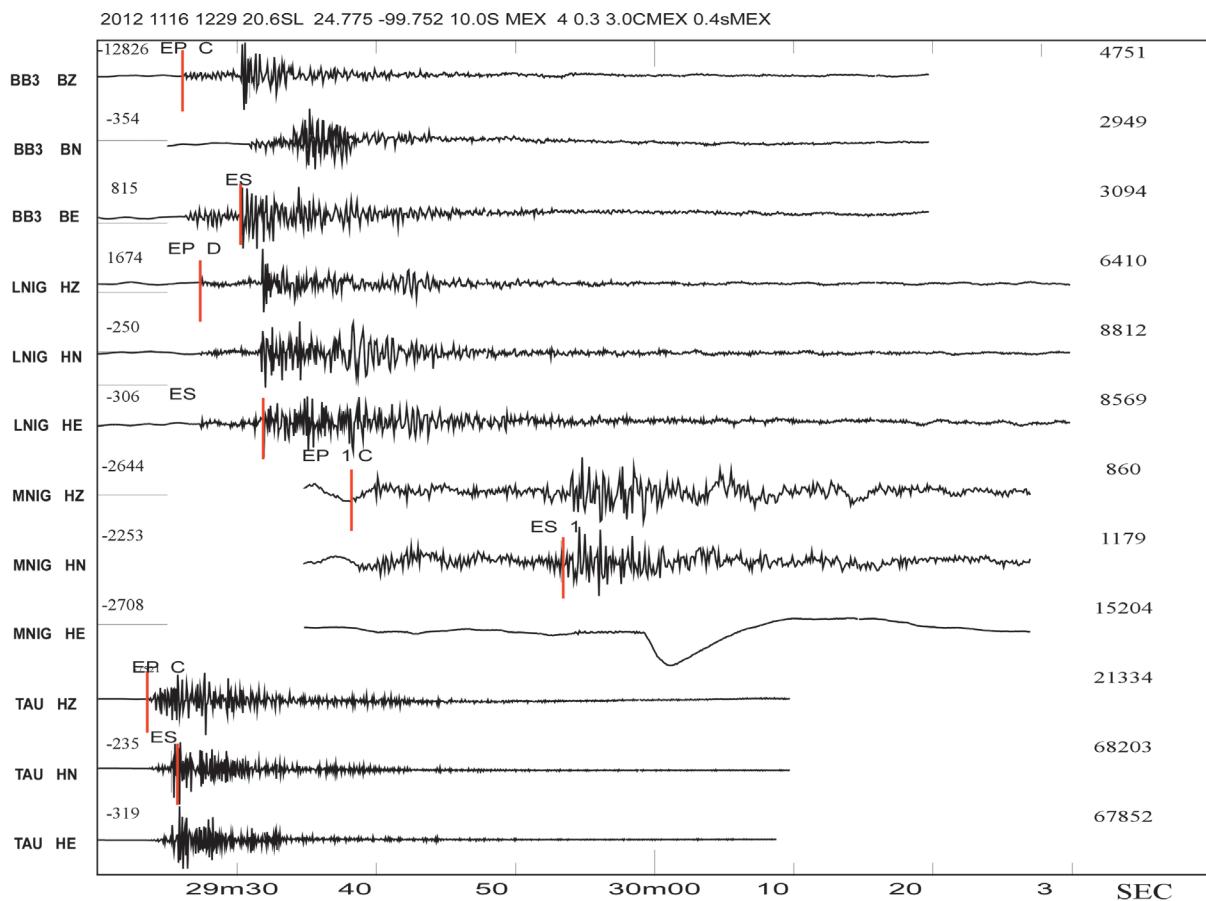


Figure 3. Seismograms for the event of 16 November, 12:29, M_c 3.0. The HE component of MNIG was not well recorded due to instrumental problems.

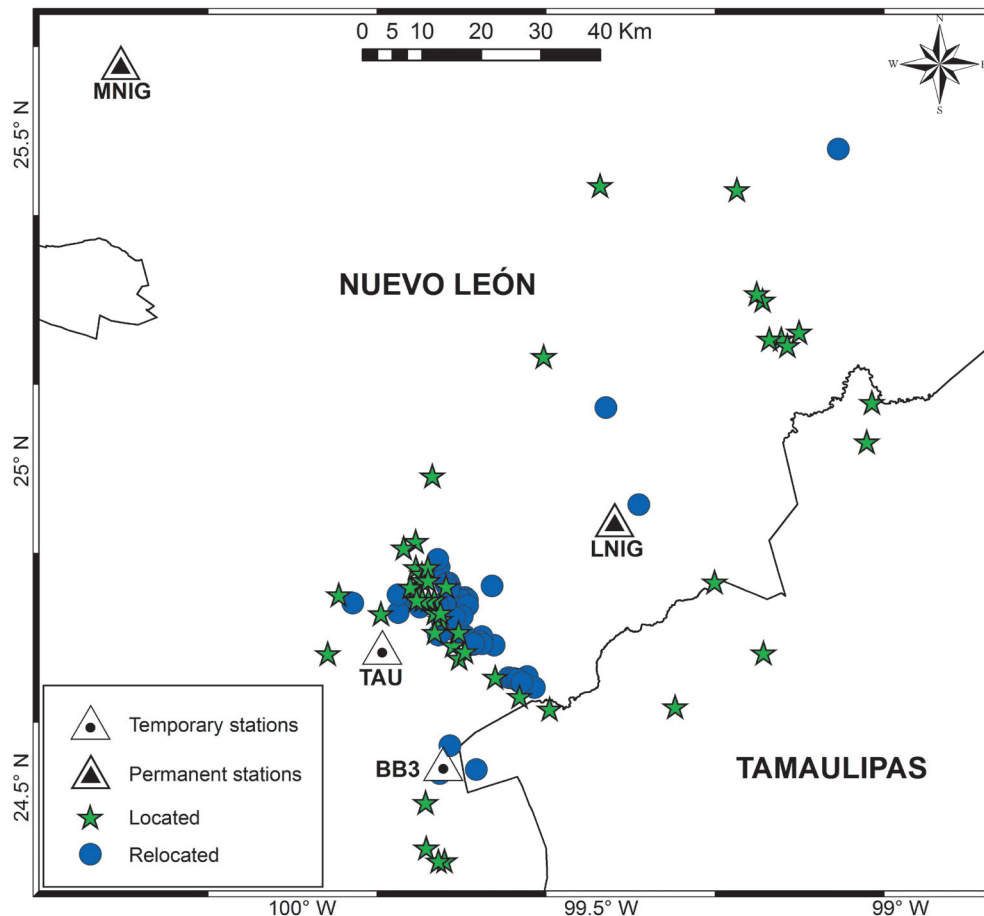


Figure 4. Epicentral comparison between the relocated events using the temporal seismic network (blue dots) and by the one station method using the LNIG (green stars). The new epicentral locations are concentrated to the southwest of LNIG.

The seismic records show similar waveforms between events of the cluster which suggests that the earthquakes come from the same seismic source (Figure 6). The well relocated hypocenters obtained by three or four stations define a focal depth of $8 (\pm 5)$ km for the seismic cluster, while the hypocenters obtained with less than three stations had higher uncertainty (depths varying from 15 to 30 km). Figure 5 (upper right) depicts the residuals obtained for the hypocentral determination of the November 16 (12:29 local time) earthquake ($M_c 3.0$), and the error ellipses of the other three relocations that were obtained with use of the entire four-station network.

To determine the coda magnitude, the seismograms were bandpass filtered between 1 and 5 Hz, and the end of the coda was assumed to occur where the coda wave amplitude had a factor of 2 above the noise amplitude. A

total of 52 well-relocated earthquakes in the magnitude range of 2.6 – 3.6 were obtained from the seismic sequence of more than 250 earthquakes. The rest of the events could not be relocated due to the poor signal-noise levels making it impossible to identify the first P arrive-time.

Focal mechanism

Four of the well relocated earthquakes were used to obtain fault plane solutions that were generated using FOCMEC and HASH. The FOCMEC program uses the first arrival polarities of the P and SH waves and a grid search technique (Snoke *et al.*, 1984). HASH computes double-couple earthquake focal mechanisms from P -wave first motion polarity observations and S/P amplitude ratios (Hardbeck and Shearer, 2003).

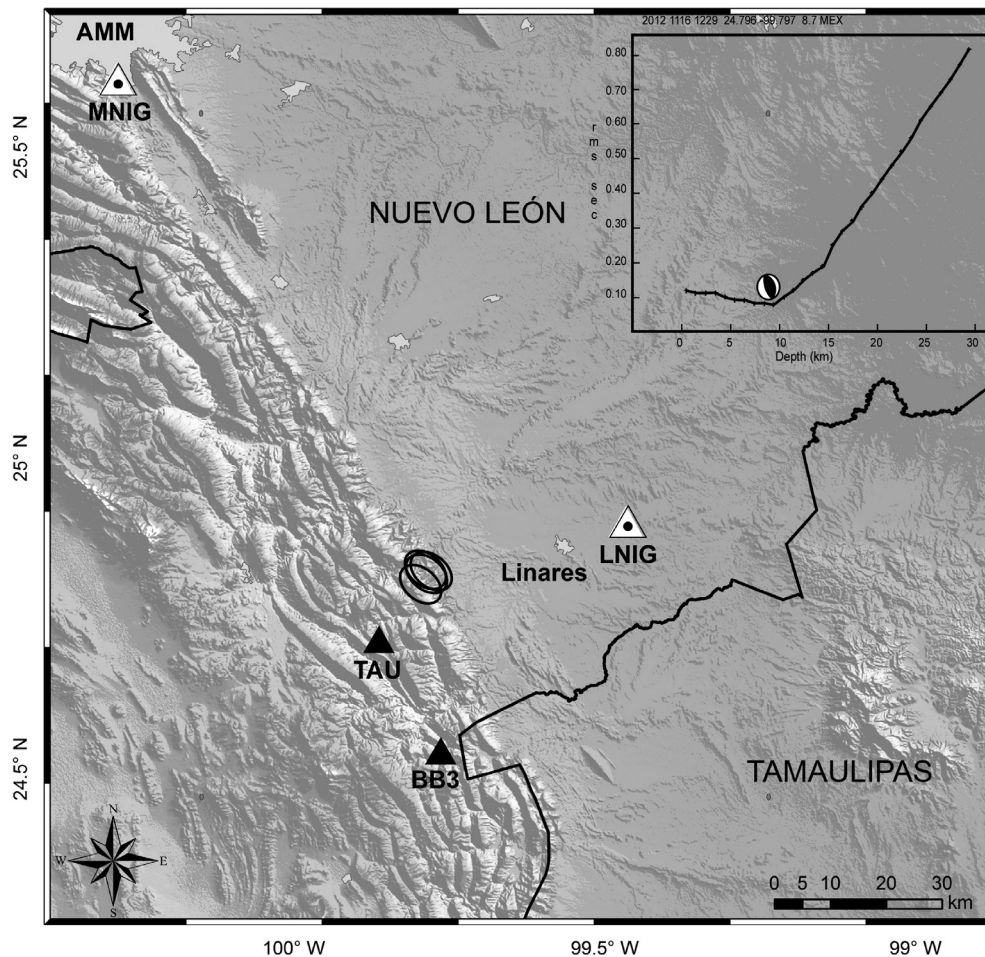


Figure 5. Error ellipses of the four best relocate earthquakes that used the complete four-station network. The upper right corner shows the change of the rms of travel time errors as a function of the focal depth for the 16 November 2012 earthquake.

The solutions obtained for the four earthquakes by FOCMEC and HASH show reverse faulting, and the southwest dipping NNW-SSE trending plane is the inferred fault-plane (Figure 7). Since there is a similarity in the waveforms of the events (Figure 6), it is possible to compute a composite fault plane solution using the 52 best-located earthquakes ($2.5 \leq M_c \leq 3.6$). A composite focal mechanism will give a robust and more general estimate of the stress field orientation. We obtained the composite focal mechanism solutions using SEISAN's FOCMEC program. The results of composite fault plane solution (Figure 8) for the seismic swarm is consistent with individual solutions. The preferred fault's strike was (ϕ) = 150° , dip (δ) = 50° and rake (λ) = 67° , which reveals that maximum horizontal stress $S_{H_{max}} > S_{H_{min}} > S_v$ is predominant in the area.

Discussion and conclusions

A good knowledge of the intraplate seismicity that occurs in northeastern Mexico is critical to understanding the actual stress field of the region. The pressure (P) and tension (T) axes derived from earthquake focal mechanisms are one of the most commonly used indicators of tectonic stress (Zoback and Zoback, 1980). The reverse focal mechanism obtained for the 2012 sequence reveals that maximum horizontal stress ($S_{H_{max}} > S_{H_{min}} > S_v$) predominates in the area (Figure 9).

As mentioned in the introduction, this region has a complex geological evolution that is manifested through the morphotectonic landscapes at surface (Ramos-Zuñiga *et al.*, 2012a), and by the series of geological features interpreted from geologic information, drill-

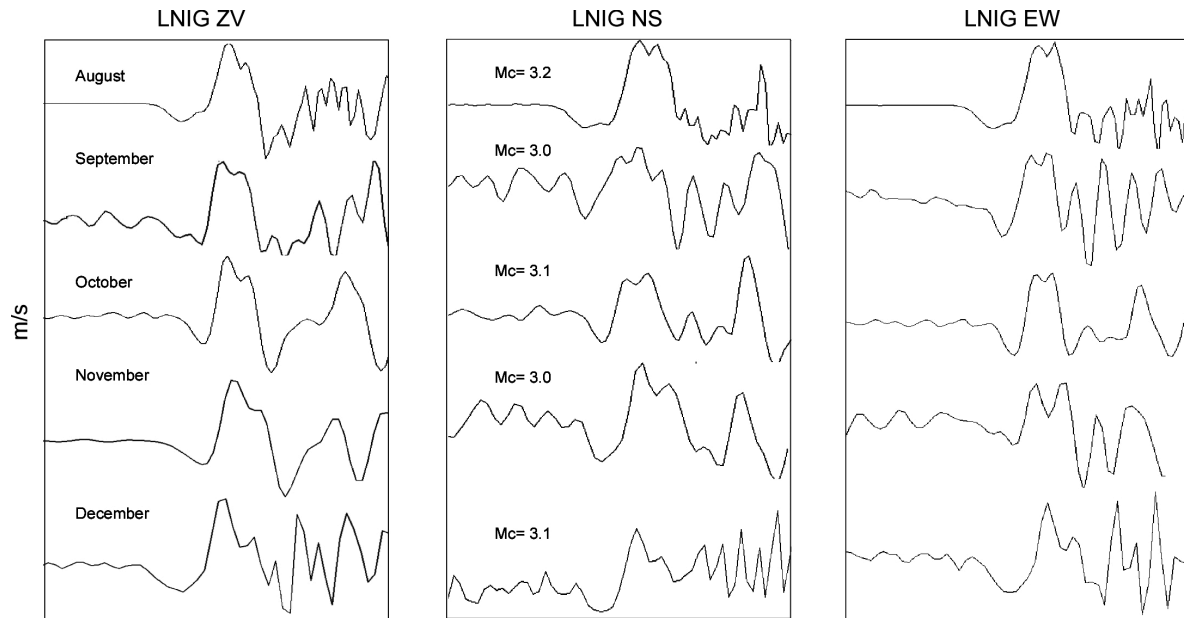


Figure 6. Similarities between waveform for some representative earthquakes of the seismic swarm recorded in LNIG.

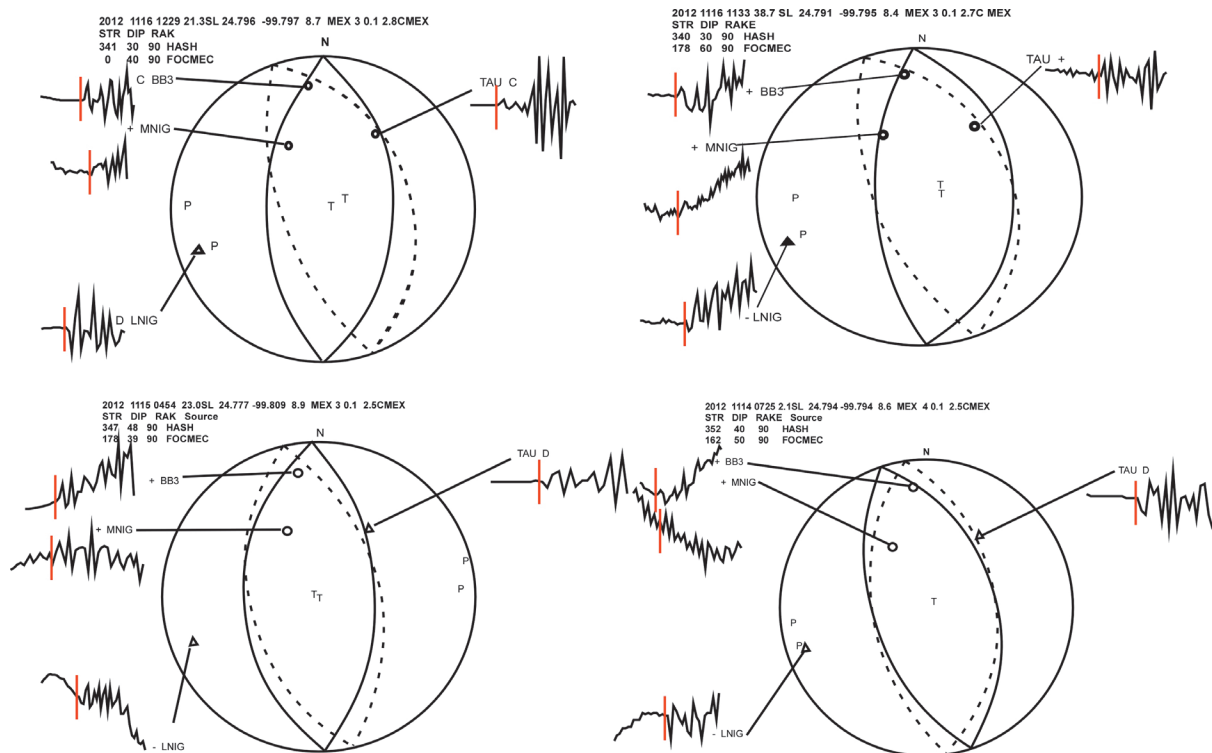


Figure 7. Focal mechanisms from earthquakes recorded by four stations. The seismogram shows the *P*-wave arrival "+" and "-" depict emergent compression and dilatation first motions, respectively; "C" and "D", corresponding impulsive first motions. The solid line is the solution obtained from FOCMEC, and the dashed line represents the solution from HASH.

Figure 8. Composite focal mechanism obtained from the relocated 52 events of seismic sequence from July to December 2012 using the FOCMEC routine. Solid green dots are compressional and the open blue dots are dilatational first motions.

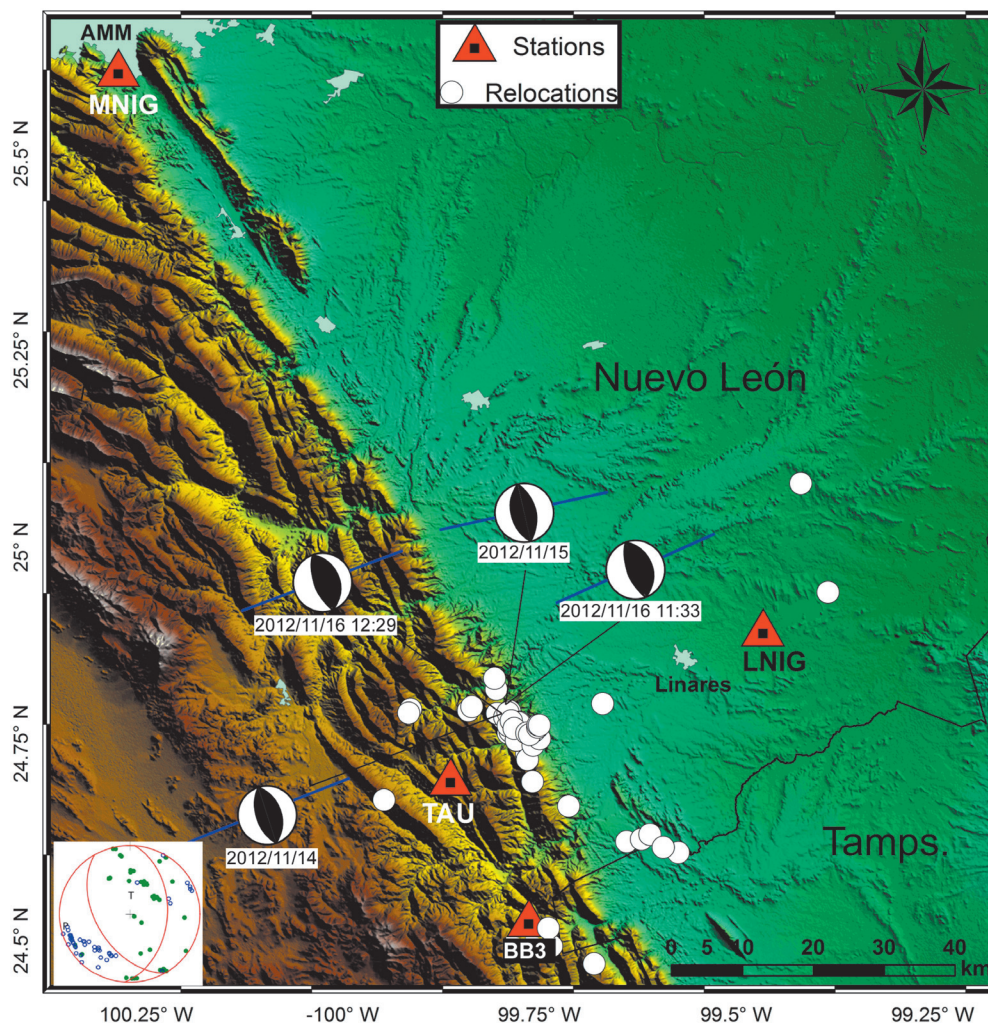
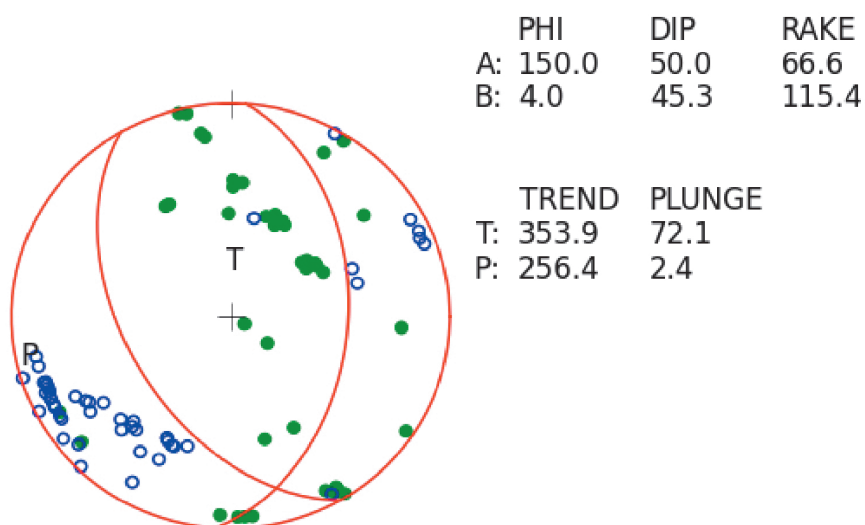


Figure 9. Comparison of relocations and focal mechanisms for the seismic sequence from July to December 2012 in the Nuevo León state. The composite focal mechanism is shown at the bottom left corner.

holle data and gravity models at the crust and upper mantle by Bartolini and Mickus (2001). These authors present a gravity model that crosses the tectonic provinces of Northeastern Mexico. In their gravity profile A-A' (Figure 1) they suggest a crustal boundary composed of two volcanic arcs of Paleozoic and Mesozoic ages, respectively, located approximately at 450 - 480 km from the western edge of their model which coincides with the SMOR and LICGM provinces boundary (Figure 10). The well relocated hypocenters appear to lie at the edge of an upper crustal sequence of Jurassic-Cretaceous strata and lie about 20 km east of the modeled Triassic-Jurassic arc.

On the other hand, at surface, the seismic swarm had an epicentral distribution parallel to the SMOR mountain range front (Figure 9). The fault-plane solution obtained shows a pure reverse faulting, being the SW dipping NNW - SSE trending nodal plane the inferred fault plane.

According to some authors, the current stress field in northeastern Mexico is extensional. Suter (1991) mentions that

the S_{Hmax} direction in the states of Coahuila and Nuevo Leon in the area of the Laramide Coahuila foldbelt is parallel to the Rio Grande rift and Quaternary faults in west Texas and northeast Chihuahua. This parallelism suggests a stress field with $S_V > S_N > S_E$ direction. In the same way, Márquez-Azúa and DeMets (2003) used observations of continuous GPS stations in Mexico to suggest that sites located in northern Mexico (Chihuahua, Tampico, and Monterrey) show residual velocities varying between 1.5 and 3.0 mm/year oriented in a southeast direction, following the present pattern of extension of the Basin and Range provinces. In this sense, the compressional stress field obtained from the 2012 seismic sequence could be considered as contradictory. However, this compressional behavior is the outcome of the deformation caused by push (movement to the East) and possible overthrust of a less dense block A (composed of Jurassic-Cretaceous strata, Triassic-Jurassic arc rocks, and Paleozoic-Jurassic upper crust) that is locked by a denser block B (composed of Permian granite, and Precambrian-Paleozoic upper crust) located just east of the SMOR

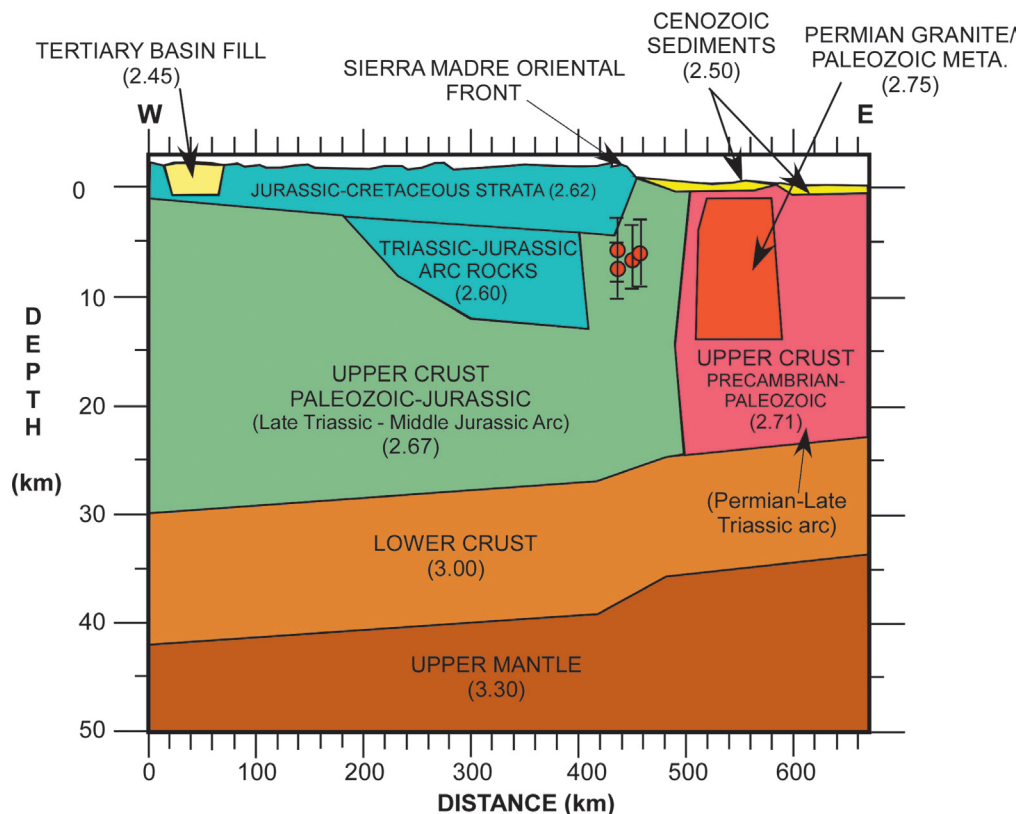


Figure 10. 2.5-D gravity model along profile A - A' (Figure 1) from Bartolini and Mickus (2001) that crosses the southern part of the state of Nuevo León. The numbers in parentheses represent the bodies' average density in gm/cc. We have projected the locations of the four best-recorded earthquakes from the seismic sequence of July to December 2012 on to the section. The error bars indicate depth uncertainty.

front (Figure 10). This results in a compressive stress field that triggers the reactivation of reverse faulting in the area near the mountain front (where the pre-existing faults zones are associated with ancient suture zones). Therefore, the lateral variations in crustal densities and thickness documented in this region can be considered to be the factor that changes the current extensional stress field proposed for northeastern Mexico into a pattern of compressional stress ($S_{Hmax} > S_{Hmin} > S_v$). The same effect is suggested to occur at the limit between the Southern Great Plains and the Mid-Continent provinces north of this region within the United States of America (Zoback and Zoback, 1980).

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