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FAULTS AND FRACTURES IN THE VALLEY OF AGUASCALIENTES. PRELIMINARY MICROZONIFICATION

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ABSTRACT

It has been known for more than ten years the existence of faults and fractures in the urban and rural areas of the Graben of Aguascalientes. The N-S orientation and vertical dips of these faults and fractures are parallel to the limits of the Graben of Aguascalientes. Its paleotopography is irregular with step-like down thrown depressions. The fractures are ascribed to the accelerated extraction of ground water in the last 20 years, and the consequential differential compaction of the sediments filling the graben. This compaction produces in the vast majority of cases, aseismic displacement in the surface (creep). However in the eastern part of the graben it has been manifested as rupturing and seismic activity. The latter was detected with the instalattion 6 years ago of the Seismological Station AGX of Servicio Sismologico Nacional (SSN) of UNAM. Additionally a temporary network of autonomous analogic seismographs were installed within the city. Analysis of the data indicates that the fractures are produced by induced seismicity. Associated to the fractures, eighteen local earthquakes were detected. On the other hand, several features indicate previous tectonic activity as recent as late Quaternary in age: a) Drainage on the tuffaceous sediments of the eastern part of the city show in a hipsometric map, a strongly prefered pattern oriented N30E, suggesting some sort of structural control; b) Statistical orientation of vertical fractures affecting the Zoyatal Tuff of Miocene age and the Quaternary tuffaceous sediments, show a bimodal distribution with orientations N-S (coincidental with the Eastern Fault of the Graben of Aguascalientes), and N30E (coincidental with the preferential orientation of the drainage pattern); c) Mud volcanoes of injected sands, aligned parallel to the direction of the main fault were developed in the Quaternary tuffs.
In order to produce a preliminary map of microzonification of fractures as a function of its hazard, a detailed mapping of the distribution of fractures was carried out, as well as mapping of the induced seismicity, and of the main structural features of the Eastern Fault. This map helped to delineate and define zones of greater, medium and low hazard within the city, and might help the city planners and county authorities in decision making for the future urban developmnet of the city.

KEYWORDS

Faults; fractures; mud volcanoes; sand boils; liquefaction; injection of sand; induced seismicity; groundwater; microzonification; Aguascalientes City, Mexico.

INTRODUCTION

For more than 10 years it has been observed the appearance of craks and fractures in the City of Aguascalientes. This problem has been tackled several times with studies whose principal objective was the geological characterization of such craks. Among those studies we can cite Aranda-Gómez (1985) and Calvillo *et al.* (1994). These studies agree to indicate the ground water withdrawal of the acquifers as the most probable cause for the generation of fractures. Also, these studies have indicated the relationship between the direction of the fractures, the local geology and the regional tectonics of the area. In this work it is intended to seek geological evidence that permit to evaluate the current state of the extensional phenomena in the graben formation.

In numerous occasions local quakes have been detected when pumping or injecting water, gas or oil from the undergorund in different parts of the world (Kovach, 1974; Simpson and Leith, 1985). Such quakes are a response to a modification of the effective state of stress in the body of soil or rock through which the fluid travels. A form of identifying these events is with the use of sismographs, installed in the vecinity of these zones. In the case of the City of Aguascalientes, thanks to the operation of the seismologic station AGX of the SSN-UNAM, located within the city (Fig.1), it was possible to identify these events. Additionally and in order to be able to locate these events, a temporary net of analogic and autonomous seismographs was installed also within the city limits. Finally, it was possible to locate 2 events in the suburbs of Jesus Terán, toward the east of the city, and an other one southward of the town of El Puertecito, just 6 Km north of the down town. This induced seismicity and the evidence of recent tectonic activity permited to delineate a map of preliminary microzonification of the fractures.

GEOLOGICAL ASPECTS

Stratigraphy

The city and the neighboring area of Aguascalientes is built upon the alluvial sediments, lavic and pyroclastic rocks of Tertiary and Quaternary ages. These in turn are affected by normal faulting associated with the development of the Graben of Aguascalientes.

Basal Complex . This unit consists of sedimentary and igneous (volcanic and intrusives) rocks, sometimes metamorfosed to the green schists facies, whose ages are Mesozoic in the range Jurassic to Cretaceous (Velasco-Hernández, 1989).

Ignimbritic Package . The oldest stratigraphic unit present in this area, is the ignimbritic package, referred informally by Hernández-Láscares (1981), as Riolita Ojo Caliente, represented by the small outcrop located about the knoll where is located the Ojo Caliente Resort (Fig.1). Here outcrops an ignimbrite of pink and redish colors in fresh surface and of creamy colorations in weathered surfaces. The thickness of this unit in the vicinity of the resort reaches more than 300 meters, and its contact with the overlying unit is extremely irregular, forming very pronounced scarps. Only an anomalous structural behavior would explain the reduced outcrop and its irregular distribution at depth.

Zoyatal Tuff. It rests discordantly on the Ignimbritic Package, a sequence clastic alluvial, fluvial and piedemonte sediments, intercalated with an apparently thick package of air fall tuffs, of riolitic composition (70 % of SiO_2; Hernández-Láscares, Op. Cit.). Its lower contact has been traced around the Ojo Caliente knoll where the Ignimbritic Package outcrops, and is not observed anywhere else (Fig.1). It has been detected however in some wells at various depths around this place.

Aguascalientes Tuff. This unit consists of alluvial clastic sediments, median to poorly consolidated, intercalated with these, a tuff horizon is intercalated with vitroclastic texture, whose essential minerals are: quartz, feldspar, oligoclase, lithic fragments and glass shards. The composition of this rock is riolitic as is deduced by the chemical analysis of a sample reported by Hernández-Láscares (Op. Cit.), with a percentage of 74.5 % of SiO_2. Its lower contact is horizontal and discordant with the Zoyatal Tuff (Fig.1). Its reported thickness in the creeks is of 15 to 20 meters. However and taking into account the highest levels where this unit is found we can estimate that its thickness is of at least 100 m. In this unit it has been reported a rich fauna of the Upper Pleistocene (Montellanos-Ballesteros, 1990).

Alluvial Valley fill. This unit is the most widely distributed in the area and intercaleted with the Aguascalientes Tuff, the distinction between the clastic products of this and the pyriclastic units is extremely difficult. It consist of the alluvial products and related deposits of the central portion of the graben (Fig.1). Its total thickness is not known but in the center of the valley the added thicknesses of this unit and of the Zoyatal and Aguascalientes Tuffs exceeds in some instances 400 m. The records and descriptions of some wells suggest that the measured total thickness corresponds mainly to these alluvions.

Geomorphology

In terms of the landscape morphology, it is remarkable the topographic contrast between the sierras located to the west of the valley of Aguascalientes, with elevations above 2800 meters above sea level (the Sierra Fria for example), with those of the hills located to the east of the valley, where the elevations hardly exceed 2050 meters. The type of drainage is also contrasting, in the west it is dendritic and irregular, in the east the drainage tends to be parallel, following a prefereential direction of N3OE. This orientation is here interpreted as inherited from a buried structural control of fractures and faults that follow that direction. Of course the main geomorphic feature is the Eastern Fault of Aguascalientes separating the two elevated areas from the valley in a conspicuous way (Fig.2).

The principal creeks in the east are: Arroyo de La Hacienda or San Nicolas in the north, Arroyo de Los Arellano (that pours in the Dam of Los Gringos), Arroyo Don Pascual, Arroyo El Cedazo, Arroyo Cobos, Arroyo San Francisco or Pargas and Arroyo Las Peñas. All these creeks tend to have a parallel direction (N20-30E), and close to their entry to the valley their course is twisted and become E-W, crossing the trace of the Eastern Fault. After that the course of the creeks transforms to a random and irregular pattern. This being mainly caused by the much more attenuated slope in the valley floor, where they finnaly join the river San Pedro, mainstream of the state (Fig.1).

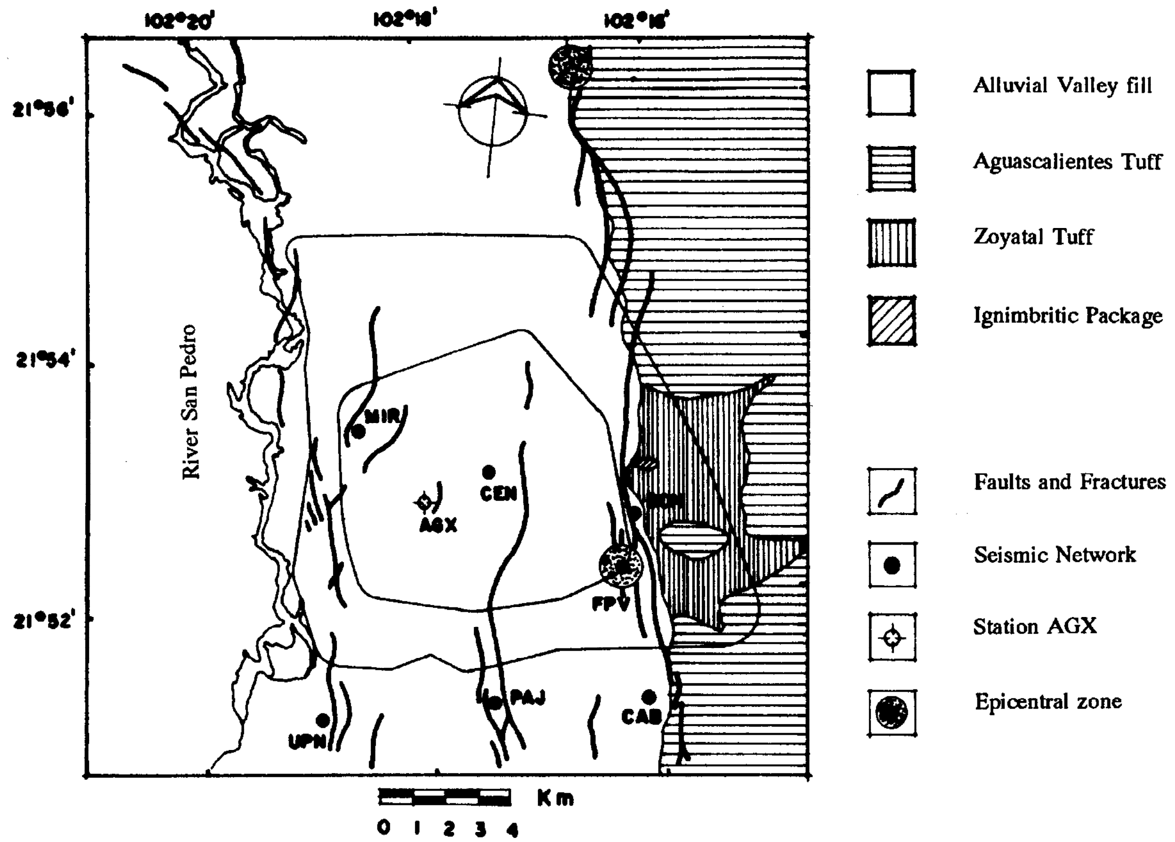

Fig.1. Geologic Map of the urban area of the city of Aguascalientes. Thick lines show the main fractures. Black circles correspond with stations of the seismic network. Big dotted circles= epicentral zone.

Structural Geology

Orientation of Fractures. In the locality of the dam El Cedazo, just downstream of the curtain there are excellent outcrops of the Zoyatal Tuff. In this locality, on the bed of the creek it is observed the top of the tuffaceous unit with excellent outcrops for a distance of a little more than 400 m, then this unit is truncated by the Eastern Fault of Aguascalientes, where it has a pronounced scarp built on the fault plane (Fig.3). At least two tuffaceous horizons are observed, intercalated with the clastic sediments of alluvial character. All these units are affected by vertical fractures, showing no important apparent displacement, and sometimes filled by a gel of silice of brown color. The width of these fractures varies from 1 up to 15 cm. In the broadest fractures it is frequent to find the growth of vegetation of the bush type, that contrasts with the sterile waterproof nature of the rest of the rock surface.
The orientations of these fractures are diverse, a statistic anlysis of them is shown in Fig. 4. In this figure it appears clearly a bimodal distribution in the directions N00-10E and N20-30E, while the rest of the fractures(N=46), present orientations that represent the value of the background.

Subsurface Geology . From the reported information of the wells in the city and its neighborhood (Calvillo *et al.*, 1994 and ETEISA, 1990) an attempt was made of configuration of the top of the Ignimbritic Package, this is presented in Fig. 5. In the west the Ignimbritic Package is not always present, and as a basement the Basal Complex was considered instead. In the east the highest part of the ignimbrites is of course the outcrop of Ojo Caliente Hill.
The most important feature of this figure is the conspicuous depression than represents the center of the graben, and on the other hand the previously unreproted topographic relief of the ignimbritic and basal complex. The spectacular character of the central depression, highlights the importance of the Eastern Fault, and these lead us to infer that similar features exist in the central part of the area (forming depressions and raised blocks); these in turn would be responsible of the fracturing of the other parallel faults that are observed in the center of the urban area. These faults could be developed in response to a differential compaction of the clayey portion of the filling sediments of the valley, during water extraction. This phenomenon would be mainly produced in the vicinity of some of the zones with abrupt slopes. This proposal would at least explain why most of these faults are parallel, oriented N-S and their down thrown blocks to the west.

Liquefaction Structures . In this section we will briefly describe some surficial observations indicative of seismic activity in the recent past, in units that are considered to belong to the Quaternary.

1. Sand injections, referred in the literature as liquefaction structures that consist of sandy material saturated in water located in a matrix of the same composition, and formed during strong jolts.
In the road cut of the Highway to San Luis Potosí, just 4 Km to the ESE of the dam El Cedazo, outcrops a sequence of alluvial materials composed of conglomerates and mildly consolidadted sands, with irregular lenses of sand of creamy colors. These lenses have the tendency to occur along irregular surfaces (Fig. 6). These seconadry structures of sand injection are produced only by the influence of big earthshakes. These injection occur in sediemnts assigned to the Aguascalientes Tuff of Upper Pleistocene age, and in this case it means ages less than 450,000 years before present.

2. Mud volcanoes, also known as sand boils or sandblow deposits, they consist of the ejection of fine materials to the surface, expelled by water that travels through tubular conduits. To the north of the city and to the east of the Suburb Soberana Convención in the foothills, faults and fractures are observed on the surface along the trace of the Eastern Fault. Just east of this zone only a few meters from the fault, mounds of sand and coarse clasts are observed, 30 to 40 cm high, 4m long and 1 to 2 meters wide. These mounds were investigated with trenches 5 to 10 m long and 3 m deep. On the walls of them it was observed that the base of the mound had a pipe-like sahpe filled with fine sand of brownish colors, with a humudity that contrasts with the dryness of the rest of the wall (Fig. 7). These observations seem to correspond with mud volcanoes or sand boils which find their exit along parallel fractures to the eastern Fault of Aguascalientes. The humidity of the conduits and the vegetation that grows along those aligned mounds support the idea of a very recent age for these mud extrusions. The mehanisms that produce these mounds may sometimes be

Fig. 2. Fault on the Quaternary sediments (Easter Fault of Aguascalientes). Vertical displacement is of approximately 1 m.

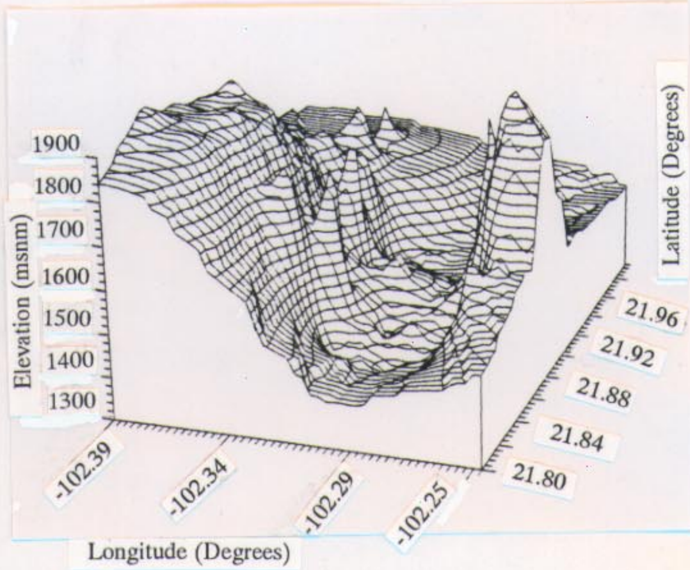

Fig. 5. Contouring of the top of the Ignimbritic basement, based on data from wells (Calvillo *et al.*) and avilable topographic information.

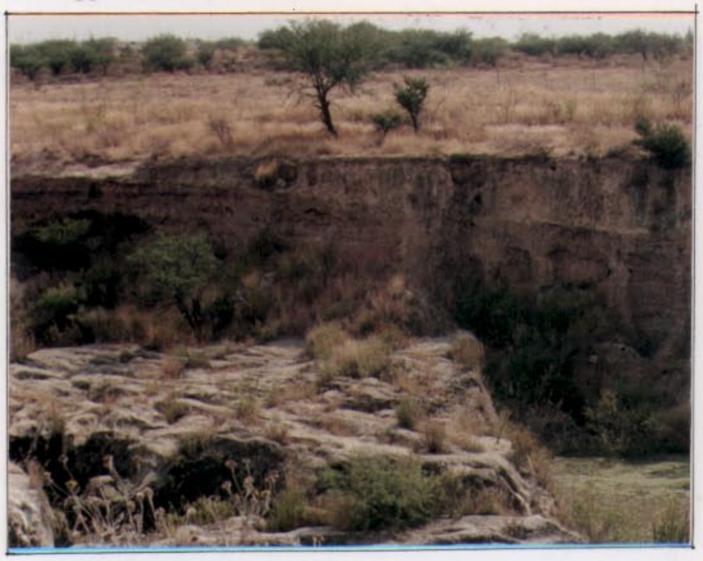

Fig. 3. Outcrop of Zoyatal Tuff on the Creek El Cedazo. The scarp shows the trace of the Eastern Fault of Aguascalientes. The growth of vegetation highlight the orientation of fractures.

Fig. 6. Outcrop of an injection of sand on the highway # 70 to San Luis Potosi. An irregular lens is observed that pinches out over an irregular surface.

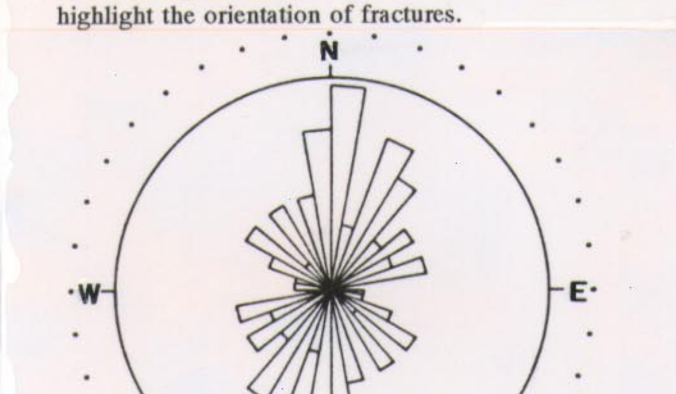

Fig. 4. Statistical orientation of fractures in the Zoyatal Tuff. Notice the strong tendency in the direction N 00-10 E and N 20-30 E.

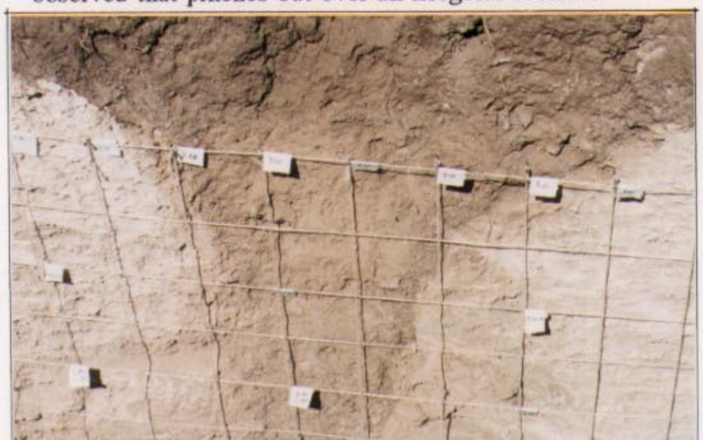

Fig. 7. Outcrop of a mud volcano. North wall of the trench. A conduit of conical shape is observed that contrasts with the dry caliche soil around it.

assigned tò seismic activity, or to water extrusion by hydraulic gradient during the rainy season.
The fact that this activity extendes along the neighboring places of the Eastern Fault assures a close relationship. On the other hand, as the age of the youngest affected sediments is Quaternary, it is implied that the tectonic and seismic activity have been preponderant in the recent past in this area.

SEISMIC MONITORING

For the analysis of the local seismic activity the analogical records of the station AGX of SSN-UNAM were checked, they are located in the downtown area of Aguascalientes. This seismograph has a seismometer L4 of 1 s natural period, and has been operating from March of 1988. Thirteen local events were identified: 2 in 1988, 7 in 1992 and 4 in 1993. During 1989, 1990 and 1991 no events were recorded because seismograph AGX was not operational during these years. These events show a similar waveform. The arrival of the emerging compresional waves are of short duration (approximately 1.5 s), they are followed by a transverse waves package of greater extent and duration (sometimes it is found saturated). This last package is sharply interrupted by the arrival of other surface wave packages that are quickly attenuated. In Fig. 8a it is shown an example of an event registered on the 19th of February of 1992, to which a magnitude of Mc=3.1 was assigned. For the calculation of this magnitude the following relationships were used Mc=2 log T-0.87, where T is the duration of the coda in seconds (Lee *et al.*, 1972).
In order to locate this observed activity in the AGX station, it was installed in the middle of 1993 a net of four MQ800 Spregnether Seismographs, with Ranger seismometers of 1 s natural period. In Fig. 1 it is indicated with black circles the location of these instruments, i.e. Stations: UPN, MIR, CEN and BON. In a second stage three of these stations were changed (MIR, UPN and CEN), toward the eastern zone (PAJ, CAB and FPV), where the first earthquake was located with this net.
On the 30th of November of 1993 at 05:17:07 (hours, minutes and seconds, universal time) it was produced another local quake of Mc=3.1 that was registered by the base station AGX and by the seismic temporary net. In the Fig. 8b this event can be observed in the station CAB of the local seismic net, together with other event of smaller magnitude that took place at 06:38:01 of that same day. For the location of this event it was used the program Hypo71 (Lee and Lahr, 1975), that reports a location in the Suburb Jesus Terán, where the Eastern Fault is subdivided in three secondary faults (Fig. 1). The depth is of approximately 0.7 km. The 11th of January, 1994 at 16:05:57 it occured another quake of greater magnitude (Mc=3.3) in the same zone, this one was felt by the inhabitants of the Suburb Jesus Terán. They reported the appearance of another fracture of approximately 100 m of length and 5 cm wide in average. This fact corroborates the relationship of the fracturing with the observed seismic activity.
Finally, other event registered by the autonomous seismic net and AGX, was the quake of the 11th of June of 1994 at 16:34:23 hours, with a magnitude greater than the previous one (Mc=3.4). It was located approximately to 6.5 Km north of the station AGX, on the eastern fault close to the town of El Puertecito (dotted circle, Fig. 1). The depth of this events was estimated to be roughly 1 km. This event was recorded also in the seismological station of Morelia (MRX) which is found at a distance of 272 Km from the city of Aguascalientes.
In Table 1 it has been summarized the time of origin and the estimate of the magnitude for 18 events. The time is referred to the universal time (GMT). The value of the magnitudes varies from 1.6 to 3.4. Those with values of Mc > 3 were felt by the people living in this area. Fig. 9a shows a plot of the number of seismic events registered versus time in years. In this graph the aftershocks were not taken into account since they were considered to belong to the same zone of rupturing. Even though there was no data for the years 1989, 1990 and 1991 it was observed an increase in the seismic activity, considering that for 1994, there had hardly passed six months. Fig. 9b shows the relationship of estimated magnitude (Mc) in AGX station against time, here it is also observed an increase in magnitude with time.

MICROZONIFICATION OF FRACTURES

With the geological and seismological information, a Preliminary Map of Microzonification of fractures was produced (Fig. 10). This map shows that the higher level of hazard is directly related to the surficial outcrop of the fractures. The higher level of hazard follows the trace of the Eastern Fault of Aguascalientes, along which the seismic activity was concentrated. This zone extends along the fault for a distance of at least 25 Km. Middle and Lower levels of hazard were assigned to the zones that border the other parallel faults within the city. The middle level of hazard was assigned to the zones where there were already faults present, but no seismic activity detected.This zone also extends for a distance of 25 Km close to the fluvial path of San Pedro River. The lower level of hazard was assigned to the zones intermidiate between the former ones, where no outcrop of faults has yet been observed or reported.

CONCLUSION

The data and observations suggest the following conclusions:

1. There exists evidence of a tectonic active in the quaternary, that together with the accelerated water extraction, is responsible for the fractures and faults appeared in the city of Aguascalientes.
2.Eighteen local earthquakes have been detected, associated with the fractures. The last three have been located in the Suburbs of Jesus Terán and to the south of the town of El Puertecito, both on the eastern fault. It was observed an increase of the seismic activity in number of events and magnitude.
3. From the map of preliminary microzonification of fractures, it has been possible to assigne a different degree of hazard for the various zones traversed by the faults and fractures produced by the induced seismic activity. The map shows a dotted band that corresponds with the zone of high hazard for distances up to 25 Km, while the horizontal and vertical ornamentation of the other two stripes shows the association with a middle and lower level of hazard. Similar lengths of these zones were observed. The width of these stripes is arbitrary.

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REFERENCES

Aranda-Gómez, J.M. and J.J. Aranda-Gómez (1985). Análisis del agrietamiento en la ciudad de Aguascalientes, *Reporte anual*, Universidad Autónoma de Aguascalientes, Dpto. de Geotécnia, Ags., México, pp.102.

Calvillo, G., J. Rodríguez and M. Zermeño (1994). Litología del Valle de Aguascalientes, *UCCyL-SOP*, Estado de Aguascalientes, Ags., México, pp.87.

ETEISA, DE C.V. (1990). Estudio geohidrológico del valle de Aguascalientes. Localidad Ojo Caliente y sureste de la ciudad de Aguascalientes, *No. Contrato 079-90, SOP, Dirección General de Agua Potable y Saneamiento. Subdirección de Fuentes de Abastecimiento*, **V.1**, Ags. México, pp. 250.

Hernández-Láscares, D. (1981). Estratigrafía de la región central de Aguascalientes, Ags., México. *La Gaceta Geológica*, **VI-31**, 17-38.

Kovach, R. (1974). Source mechanisms for Wilmington Oil Field, California, subsidence earthquake, *Bull. Seism. Soc. Am.*, **64**, 699-711.

Lee, W.H.K., R.E.Bennett and K.L. Meagher (1972). A method of estimating magnitude of local earthquakes from signal duration, *Geol. Surv. Open-File Rep.*, pp. 28.

Lee, W.H.K., and J.C. Lahr (1975). HYPO71 (revised): A computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes, *Geol. Surv. Open-File Rep.*, **75-311**, 1-116.

Montellanos-Ballesteros, Marisol (1992). Una edad del irvingtoniano al Rancholabreano para la Fauna Cedazo del estado de Aguascalientes, *Revista Instituto de Geología*, **V-9**, 195-203.

Simpson, D. and W. Leith (1985). The 1976 and 1984 Gazli, USSR, earthquake were they induced?, *Bull. Seism. Soc. Am.*, **75**, 1465-1468.
Velásco-Hernández, M. (1989). Relaciones Litoestratigráficas del área de Jesús María, Estado de Aguascalientes. Tesis profesional, Facultad de Ingeniería, UNAM, pp.95

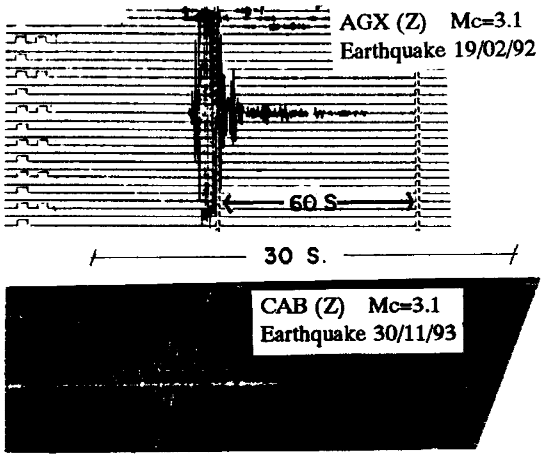

Fig. 8: a) Sismogram on station AGX, of the earthquake of 19/02/92, Mc=3.1. b). Sismogram on station CAB, of the earthquake of 30/11/93, Mc=3.1.

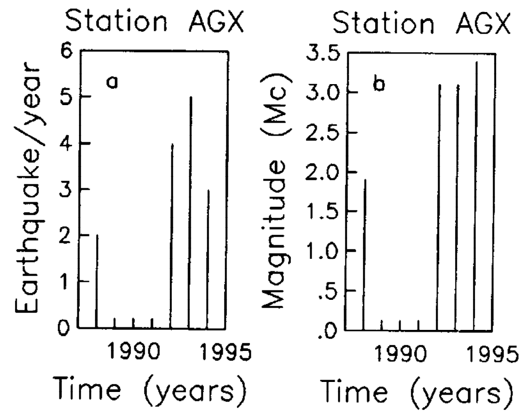

Fig. 9: a). Plot of the number of events versus time in years. Aftershocks were not taken into account. b)Plot of estimated Coda Magnitude in station AGX, versus time in years. Only the largest earthquake of each year was considered to construct this figure.

Table 1. Events recorded by the station AGX and Network

DATE (d/m/yr)	T (sec)	Mc
16 05 88	22	1.6
17 05 88	29	1.9
30 01 92	16	1.3
19 02 92	90	3.1
19 02 92*	29	1.9
19 02 92*	29	1.6
19 02 92*	32	2.0
17 03 92	80	2.9
26 06 92	50	2.5
16 01 93	42	2.3
22 01 93	80	3.0
04 03 93	42	2.3
11 08 93	45	2.4
30 11 93	90	3.1
30 30 93*	35	2.1
11 01 94	100	3.3
11 01 94*	109	3.2
11 06 94	110	3.4

*afterschocks

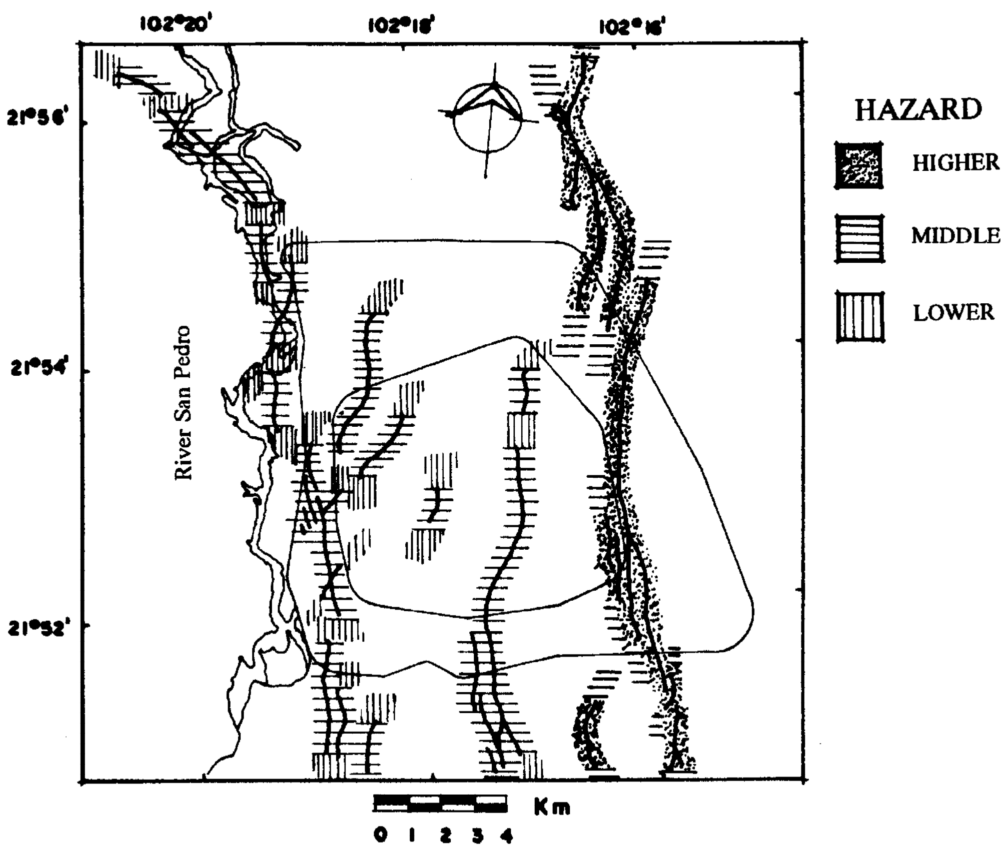

Fig. 10. Preliminary Microzonation Map of fractures in the city of Aguascalientes.