Microzonation of the Linares, Northeast Mexico area, based on geology and shear-wave velocity measurements

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RESUMEN

En este trabajo se ha definido la estructura de velocidades de ondas *S* (V_S) y *P* (V_P), así como el promedio de velocidades ($\overline{V}_{s30}$) para los primeros 30 metros del subsuelo, a partir de perfiles sísmicos de refracción en el área de Linares, Nuevo León, tomándose como indicador de las condiciones de sitio. Se identificaron cuatro diferentes unidades litológicas para estos 30 m de profundidad: limos con velocidades de V_P y V_S de 338 m/s y 221 m/s, los cuales corresponden a los valores más bajos y someros (primeros 3 m) medidos en el área; aluvión (depósitos Cuaternarios) con velocidades respectivas de V_P y V_S de 957 m/s y 559 m/s; conglomerados (Terciario) con velocidades de V_P y V_S de 2471 m/s y 1220 m/s; finalmente lutitas de la Formación Méndez (Cretácico Superior) con velocidades de V_P y V_S de 3195 m/s y 2149 m/s respectivamente. De acuerdo con códigos internacionales de construcción aplicados a la clasificación de suelos y rocas (por ejemplo, the National Earthquake Hazard Reduction Program, USA, por sus siglas en inglés) en el área de estudio predominan los sitios clase C ($\overline{V}_{s30}$ < 760 m/s), los cuales presentan una correspondencia con los espesores máximos (≤ 16m) de sedimentos suaves observados en el área de estudio.

PALABRAS CLAVE: Datos de pozo, curvas de tiempo de viaje, estructura sísmica de velocidades, sismicidad, efectos de sitios, perfiles sísmicos de refracción.

ABSTRACT

We determined the velocity structure of *S*-wave (V_S), *P*-wave (V_P) and the average shear velocity to 30 meters depth ($\overline{V}_{s30}$) at 30 locations in the Linares, Nuevo León area. V_S and V_P measurements were made from seismic refraction profiles. Four different lithologic units were defined in the upper 30 m: silts with 338 m/s and 221 m/s for V_P and V_S respectively, which correspond to the lowest velocities measured in the area; Quaternary deposits with 957 m/s and 559 m/s for V_P and V_S; Tertiary conglomerates with 2471 m/s and 1220 m/s for V_P and V_S; and shales of the Upper Cretaceous Mendez Formation with 3195 m/s and 2149 m/s for V_P and V_S. Sites of class C ($\overline{V}_{s30}$ < 760 m/s) are dominant in the area, corresponding to maximum thicknesses of less than 16 m of soft sediments.

KEY WORDS: Borehole data, travel time curves, seismic velocity structure, seismicity, site effects, seismic refraction profiles.

INTRODUCTION

Seismic methods are useful for determining the strength of earth materials. It has long been established that different soil types respond differently when subjected to ground motion from earthquakes. Usually the younger and softer soils amplify ground motion more strongly than older and more competent soils or bedrock (Montalvo-Arrieta *et al.*, 2002). A simple way to characterize site conditions is by estimating the shear-wave velocity of shallow soils. The average velocity of the first 30 m ($\overline{V}_{s30}$) is a widely used parameter to predict the potential amplification of seismic shaking. This parameter has been used in recent developments of building codes (e.g., Dobry *et al.*, 2000; Wills *et al.*, 2000; Boore, 2004). A decreasing value of $\overline{V}_{s30}$ often correlates with an increase in amplification of earthquake ground motion, and with unconsolidated Quaternary deposits (Williams *et al.*, 2003). The site classification obtained from shallow shear-wave velocity models is important in deriving strong-motion prediction equations (e.g., Boore *et al.*, 1997; Toro *et al.*, 1997).

The Linares area is located in the Coastal Plain of the Gulf of Mexico (Figures 1 and 2). It is generally considered tectonically stable as it is characterized by low seismicity and a lack of ground-motion records (Galván-Ramírez and Montalvo-Arrieta, 2005). In northern Mexico and the U. S. border region, the main historical earthquakes are the 1887 Bavispe, Sonora (M_W = 7.4; Natali and Sbar, 1982), the 1928 Parral, Chihuahua earthquake (M_W = 6.5; Doser and Rodríguez, 1993), the 1931 Valentine, Texas earthquake (M_W = 6.4; Doser, 1987), and the Southwest Texas earthquake of April 14, 1995, (M_W 5.7; Xie). Only about 5% of the global seismic energy is released in continental interiors (Talwani, 1999; Crone *et al.*, 2003), but the human impact of intraplate earthquakes justifies efforts to understand and assess the potential hazards in stable regions. Galván-Ramírez and Montalvo-Arrieta (2005) made a compilation of the historical seismicity and estimated the peak ground acceleration for three seismic scenarios in northeast Mexico, using attenuation relationships by Toro *et al.* (1997). Their results did not include site effects. In this work we investigate the seismic velocity structure of *P* y *S* waves in the upper 30 m

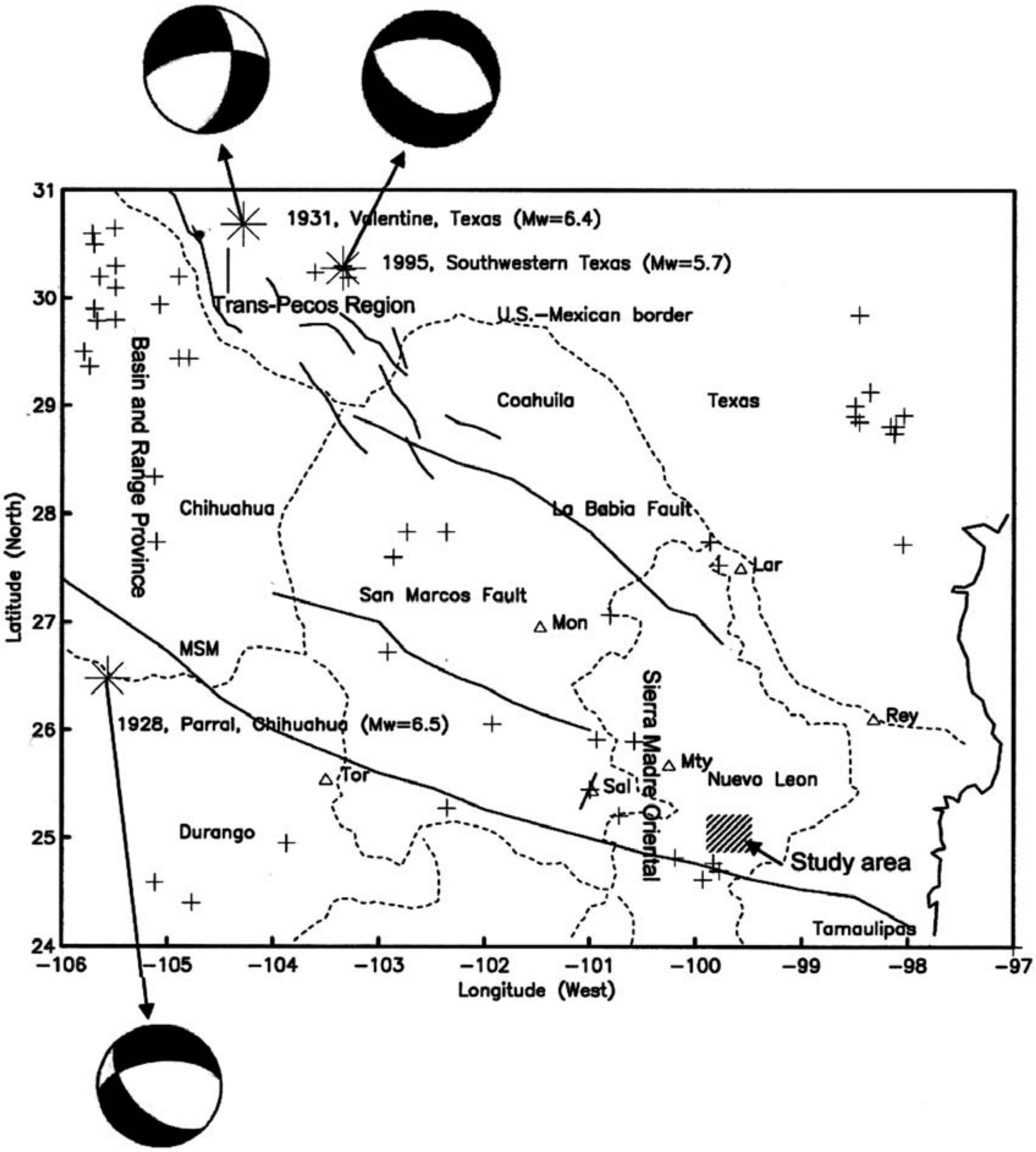

Fig. 1. Historic seismicity of northeast Mexico and south Texas (1928-2003). The asterisk represents the largest earthquakes in the region. The crosses show the seismic activity less than 4.8. The solid lines depict the three general zones of north-northwest trending lineaments and faults that have been identified or postulated in northeast Mexico. The La Babia fault, San Marcos fault, the Mojave-Sonora megashear (MSM). Triangles are some cities (Chi: Chihuahua; Tor: Torreón; Mon: Monclova; Sal: Saltillo; Mty: Monterrey; Lar: Nuevo Laredo; Rey: Reynosa). The focal mechanism was taken from Doser (1987); Doser and Rodríguez (1993), and Harvard-CMT (2005).

for the Linares region by means of seismic refraction profiles and borehole data.

GEOLOGICAL FRAMEWORK

Northeast Mexico is underlain by Mesozoic-Cenozoic sedimentary rocks deposited over rocks of Paleozoic age. Mickus and Montana (1999) review the tectonic evolution in this region.

In the Linares area the oldest outcrops are in the Méndez Formation (Fm), north and south of the study region. This formation is composed of shales of Upper Cretaceous age, with a thickness greater than 45 m (López Ramos, 1982), and will be taken as bedrock. The younger rocks include conglomerates (Tertiary age), Quaternary alluvium and recent soils, mostly silts (Lizarraga-Mendiola *et al.*, 2005). The alluvium and silts are distributed mainly in a west-east direction (Figure 2), where deep soils that correspond to old stream beds are located (Figure 3). Under the town of Linares, the thickness of sediments decreases as shown in section B-B’ of Figure 4. This is due to erosion from Pablillo and Camachito rivers. To the east of La Petaca the thickness of sediments increases.

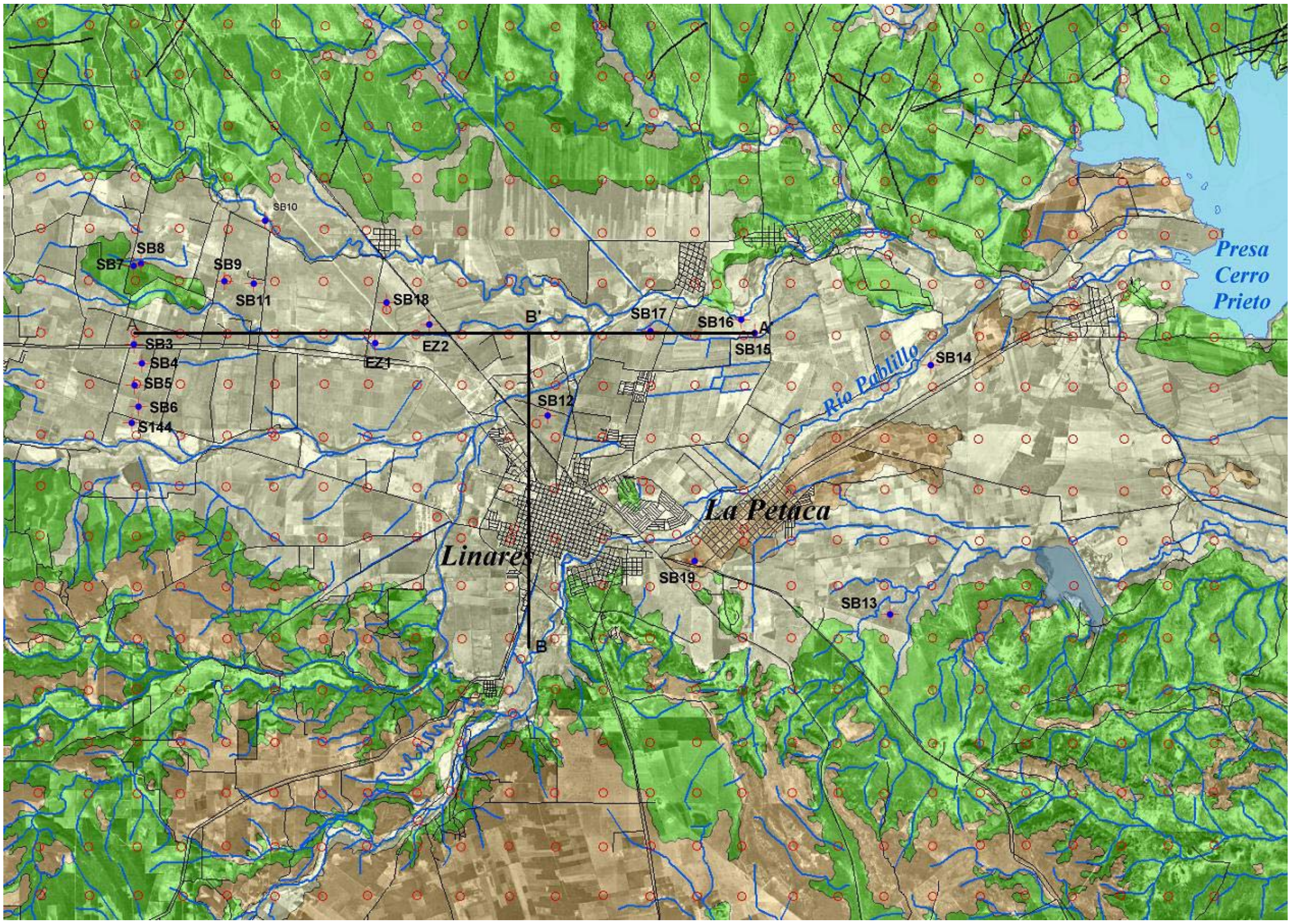

Fig. 2. Geologic map of the Linares region (green: shales of the Méndez Fm. (Upper Cretaceous), brown: conglomerates (Tertiary) and gray: Quaternary sediments (alluvium and silts). Location of the borehole data and the seismic refraction profiles.

SEISMIC DATA

The seismic velocity structure in the upper 30 meters was measured at 13 locations in the Linares region by seismic refraction, and from earlier borehole data at 17 sites (Figure 2). The seismic refraction data was interpreted using travel-time curves. First-arrival phases were picked assuming they were refracted from the same interface (Figure 5). Velocities were computed from the slope of the line connecting arrivals, assuming that the velocity is constant along the profile. We used a RAS-24 Remote Acquisition System with 24-bit A/D conversion in a 24-channel box, with horizontal and vertical geophones and a sledgehammer as seismic source.

The geophone array had variable intervals of 1.0 m, 5.0 m, and 10 m for both *P* and *S* waves. Source-receiver distances ranged from 11m to 110 m, in both direct and inverse profiles. From the dimension of the geophone array, we expected to reach a maximum penetration of 40 meters. In long profiles the signal-noise ratio was low at distances

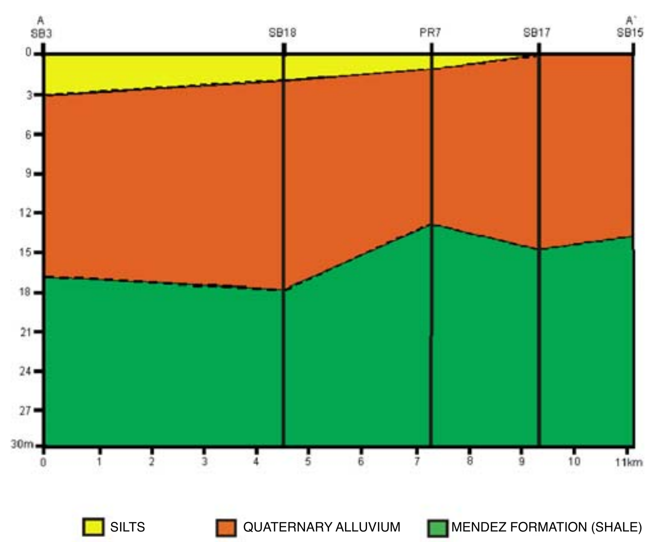

Fig. 3. Geologic cross section with east-west direction constructed from borehole and seismic refraction data.

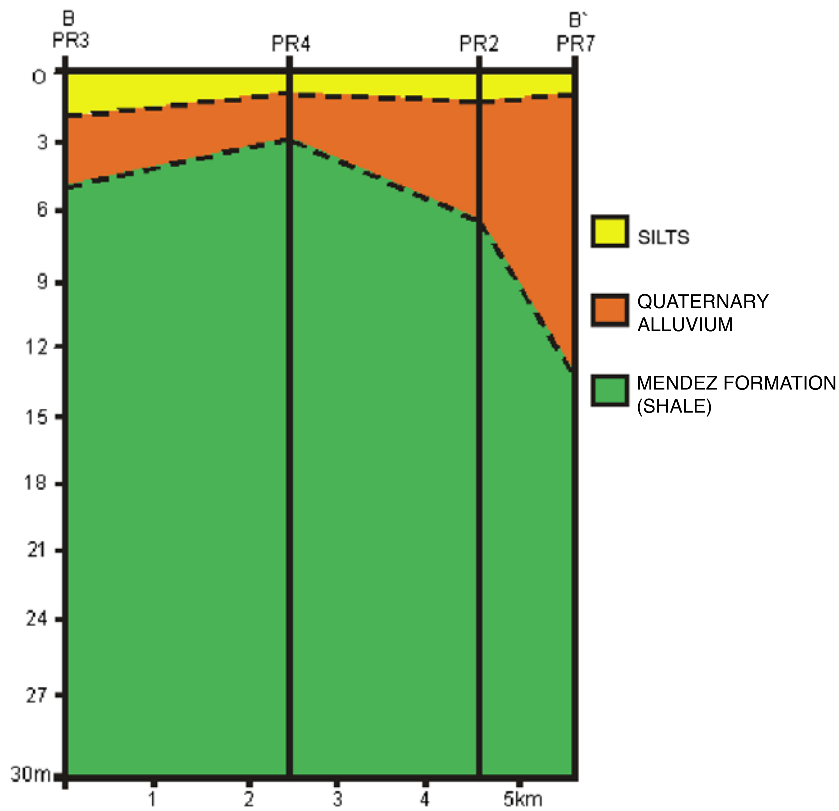

Fig. 4. Geologic cross section with north-south direction constructed from seismic refraction data.

greater than 70 m. However, the seismic energy was adequate for studying the upper 30 m. Figures 6 and 7 show the calculated travel-time curves at sites PR5 and PR3 for *S* and *P* waves, using 5 and 10 m separation intervals between geophones. At PR5, we identified three different materials (alluvium, conglomerate and shales) with the following velocities: 512, 800 and 1707 m/s for *S* waves, and 714, 1351 and 2393 m/s for P waves. Figure 7 shows the direct and inverse profiles for a 110 m profile at PR3. The velocities obtained were 2500-2500, 4019-4024 m/s for P waves and 1600-1666, 2468-2498 m/s S waves.

Table 1 shows the average results for *P* and *S* waves obtained in the four lithologic units: shales, conglomerates, alluvium and silts. Figure 8 shows the thickness and seismic velocities for all seismic profiles in the study area. From borehole data, for the upper 30 meters (Figure 9), the same lithological units are present. We measured seismic profiles near some boreholes. The thicknesses obtained from seismic velocity structure are very close to the lithologic description of the borehole data. This allows us to correlate *P* and *S* wave velocities of superficial material with the same materials at depth. Figure 10 compares the seismic velocity structure with the borehole data for sites PR6 and SB19. At SB19 we assigned the average *P* and *S* velocities from Table 1 to the material found in the borehole, and we constructed the seismic velocity structure for this site.

According to NEHRP building codes, the soil conditions were classified in six different groups (Table 2). We

Table 1

Average of *P* and *S* waves for the different geological units in the study area

Geological unit	V_{Smin}	V_{Smean}	V_{Smax}	V_{Pmin}	V_{Pmean}	V_{Pmax}
Recent Soils (silts)	160	221	330	255	338	470
Alluvium (Quaternary)	375	559	760	640	957	1770
Conglomerate (Tertiary)	1040	1220	1405	1915	2471	3750
Shales (Upper Cretaceous)	1640	2149	2750	2350	3195	4090

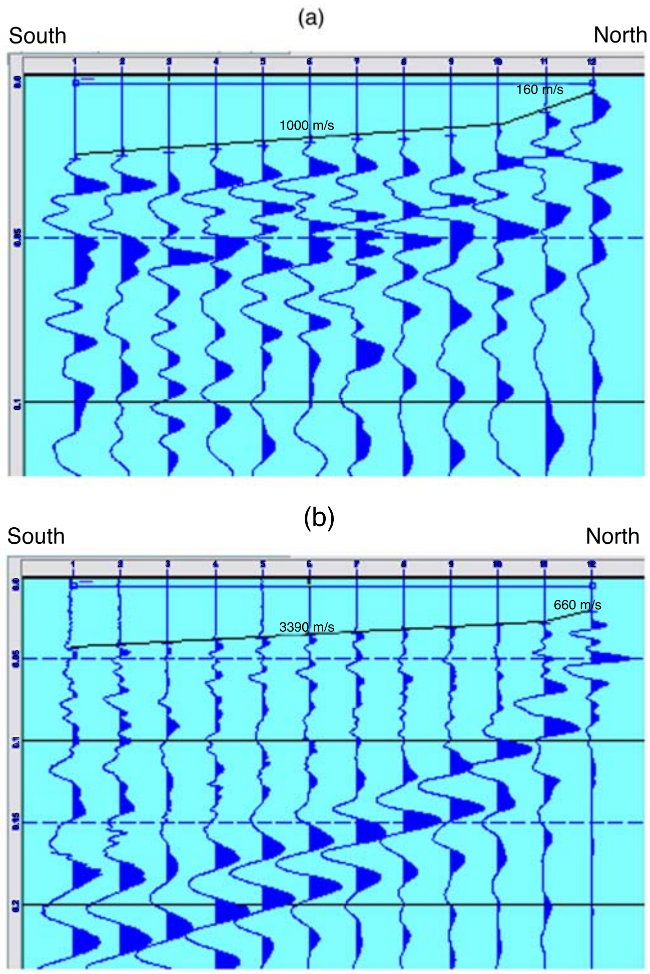

Fig. 5. (a) *S* wave seismic refraction profile at PR3 site, the interval of separation between geophones is 1 m (11 m of longitude) and 1 s of record length. The seismic velocities obtained were: 160 m/s and 1000 m/s, respectively; (b) *P* wave seismic refraction profile at PR5 location, the interval of separation between geophones is 5 m (55 m of longitude) and 0.5 s of record length, with velocities of 660 m/s and 3390 m/s, respectively.

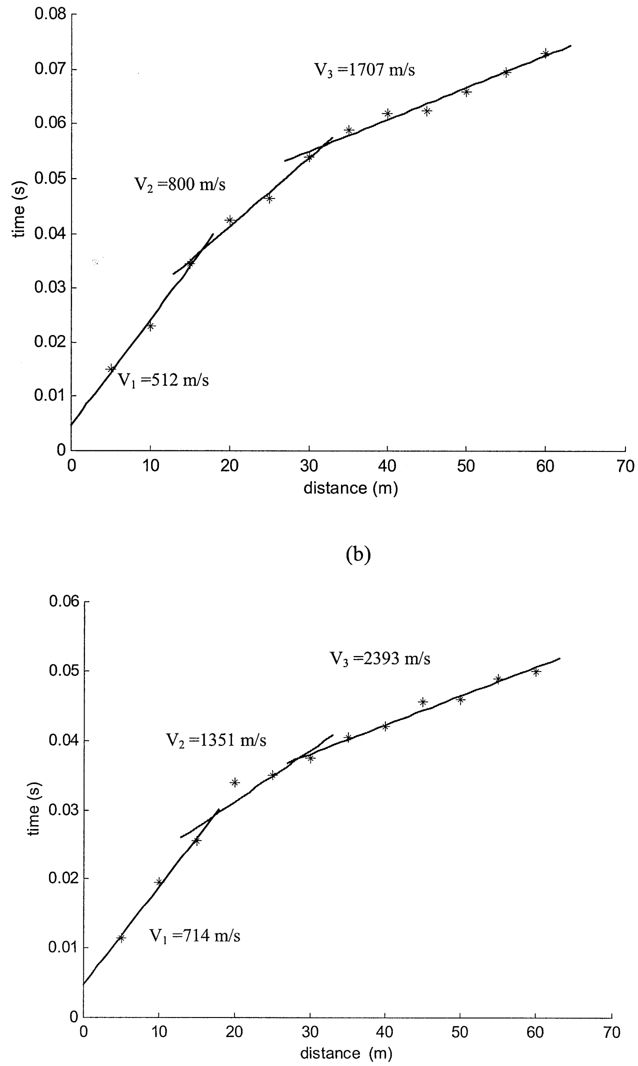

Fig. 6. (a) Travel time curves of *S* waves for site PR5 (the interval of separation between geophones is 5 m), where 3 layers were determinate (alluvium, conglomerates and shales); (b) Same as (a) but for *P* waves. The travel time curves correspond to direct profile.

estimated the average shear-wave velocity $\overline{V}_{s30}$ as an indicator of site response by means of:

$$\overline{V}_{s30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}} ,$$

where d_i is the thickness of the i^{th} layer between 0 and 30 m and V_{Si} is the shear-wave velocity layer in the i^{th} layer (Williams *et al.*, 2003; Boore, 2004). Table 3 shows the location of the seismic profiles and the borehole data. The $\overline{V}_{s30}$ values for each site and their corresponding site classification are given in Table 2.

RESULTS

We carried out 13 seismic refraction profiles in the Linares area. These seismic profiles cover the main geologic structures in the study area: (a) old streamchannels west and east of Linares city, where the maximum thickness of Quaternary sediments is found, (b) recent deposits of Camachito and Pablillo rivers, within the urban area of Linares; (c) some outcrops of bedrock north and south of the study area (Figure 2). We combined our seismic data with information from 17 earlier boreholes that had a lithologic description. Taking data from Table 1, we assigned an average velocity of *S* waves to the different units defined in each borehole site and we obtained the $\overline{V}_{s30}$ values for these locations, as in Table 3.

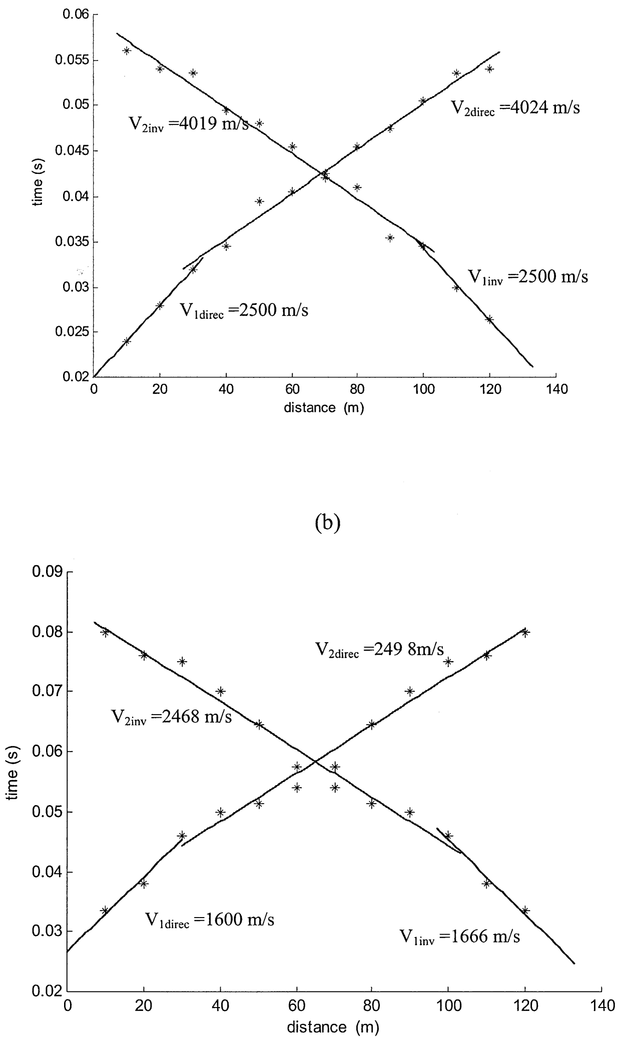

Fig. 7. (a) Travel time curves of *P* waves for site PR3 (the interval of separation between geophones is 10 m); (b) Same as (a) but for *S* waves. The travel time curves correspond to direct and inverse profiles. The velocities obtained for *P* and *S* waves correspond to the bedrock (fractured and dense shales).

Table 2

Site classifications using $\overline{V}_{s30}$ as an indicator of site response (NEHRP)

Soil Profile Type	Rock/Soil Description	$\overline{V}_{s30}$ (m/s)
A	Hard rock	> 1500
B	Rock	760-1500
C	Very dense soil/soft rock	360-760
D	Stiff soil	180-360
E	Soft soil	< 180
F	Special soils requiring site-specific evaluation	

Figures 8 and 9 show the velocity for *P* and *S* waves, and the thickness of sediments for all sites. These 30 sites (seismic profiles plus borehole data) cover the study area, which enables us to define the seismic velocity structure of the upper 30 meters and the geometry of the valley. The lowest values of V_s were usually found in the upper 3 m and varied from 160 m /s at PR12 to 330 m /s at PR5. The average velocity obtained for the silts was 221 m/s.

Only six sites (PR8, SB3, SB4 SB8, SB12 and SB18) correspond to class C according to the site classification. The remaining sites are classified as A and B. Figure 11 shows a contour map of $\overline{V}_{s30}$ in the Linares area using program ArcGis with a combined topogrid/spline gridding approach (Schuster, 1999; Masuch Oesterreich, 2001). Note that the low values of $\overline{V}_{s30}$ (≤ 760 m/s) are located west of Linares city. These low values are correlated with large thicknesses of recent soils and of Quaternary alluvium (green), as shown in Figure 3. They are interpreted as old paleo-channels filled with alluvium with thicknesses 14 to 16 meters (boreholes SB3, SB18). In Linares city the thickness of Quaternary material decreases (Figures 3 and 4). The decrease is attributed to

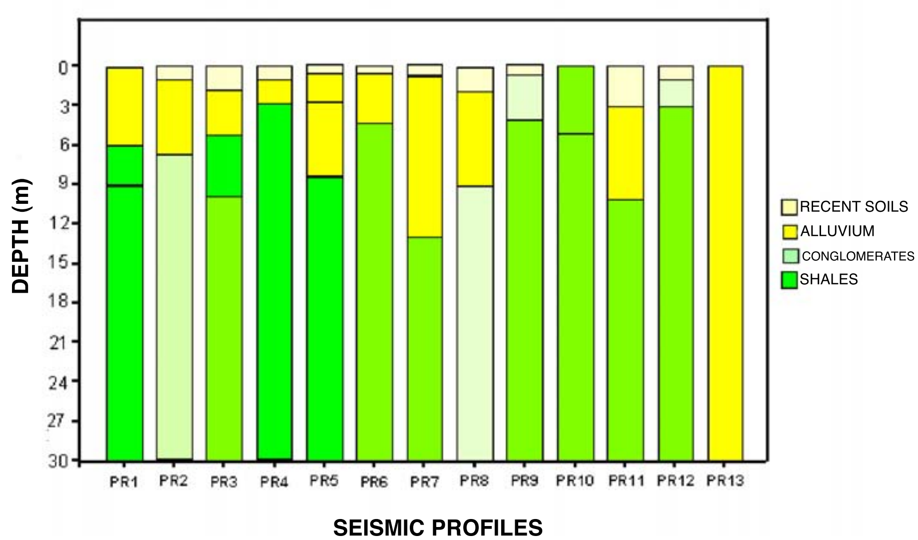

Fig. 8. Depth of the different geologic units in the study area, interpreted from refraction profiles.

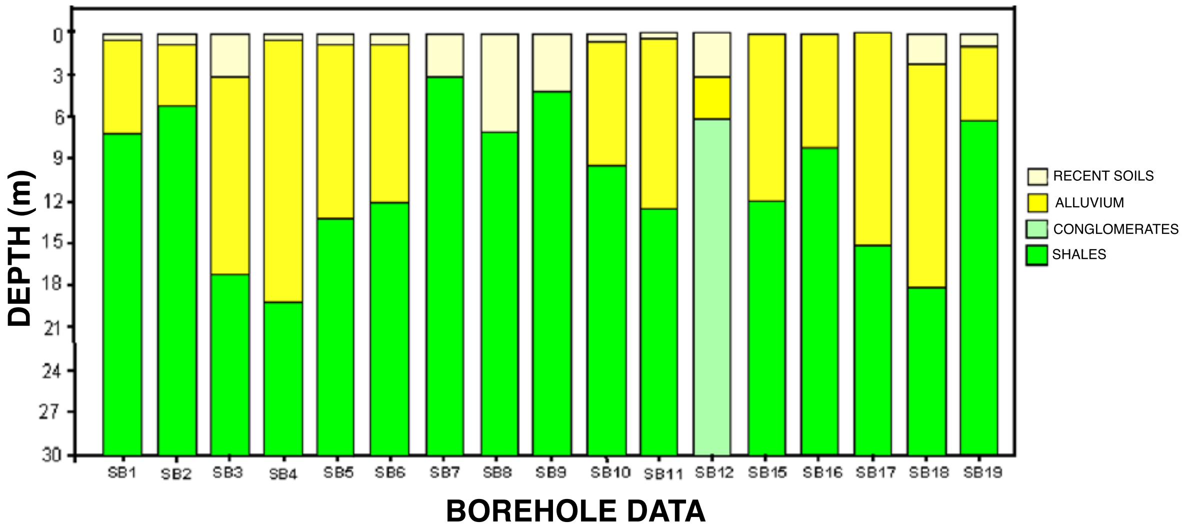

Fig. 9. Description of the borehole data used in this study. The seismic velocities defined in each borehole correspond to the average of *P* and *S* waves (Table 1) obtained from seismic refraction data (Figure 8) for all geologic units identified in the area.

Table 3

Station parameters

Site	Latitude (N)	Longitude (W)	$\overline{V}_{s30}$ (m/s)	Soil Profile Type
PR1	24.868	99.552	1592	A
PR2	24.877	99.573	793	B
PR3	24.838	99.573	1225	B
PR4	24.858	99.576	1170	B
PR5	24.859	99.545	1119	B
PR6	24.862	99.533	2023	A
PR7	24.856	99.569	928	B
PR8	24.791	99.539	737	C
PR9	24.897	99.465	1710	A
PR10	24.911	99.502	2504	A
PR11	24.875	99.619	950	B
PR12	24.862	99.588	1656	A
PR13	24.932	99.500	2504	A
SB1	24.873	99.657	1248	B
SB2	24.8725	99.657	1318	B
SB3	24.887	99.641	716	C
SB4	24.882	99.639	731	C
SB5	24.879	99.643	851	B
SB6	24.876	99.647	921	B
SB7	24.903	99.643	1148	B
SB8	24.901	99.643	708	C
SB9	24.900	99.625	993	B
SB10	24.909	99.619	1086	B
SB11	24.900	99.622	938	B
SB12	24.878	99.569	724	C
SB15	24.890	99.532	1005	B
SB16	24.893	99.534	1222	B
SB17	24.890	99.551	887	B
SB18	24.896	99.589	694	C
SB19	24.854	99.542	1516	B

erosion from Pablillo and Camachito rivers. Sites PR2, PR4, PR3, between these streams show the thickness of the alluvium. At sites PR3 and PR4 the thickness of Quaternary sediments was of 3 m and 2 m respectively, corresponding to the minimum values in the area. To the east of La Petaca the thickness is increased to depth of 14 meters at SB15.

The Méndez formation is shown in brown color. Light brown to green tones corresponds to the Tertiary conglomerates. In the northern part of the area we detected some alluvial structures that were not known to exist. In its southern part the study outlines areas where the Méndez formation is covered by Tertiary conglomerates. Note the good correlation between the geological formations (Figure 2) and the seismic data (Figure 11).

Based on these data we present two geologic sections: A-A' and B-B' (Figures 3 and 4) across the study area. Section A-A' contains the maximum thickness in the study area which corresponds to a site class C. Linares city is crossed by the Camachito and Pablillo rivers, where we found low thickness of Quaternary materials (section B-B') corresponding to class B in the soil classification. East of Linares city, in La Petaca area, the alluvium thickness decreases drastically; the $\overline{V}_{s30}$ value is 1600 m/s, corresponding to conglomerates with a thickness of three to four meters. This area is classified as class A.

Depth to bedrock in Linares city and La Petaca is relatively shallow, with depths of approximately 2 to 6 meters. The bedrock corresponds to shales of the Méndez Formation. From the average of the V_S and V_P values obtained in this study, we estimated the V_P/V_S ratio for different geological units in the area (Table 1). We found: 1.49 for Shales, 2.03 for conglomerates, 1.71 for alluvium, and 1.53 for silts.

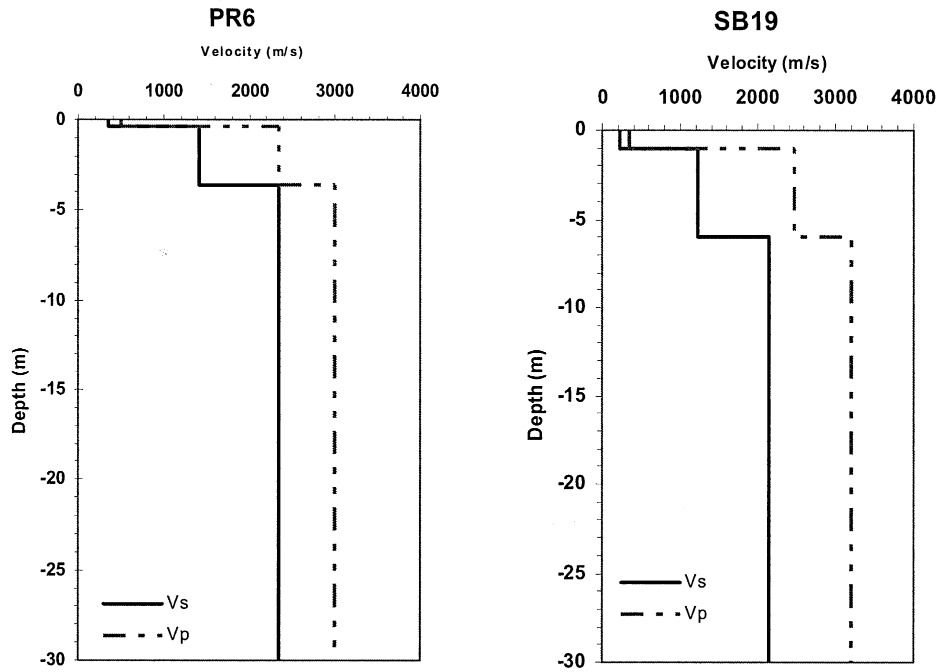

Fig.10. Comparison between the velocity structures obtained at PR6 site from refraction data and the SB19 borehole site (thickness of the lithologic units). We assigned the average of *P* and *S* waves obtained in this study for silts, conglomerate and shales to the geologic units of the SB19 location.

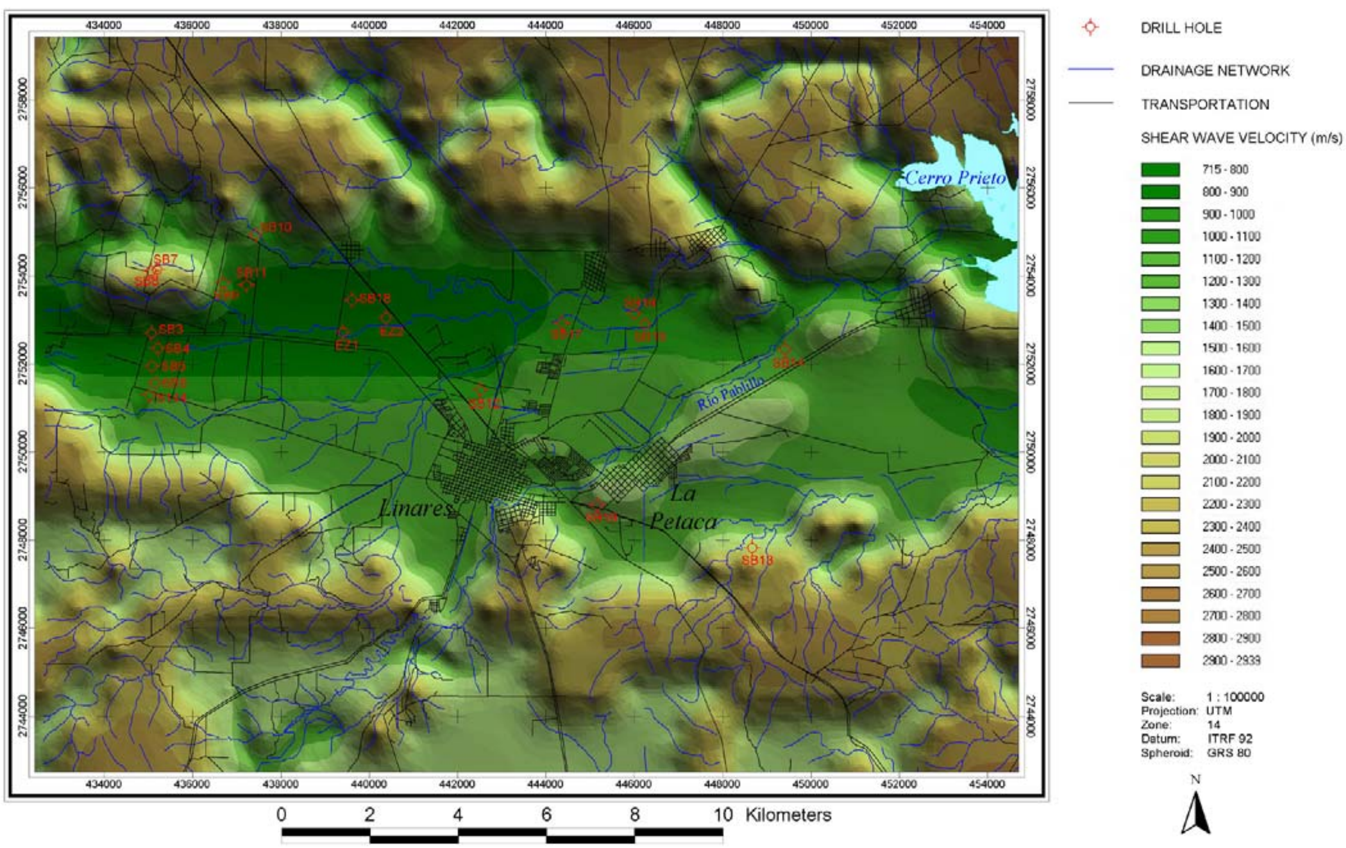

Fig. 11. Contour map of $\overline{V}_{s30}$ in the Linares, Nuevo León region. To the west of Linares city it are velocities less than 760 m/s that correspond to soil class C observed. In Linares city the velocities varied from 800 to 1400 m/s that correspond to soil class B.

DISCUSSION AND CONCLUSIONS

This work constitutes the first attempt at a microzonation of a major city in northeast Mexico. The area was considered seismically stable, but there is little information. We used well data and shear-wave velocity data. The results are of interest for seismic risk assessment as the average velocity of the first 30 m ($\overline{V}_{s30}$) is a widely used parameter to characterize site conditions and to predict the amplification of seismic shaking. We propose to use the results of this work for calculating seismic hazard maps for the state of Nuevo León. Shallow shear wave velocities are also useful for seismic hazard evaluation in the design of large buildings.

The data obtained from this study allowed us to map the bedrock topography and the distribution of alluvial gravel deposits, which may be of interest for ground-water hydrology.

According to NEHRP soil classification, site class C is predominant in the area. Four different lithologic units were defined in the upper 30 m: silts with 338 m/s and 221 m/s for V_P and V_S respectively that correspond to the lowest Vs measured in the area, usually within the upper 3m; Quaternary deposits (alluvium) with 957 m/s and 559 m/s for V_P and V_S, respectively; conglomerates (Tertiary) with 2471 m/s and 1220 m/s for V_P and V_S; and finally shales of the Méndez Formation (Upper Cretaceous) with 3195 m/s and 2149 m/s for V_P and V_S, respectively. Maximum thicknesses (≤ 16m) of the soft sediments Class C (< 760 m/s) are located to the west of Linares city and to the east of La Petaca. In Linares city, the thickness of the soft sediments diminishes by erosion of the Camachito and Pablillo rivers and the values of $\overline{V}_{s30}$ are increased to between 800 to 1400 m/s that correspond to sites Class B. The decreasing $\overline{V}_{s30}$ values generally correlate with the increasing thickness of unconsolidated Quaternary deposits in the study area. Sites Class A corresponds to bedrock.

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