GeoPatterns, Vol. VII (2022), pp. 21-33, https://doi.org/10.5719/GeoP.7/3

Four Decades of Spatial-Temporal analysis of Seismicity Patterns in the Pinotepa Nacional region, Oaxaca, Mexico

FIDEL MARTÍNEZ-GARCÍA

Independent Research in Environmental Sciences, retired staff of the Federal Electricity Commission, Mexico
Eco599395@gmx.com

Abstract. Contributing to the knowledge of the spatial distribution patterns involved in the most seismic regions of the world is an alternative way of anticipating the destructive consequences associated with significant earthquakes (>5.5Mw). This document provides evidence of the spatial aggregation patterns that are implicated in the spatial distribution of 32,046 seismic events from 1980 to 2021 period, in the Pinotepa Nacional region, Oaxaca, Mexico (Middle America Trench) and its relationship with intense local seismic activity and indirectly with possible hidden local unknown structures, settled some kilometers below the surface. Using GIS tools, to identify spatial patterns, the Local Indicators of Spatial Association analysis (LISA) and the Space–Univariate Local Moran's Index (SULMI) were applied. The analysis revealed that 21.0% of the epicenter's spatial distribution is not random but tends to cluster toward seismicity potential zones. According to the LISA-SULMI approach applied, for each significant earthquake greater than 5.5Mw, a map of color intensities was obtained representing the degree of global spatial autocorrelation between the data. After a sequence of two significant earthquakes in 2018 (7.6 - 6.0 Mw), a hidden local tectonic feature 43 kilometers in diameter was revealed just 10 kilometers below the surface by micro-seismicity (2.0 and 2.9 Mw).

Keywords: Middle America Trench, Cocos Plate, LISA analysis, Moran's Index, spatial autocorrelation 1980-2021.

1. INTRODUCTION

Contemporary knowledge about the inner structure of the Earth all over the world, the is a consequence of the natural seismic activity studies using geophysical and Earth sciences within regions with high seismic hazards like Mexico, particularly throughout the Middle America Trench (MAT). Another source of information is handmade blast-induced seismicity and scientific prospecting to understand the lithosphere by scientific drilling (Arai, 1982). For example, the Kola Superdeep Borehole (KSDB) project or SG-3 (Carr et al., 1996). One more source has been the use of current and updated methods of seismic tomography (Bianco et al., 2019) and seismic refraction to measure the thickness of the terrestrial internal layers and discontinuities between the trenches (MAT) and the continental lithospheric plate or metropolitan areas (Montalvo Arrieta et al., 2008). Likewise, MAT seismic potential (Dominguez et al., 2016) and the connection between earthquake – faults exposed by observation of seismic waves (Julian et al., 1998).

Nevertheless, joint behavior of spatial-temporal data (patterns) of the epicenters and hypocenters recorded by seismic instrumentation have also contributed importantly to delineating and locating shapes over or within the layers of the earth, within regions of seismic belts characterized by frequent seismic activity. The best-known mega-form outlined is the Pacific Ring of Fire of which numerous trenches form a part, as is the case in the Middle America Trench (northern part, also called like Acapulco Trench) (Ducea et al., 2004).

But within these regions of high seismicity and intense volcanism caused by the subduction of plates, there are subregions where the space-time pattern could show ancient internal forms still unknown, excluding fault tectonics. Under this reasoning, the geographic position and behavior of horizontal and vertical seismic activity studied over long periods can be a useful tool to define its limits within the Earth's shallow crust.

The relative geographical position (X, Y, and Z) of a group seismic event can show hitherto unknown internal tectonic features, which would demonstrate moreover, that the spatial distribution of data in narrow areas is not random in time and space.

Under this reference frame, the main objective of this research is to demonstrate that 42 years of seismicity data within a study area located near the coastal limits of the states of Guerrero and Oaxaca, Mexico, are not distributed randomly but are clustered horizontally and vertically in specific regions of the geographical space, outlining possibly hidden tectonic features.

1.1. Study area

The study area is located entirely within the boundaries of the Jamiltepec District and the most distinctive municipality is Santiago Pinotepa Nacional, in the state of Oaxaca, Southern Mexico. It is a region immersed in the coastal border within the Middle America Trench, Cocos Plate subduction tectonic region under the North America Plate, a territory characterized by a very complex tectonic history of folding, magmatism, and metamorphism (Yamamoto, González-Moran, et al., 2013), this seated over the Xolapa complex's metamorphic basement (Perez-Gutierrez et al., 2009; Servicio Geológico Mexicano (SGM), 1998). It is bounded by the extreme coordinates 16°47'31.5533" N, 98°33'44.9830" W and 15° 59' 23.7841" N, 97°40'30.9486" W, with an extension of 8458.7 km^2 (94.58-km x 88.76 km, Figure 1).

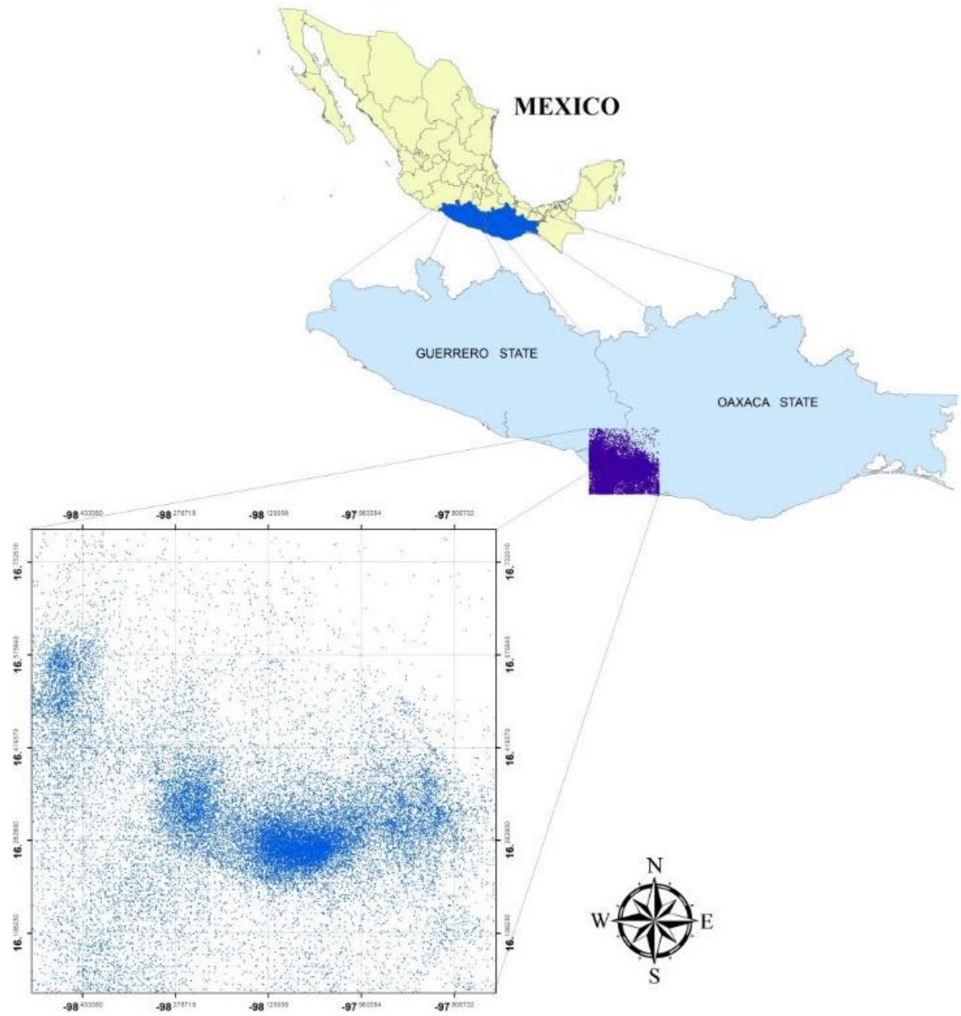


Figure 1. *Study area geographical location*

The historical antecedents of folding, magmatism, and metamorphism confer to the region under study an exceptional seismicity attributes, which has also been justified because the local continental crust could be highly fractured in several blocks that move independently

(Yamamoto, González-Moran et al., 2013). Another distinctive aspect of the study area and its surrounding area is the manifestation of pairs of significant earthquakes (<5.5Mw) or also so-called doublet, EQs with very close magnitudes (0.2Mw units) and no more than 100 km away from each other (Martínez-García, 2017; Martínez-García et al., 2015, 2016; Riga & Balocchi, 2018; Yamamoto et al., 2002; Yamamoto, González-Moran, et al., 2013). An example of this earthquake is the event that occurred on June 7, 1982 (6.9, 7.0 Mw).

2. METHOD

In this study, 32,046 seismic records (2.0 to 7.5Mw, 1980 to 2021 period) obtained from the National Seismological Service catalog (SSN, UNAM, Mexico, Doi: 10.21766/SSNMX/EC/MX) were analyzed, 21 of them are considered significant earthquakes (5.5 to 7.5Mw) and the last one occurred on February 16–19, 2018 (7.2 and 6.0Mw). After that date, 20176 seismic events occurred but none were considered significant (5.3–2.0 Mw)

The original table "txt" format with plain text containing the earthquake data list was exported to the geographic information system (*ArcGis Desktop* 10.6 and *Global Mapper* V18). This geographic tool contributed significantly to the initial analysis and allowed the display of a bunch of geographically referenced information about the study area. (Toma-Danila et al., 2017).

To identify the most statistically significantly related data value clusters, an analysis series of LISA (Local Indicators of Spatial Association) and Moran's I maps, was conducted with the purpose to obtain cluster maps through spatial autocorrelation data exam using a Spatial Data Science Tools (SDScT, *GeoDa* 1.20.0.8) (Zhang et al., 2009). Spatial autocorrelation analysis, namely the global and local spatial autocorrelation test, Moran's I index is considered a reliable strategy for identifying patterns applied in seismology, it has been used in Romania (Bucharest), Indonesia (Tripa Fault in Aceh Province), Iran, China (mainland China and Alpine Himalayan), Pakistan, which has provided consistent results locating seismic hot spots, spatial configurations of earthquake events, earthquake clusters, besides spatiotemporal dynamic, mechanisms and characteristics of seismic activity (Al-Ahmadi et al., 2014; Armaş, 2012; Aslam & Naseer, 2020; Cao et al., 2022; Catita et al., 2019; Harini, 2019; Li et al., 2020; Sofyan et al., 2019; Toma-Danila et al., 2017; Yousefzadeh et al., 2021). This approach and the applied statistical method employed in this paper are considered unprecedented in their application to the identification of patterns in the spatial distribution of seismic events in MAT.

Each SHP format table was set in *SDScT* using the Space - Univariate Local Moran's I menu option (SULMI), setting the magnitude variable. Previous has attained the spatial weights file (GAL file), a simple text file that contains the number of neighbors and their identifiers for each observation.

As a result, the LISA cluster map is obtained according to the series of earthquakes involved in each study period (1980 to 2021). SULMI has been applied to reveal that EQ spatial distribution records are not randomness but clustering. Moran's I statistic for spatial correlation is established as the following:

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} z_i^2}$$

The details of the statistical principles applied in this research can be consulted in the following link: https://geodacenter.github.io/workbook/6a_local_auto/lab6a.html, (Hamylton, 2013; Zhang et al., 2009).

For each EQ LISA cluster analysis, three colored map legends were obtained: not significant, high and low values clustered maps (grey, red and blue dots, respectively), emphasizing only the array of earthquakes with the largest amount of recorded data (2012 to 2021 events). The high color intensity in each map will represent a positive global spatial autocorrelation outcome, while lighter colors signify a negative spatial autocorrelation.

3. RESULTS

Within the study area among the states of Guerrero and Oaxaca coastal limits, Mexico, from January 1, 1980, to December 31, 2021, 21 significant earthquakes (5.5 to 7.5Mw) have been felt, these and 32,025 events less intense were analyzed applying some series of LISA and Univariate Local Moran's I tool.

From 1980 to 2011, just 1730 seismic events (5.4% including 11 significant events) of the 32,046 records used for this study occurred, but the lack of data in this period was not entirely attributable to poor seismic network coverage, at least for the first nine years of the interval under study (Armendáriz, 2006). From 2012 to 2021 there was a significant increase (Figure 2, Table 1), reaching a maximum peak of 27.7% (8861 events) in 2018 (UNAM, 2013), after this year, the seismic activity progressively decreased, in 2019 (16.0%), 2020 (11.5%) and 2021 (8.79%) respectively, this distribution includes eight events considered significant (5.5 to 7.5Mw).

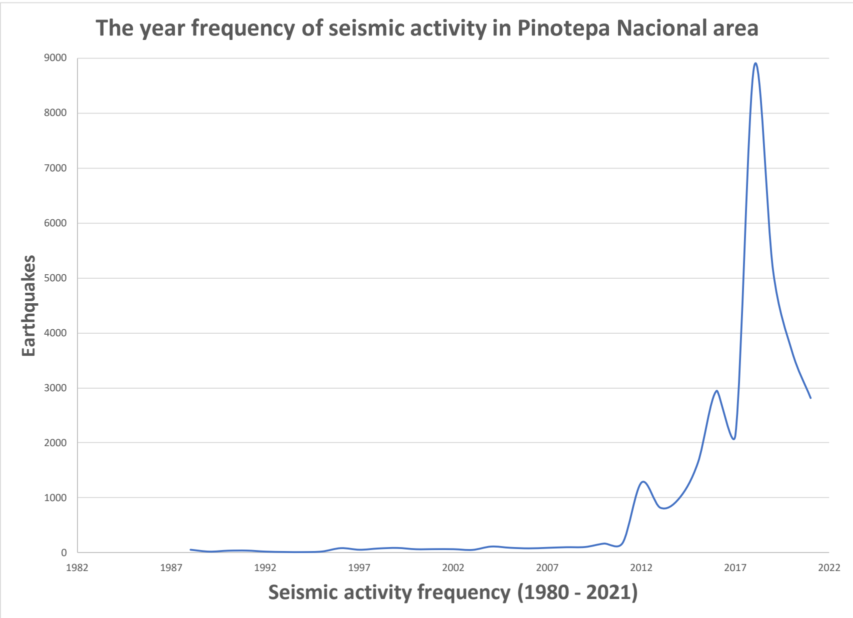


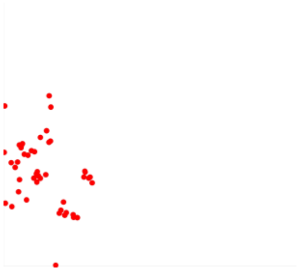
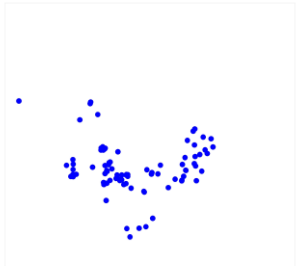
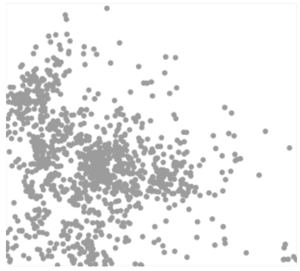
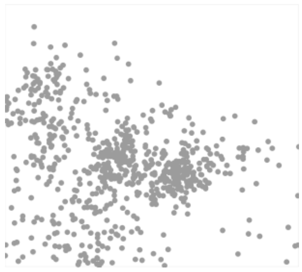
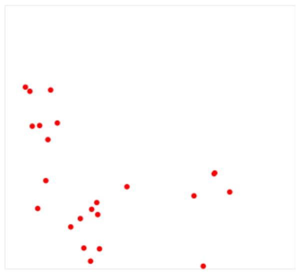
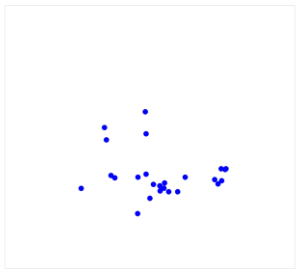
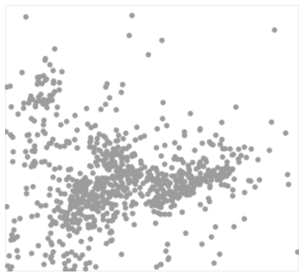
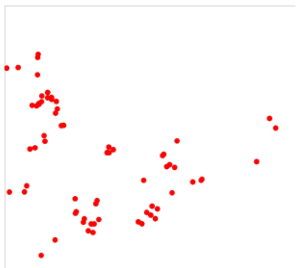
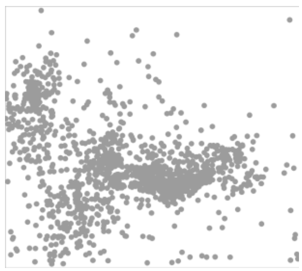
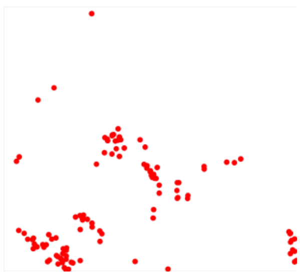
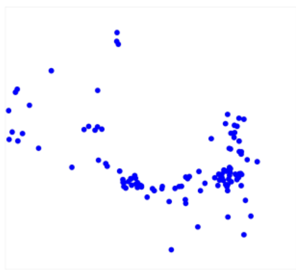
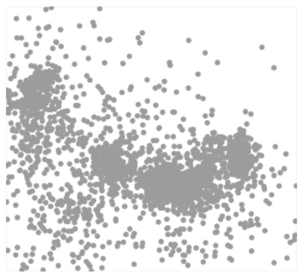
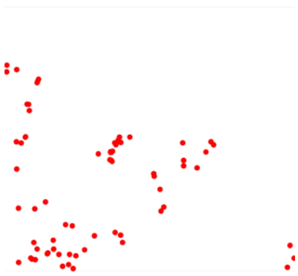
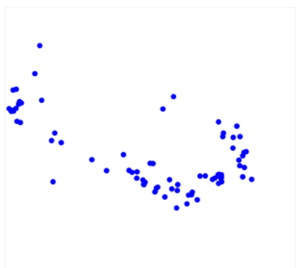
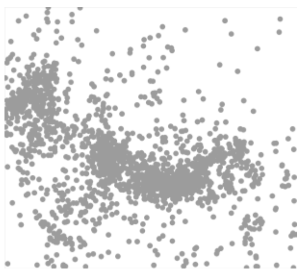
***Figure 2**. 40 years of seismic activity in the Pinotepa Nacional region*

Based on the statistical reliability of the expected results, this trend led to identifying the ideal period to apply the LISA and SULMI analysis that would allow identifying the spatial patterns of the region seismicity data, this period was from 2012 to 2021 (Table 1). Ten LISA cluster maps were obtained for the years 2012-2021 (Figure 3).

Table 1. LISA cluster data analysis, period 1980 to 2021

EARTHQUAKE	1980-1987	1988	1996	1997	2002	2004	2005	2010	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Total EQ data	25	55	84	55	65	113	91	167	1279	820	989	1639	2948	2155	8861	5136	3673	2816
Mw (significant)	6.9, 7.0, 5.9, 5.5 (4)	0	5.5	5.6	5.5	6.4	5.8	6	7.5, 6.0	0	5.5, 5.7	0	6.0, 5.7	0	7.2, 6.0	0	0	0
No significant	20	37	76	47	55	104	83	148	1085	710	844	1424	2568	1885	6914	4289	3058	2380
High	2	8	2	3	1	2	0	2	47	26	45	68	114	70	692	255	169	120
Low	2	7	5	2	3	0	2	4	83	42	50	45	114	79	645	293	229	146
Low - High	1	1	0	0	5	4	3	7	30	28	24	37	89	79	228	156	105	92
High - Low	0	2	1	3	1	3	3	6	34	14	26	65	63	42	382	143	112	78
									Identified ideal period for analysis									

Mw = moment magnitude scale
It is omitted years without significant seismic events (<5.5Mw)

Year	High - High	Low - Low	No significant
2012			
2013			
2014			
2015			
2016			
2017			

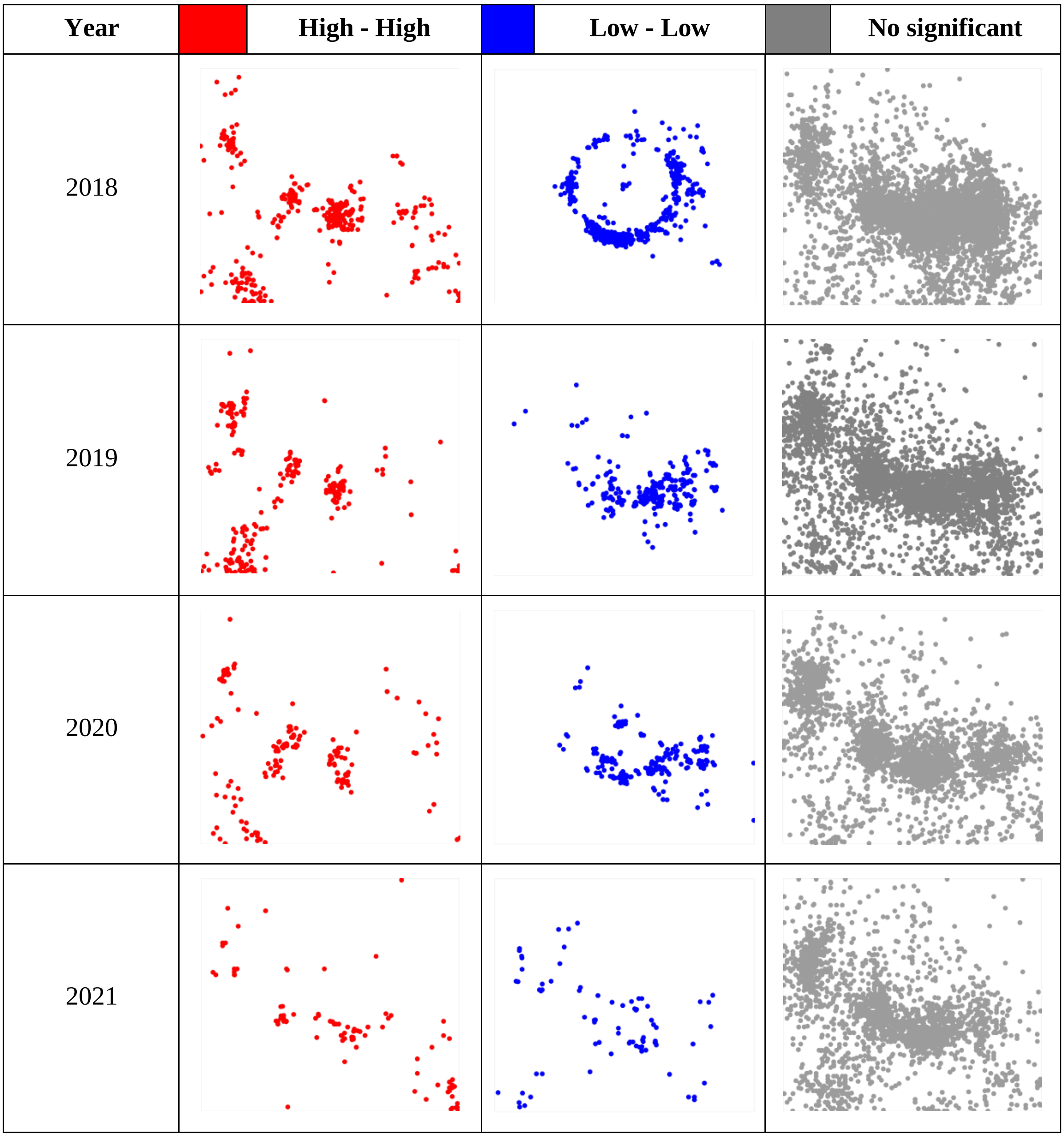


Figure 3. *Local Indicators of Spatial Association (LISA) clusters EQ maps from 2012-2021*

SULMI analysis results show a conclusive tendency to cluster in specific spatial directions. The statistical significance analysis among data shows that only on average 21% of the data are subject to cluster to peculiar areas of the geographic space under study, which suggests that they are associated with three very particular processes within the local seismic activity (Figure 3), namely,

- Potential zones of significant seismicity and foreshocks-mainshock-aftershocks events (Figure 3, *High-High column*), dots in red.
- Structures or geographical hidden tectonic features (Figure 3, *Low-Low column*), dots in blue, data particularly associated with 2018.
- Continuous subduction movement (Figure 3, *No significant column*), dots in gray.

To be more consistent in the delineation of possible hidden tectonic features observed in the map (Figure 3, 2018, blue dots), the data with the greatest significant spatial association were filtered saving in a separate SHP file (*GeoDa Tool)*, considering only the field of Magnitude (micro-seismicity) and depth, in the intervals of

2.0-2.9Mw and 10 km depth preferentially, this procedure, the delineated structure was more evident, and likewise is aligned with the 21 significant earthquakes (5.5 to 7.2 Mw) occurred in the surrounding area from 1980 to 2021 (Figure 3, *Low-Low column*; Figure 4).

The patent evidence of the structure presence referred to above is the delineation of almost circular shape shown on the LISA cluster map in Figure 3, *Low-Low column*. The tectonic nature of this structure is unknown, it is a form that was delineated only after the two earthquakes of 7.2 and 6.0 that occurred on February 16 and 19, 2018 but narrowly related to 579 earthquakes (Figure 3, *blue dots column*) with magnitudes from 2.0 to 2.8, 54.0% of 1846 statistically significant data (red and blue dots) recorded from the earthquake occurred in 2018, almost all of them located to almost 10 km depth, the shape delineated has a diameter of 43 km approximately (Figure 4).

The reliability of the results related to the structure located 10 kilometers over the surface also suggests that there is some kind of very particular spatial autocorrelation worth studying, therefore such an argument was revalidated using two statistic procedures. The first was modifying the significance value limits from P = 0.05 to P = 0.01 and increasing the number of interactions from 999 to 9999.

Another technique was to apply two statistical indicators, the first is the Geary Local Univariate statistic (Geary LU) is another Local Indicator of Spatial Association (LISA) that focuses on squared differences, or dissimilarity. It is a complementary statistic to Moran's I, giving inverse processing to the data, statistics small values suggest positive spatial autocorrelation and *vice versa*.

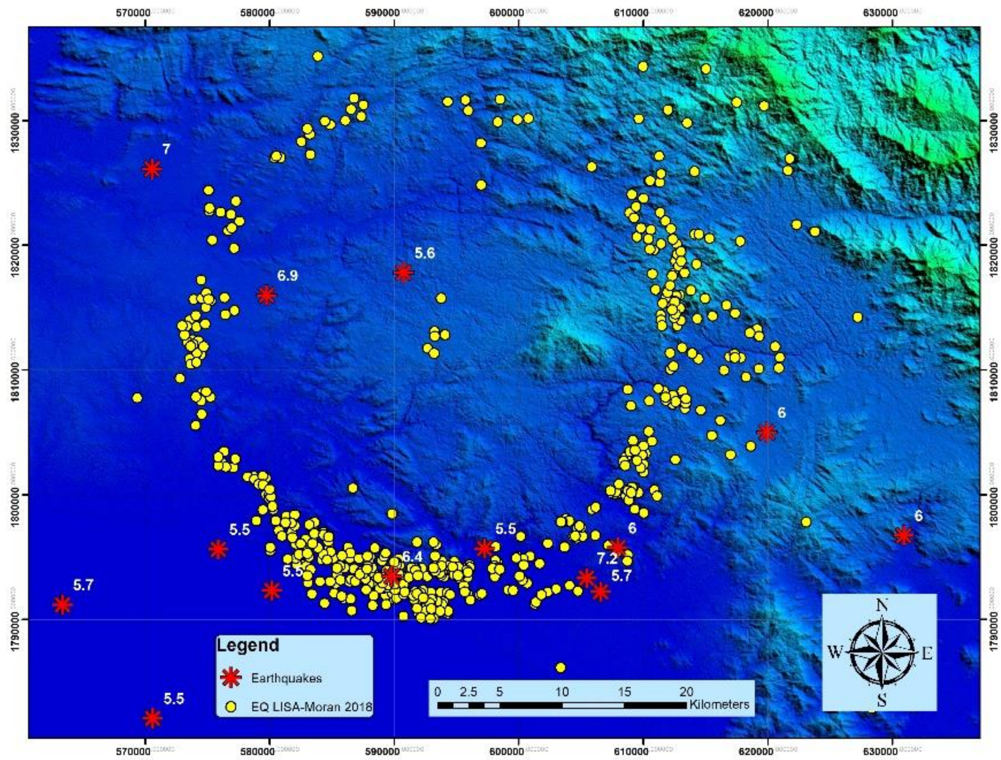


Figure 4. *Spatial alignment between Figure 3 (Low-Low column), data (2018), and earthquakes that occurred around*

The second statistic was the Getis-Ord Local Univariate (Gi* LU) which is interpreted as the relationship of each datum, a high value must be surrounded by other features with high values, as result, high values or greater than the mean represent high-high clusters or *hot spots* and low values or less than the mean indicates Low-Low cluster or *cold spot*. The result of the revalidation process described above is included in Figures 5 and 6.

4. DISCUSSION

With the LISA and SULMI analyses have been possible to identify theoretically, the spatial patterns of the most statistically significant seismic data (21.0%). The potential clusters of seismicity data recognized allow us to affirm that there is an assembly of data whose distribution in the study area is not entirely random.

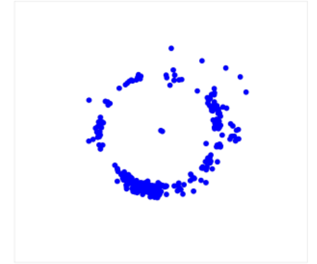
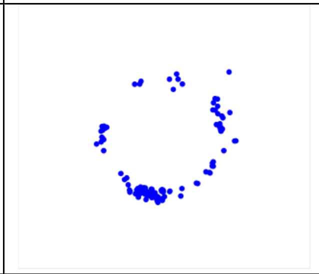
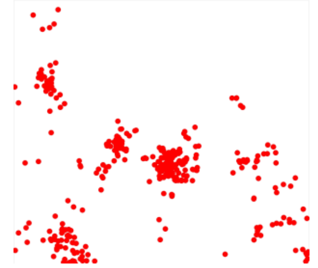
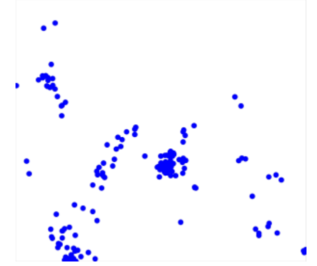
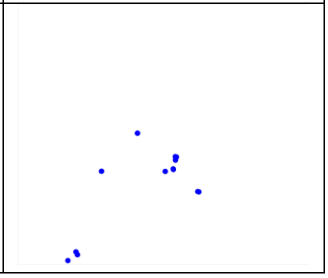
Año/Mw	9999 per, P = 0.05	9999 per, P = 0.01	9999 per, P = 0.001
2018 Mw: 2.0 to 2.8 Low values			
2018 Mw: 3.3 to 4.6 High values			

Figure 5. *Results of the modification to the permutation and P values data from the year 2018*

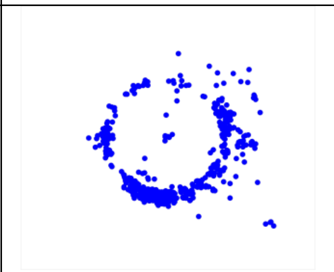
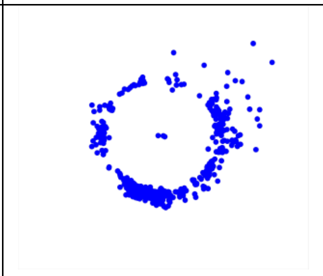
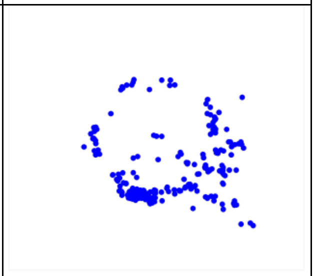
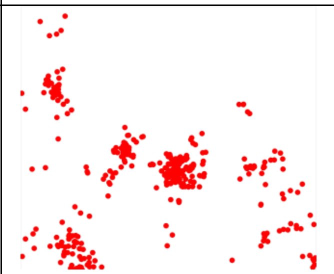
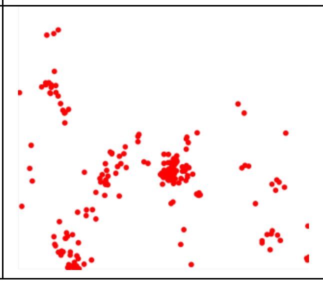
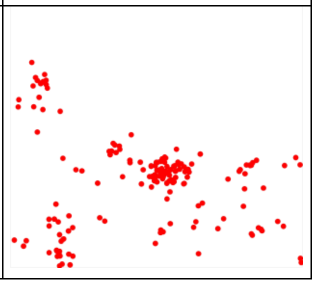
Año/Mw	SULMI	Gi*LU	Geary LU
2018, Low values; Moran's I; Mw: 2.0 to 2.8. GT; Mw: Mw: 2.0 to 4.7. Geary LU; Mw: 2.0 to 3.2			
2018, High values Moran's I; Mw: 3.3 to 4.6. GT; Mw: Mw: 2.4 to 4.6. Geary LU; Mw: 3.3 to 4.6			

Figure 6. *Validation results of Gi*LU and Geary LU statistics applied to 2018 seismic data*

About 21.0% of information is related to potential zones of significant seismicity, foreshocks-mainshock-aftershocks events (4 to 7.5Mw), and structures or geographical hidden tectonic features (2 to 2.8Mw), data that are interspersed with a wide percentage of seismic information (2.9 to 3.9Mw) associated with the continuous subduction movement between the Cocos Plate and the MAT (79.0%).

The 2018 data suggest the presence of a tectonic structure, an almost circular shape included in the LISA cluster map of 2018 (Figure 3, *Low-Low* *column*). The presence of the structure delineated within the study area could provide an alternative response to the intense local seismic activity since 14 earthquakes occurred and are closely aligned with such structures, Table 2.

Table 2. Earthquakes most significant from 1982 to 2018

No	Date	Hour	Mw	LN	LW	Depth
1	07/06/1982	00:52:33	6.9	16.424	-98.253	6
2	07/06/1982	04:59:40	7	16.516	-98.339	19
3	14/12/1982	08:11:51	5.7	16.46	-98.51	16
4	21/01/1997	15:19:58	5.6	16.44	-98.15	18
5	14/06/2004	17:54:21	6.4	16.22	-98.16	10
6	13/08/2005	21:51:58	5.8	15.99	-98.4	15
7	30/06/2010	02:22:27	6	16.24	-97.99	4
8	20/03/2012	12:02:48	7.5	16.264	-98.457	18
9	02/04/2012	12:36:43	6	16.2948	-98.544	12
10	24/05/2014	03:24:46	5.7	16.2002	-98.4073	4
11	08/05/2016	02:33:59	6	16.323	-97.8773	7
12	27/06/2016	15:50:31	5.7	16.208	-98.003	4
13	16/02/2018	17:39:39	7.2	16.218	-98.0135	16
14	19/02/2018	00:56:58	6	16.2477	-97.775	10

The presence of the delineated structure within the zone perhaps may be correlated, in the first instance, with the regional geological history of folding, magmatism, and metamorphism (Figure 7), this may be an ancient magmatic intrusion of material from the earth's mantle favored by the existence of remaining tectonic vulnerabilities. According to the outlined object dimensions, it could be associated also with an age-old volcanic arc that results in an ancient volcanic caldera, a batholith, a volcanic chamber, or a duct. However, its large dimensions and its almost circular shape could be associated with an ancient impact of an asteroid, particularly due to the existence of the mountainous relief deformation seen to the north of the structure (Figures 8–9).

The notable physical evidence of relief deformation and the slight bulge (dome) in the center of the structure are very similar to characteristics observed to those existing in other impacts recorded in other regions of the Earth’s surface (Figure 8, DEM source: https://asterweb.jpl.nasa.gov/gdem.asp).

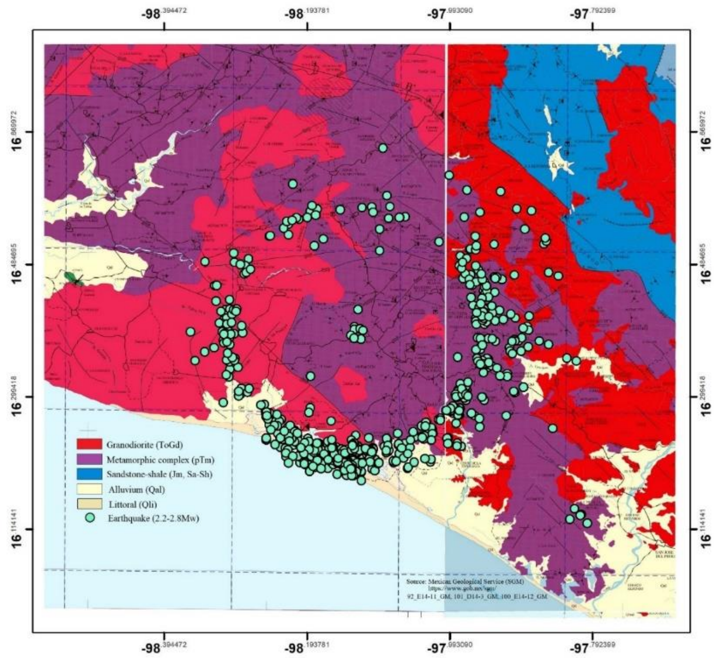


Figure 7*. Geology characteristics around the structure delineated within the area thru 2018 seismic activity*

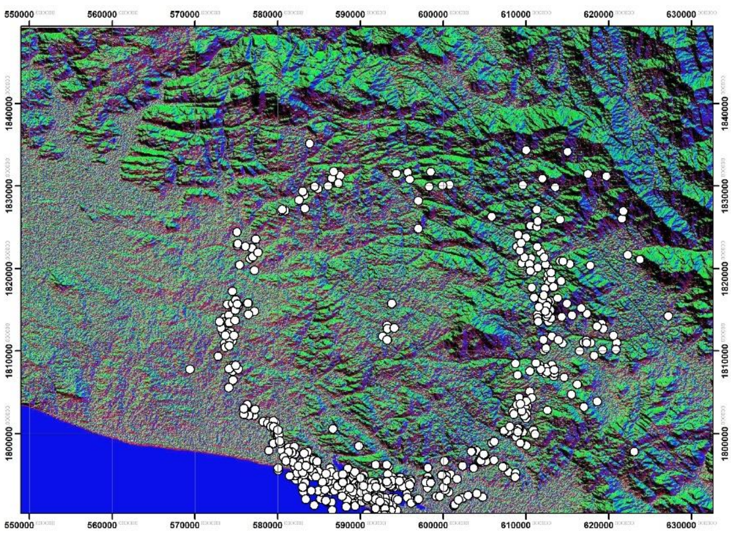


Figure 8*. Evidence of relief deformation to North of the tectonic feature delineated*

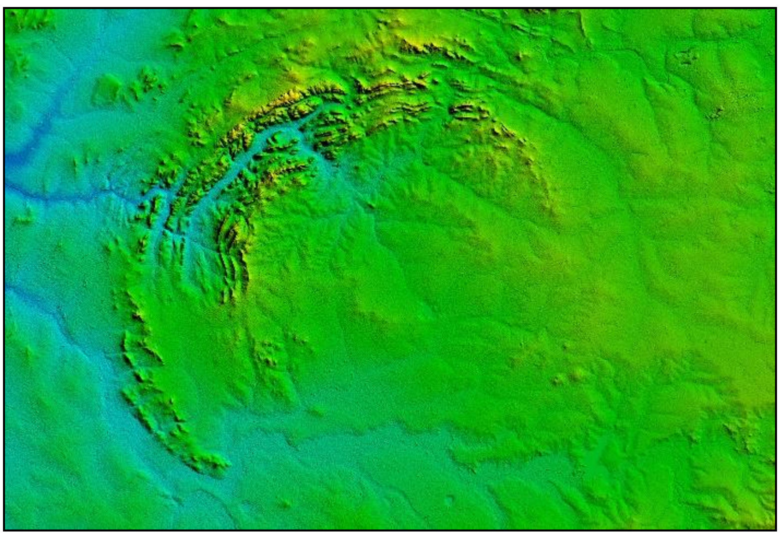


Figure 9*. Vredefort Crater, Free State, South Africa, with almost 40 km inside diameter*

5. CONCLUSIONS

The seismic activity within the region under study from 1980 to 2021 registered 32,046 earthquakes. However during a period of 30 years (1980 to 2011), the number of seismic events represented only 5.4% of the records.

From 2012 to 2021 there was a significant increase, reaching a maximum peak of 27.7% (8861 events) in 2018 (UNAM, 2013), after this year, the seismic activity progressively decreased, in 2019 (16.0%), 2020 (11.5%) and 2021 (8.79%) respectively.

The space-time distribution of 32,046 earthquakes over 42 years is not randomly, earthquakes are associated with particular regions within the study area.

a) Continuous subduction movement (79% of data, considered “statistical noise”).
b) The 21.0% remaining data suggest potential zones of significant seismicity (at least >5.5Mw) and foreshock-mainshock-aftershock events.
c) And some records suggest (2.0 to 2.8Mw) the presence of hidden structures or tectonic features within the study region.

The local seismic data pattern analyzed has contributed to delineating forms hidden beneath the area's surface as mentioned in this document, located just a few kilometers below. Micro-seismicity between 2.0 and 2.8 Mw originated principally in 2018 and showed a geographical feature hidden until now. It is a shape that is 43 kilometers in diameter, hidden 10 kilometers deep.

The results obtained with the application of the Gi*LU and Geary LU statistics to the records of 2018 suggest that the probability that the spatial arrangement (2.0 to 2.8Mw earthquakes) obtained at *P=0.05* and *0.01* of significance level responds to some type of spatial autocorrelation that is worth studying (Figure 3, *Low-Low column*; Figures 5-6*)*. This supports also the clustering results of potential zones of significant seismicity (>5.5Mw) and foreshock-mainshock-aftershock events also applicable to years before and after 2018.

The focus and results carried out with LISA and SULMI referred to seismic pattern analysis applied to Pinotepa seismic region can be considered outstanding with the potential for application to other seismic geographical regions.

The approach applied to study the seismicity data in the region evaluated, demonstrated to be a sensitive statistical tool and adequate (*Geoda tool*), with filters that make it possible to tabulate with certain precision the numerical limits between the data clusters (grey, red and blue dots), which would allow choosing only those data statistically significant to the seismic variations monitoring, spectra and waveforms study and forecasting future seismic events (spatial path, direction, and trend), even considering that each significant event has its own characteristics, as could be the case of the region under study.

REFERENCES

Al-Ahmadi, K., Al-Amri, A., & See, L. 2014, 'A spatial statistical analysis of the occurrence of earthquakes along the Red Sea floor spreading: Clusters of seismicity'. *Arabian Journal of Geosciences*, *7*(7), 2893–2904. https://doi.org/10.1007/s12517-013-0974-6

Arai, S. 1982, 'Petrology of Basalts from Site 487, Deep Sea Drilling Project Leg 66, Middle America Trench Area off Mexico'. In *Initial Reports of the Deep Sea Drilling Project*, *66* (I, pp. 711–722) U.S. Government Printing Office. https://doi.org/10.2973/dsdp.proc.66.134.1982

Armaş, I. 2012, 'Multi-criteria vulnerability analysis to earthquake hazard of Bucharest, Romania'. *Natural Hazards*, *63*(2), 1129–1156. https://doi.org/10.1007/s11069-012-0209-2

Armendáriz, E. 2006, 'Estación Linares (CENAPRED-UANL) nuevo observatorio de la Red Sismológica Nacional'. *Ciencias UANL*, *IX*(002), 192–196.

Aslam, B., & Naseer, F. 2020, 'A statistical analysis of the spatial existence of earthquakes in Balochistan: clusters of seismicity'. *Environmental Earth Sciences*, *79*(1). https://doi.org/10.1007/s12665-019-8790-2

Bianco, M. J., Gerstoft, P., Olsen, K. B. & Lin, F. C. 2019, 'High-resolution seismic tomography of Long Beach, CA using machine learning'. *Scientific Reports*, *9*(1), 1–11. https://doi.org/10.1038/s41598-019-50381-z

Cao, Z., Zhang, H., Liu, Y., Liu, S., Feng, L., Yin, L., & Zheng, W. 2022, 'Spatial distribution analysis of seismic activity based on GMI, LMI, and LISA in China'. *Open Geosciences*, *14*(1), 89–97. https://doi.org/10.1515/geo-2020-0332

Carr, B. J., Smithson, S. B., Kareav, N., Ronin, A., Garipov, V., Kristofferson, Y., Digranes, P., Smythe, D., & Gillen, C. 1996, 'Vertical seismic profile results from the Kola Superdeep Borehole, Russia'. *Tectonophysics*, *264*(1–4), 295–307. https://doi.org/10.1016/S0040-1951(96)00133-3

Catita, C., Teves-Costa, M. P., Matias, L., & Batlló, J. 2019, 'SPATIAL DISTRIBUTION OF FELT INTENSITIES FOR PORTUGAL EARTHQUAKES'. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-3/W8*(3/W8), 87–92. https://doi.org/10.5194/isprs-archives-XLII-3-W8-87-2019

Dominguez, L. A., Taira, T., & Santoyo, M. A. 2016, 'Spatiotemporal variations of characteristic repeating earthquake sequences along the Middle America Trench in Mexico'. *Journal of Geophysical Research: Solid Earth*, *121*(12), 8855–8870. https://doi.org/10.1002/2016JB013242

Ducea, M. N., Valencia, V. A., Shoemaker, S., Reiners, P. W., DeCelles, P. G., Campa, M. F., Morán-Zenteno, D., & Ruiz, J. 2004, 'Rates of sediment recycling beneath the Acapulco trench: Constraints from (U-Th)/He thermochronology'. *Journal of Geophysical Research: Solid Earth*, *109*(9), 1–11. https://doi.org/10.1029/2004JB003112

Hamylton, S. 2013, 'Five practical uses of spatial autocorrelation for studies of coral reef ecology'. *Marine Ecology Progress Series*, *478*(Tobler 1970), 15–25. https://doi.org/10.3354/meps10267

Harini, S. 2019, 'The earthquake events and impacts mapping in Bali and Nusa Tenggara using a clustering method'. *IOP Publishing*, *476*, 1–6. https://doi.org/10.1088/1755-1315/456/1/012087

Julian, B. R., Miller, A. D., & Foulger, G. R. 1998, 'Non-double-couple earthquakes'. *Reviews of Geophysics*, *36*(4), 525–549. https://doi.org/10.1029/98RG00716

Li, X., Yin, L., Yao, L., Yu, W., She, X., & Wei, W. 2020, 'Seismic spatiotemporal characteristics in the Alpide Himalayan Seismic Belt'. *Earth Science Informatics*, *13*(3), 883–892. https://doi.org/10.1007/s12145-020-00468-3

Martínez-García, F. 2017, 'Statistical Analysis of Natural Water Conductivity Data Behavior in Two Wells: Seismic Coastal Border Limits of Guerrero-Oaxaca States, Mexico'. *OALib*, *04*(09), 1–37. https://doi.org/10.4236/oalib.1103900

Martínez-García, F., Colín-Cruz, A., Adame-Martínez, S., & Ramírez-García, J. J. 2015, 'Atypical Variations of Water Conductivity Prior to Tectonic Earthquakes'. *International Journal of Geosciences*, *06*(12), 1367–1385. https://doi.org/10.4236/ijg.2015.612108

Martínez-García, F., Colín-Cruz, A., Pereira-Corona, A., Adame-Martínez, S., & Ramírez-García, J. J. 2016, 'Natural Water Conductivity Behavior within the Seismic Pacific Coast of Southern Mexico'. *OALib*, *03*(07), 1–21. https://doi.org/10.4236/oalib.1102836

Montalvo Arrieta, J. C., Cavazos Tovar, P., Navarro de León, I., Alva Niño, E., & Medina Barrera, F. 2008, 'Mapping Seismic Site Classes in Monterrey Metropolitan Area, northeast Mexico'. *Boletín de La Sociedad Geológica Mexicana*, *60*(2), 147–157. https://doi.org/10.18268/bsgm2008v60n2a1

Perez-Gutierrez, R., Solari, L. a, Gomez-Tuena, A., & Martens, U. 2009, 'Mesozoic geologic evolution of the Xolapa migmatitic complex north of Acapulco, southern Mexico: implications for paleogeographic reconstructions'. *Revista Mexicana De Ciencias Geológicas*, *26*(1), 201–221.

Riga, G., & Balocchi, P. 2018, 'Double Earthquakes Classification and Seismic Precursors'. *Open Journal of Earthquake Research*, *07*(01), 1–27. https://doi.org/10.4236/ojer.2018.71001

Servicio Geológico Mexicano (SGM) 1998, *Carta Geológico Minera Chilpancingo E14-8* (p. 1) Secretaría de Economía.

Sofyan, H., Rahayu, L., & Lusiani, E. 2019, 'Spatial Autocorrelation of Earthquake Magnitudes in Tripa Fault, Aceh Province, Indonesia'. *IOP Publishing*, 1–7. https://doi.org/10.1088/1755-1315/273/1/012048

Toma-Danila, D., Cioflan, C. O., & Armas, I. 2017, *GIS in seismology : contributions to the evaluation of seismic hazard and risk II*(2), 10–16. http://www.geodinamic.ro/assets/geo-patterns/volumes/v2.2_10-16.pdf

UNAM 2013, 'Ometepec-Pinotepa Nacional, Mexico Earthquake of 20 March 2012 (Mw7.5): A preliminary report'. *Geofisica Internacional*, *52*(2), 173–196. https://doi.org/10.1016/S0016-7169(13)71471-5

Yamamoto, J., González-Moran, T., Quintanar, L., Zavaleta, A. B., Zamora, A., & Espindola, V. H. 2013, 'Seismic patterns of the Guerrero-Oaxaca, Mexico region, and its relationship to the continental margin structure'. *Geophysical Journal International*, *192*(1), 375–389. https://doi.org/10.1093/gji/ggs025

Yamamoto, J., Quintanar, L., & Jiménez, Z. 2002, 'Why earthquake doublets in the Ometepec, Guerrero, Mexico subduction area?'. *Physics of the Earth and Planetary Interiors*, *132*(1–3), 131–139. https://doi.org/10.1016/S0031-9201(02)00048-1

Yousefzadeh, M., Hosseini, S. A., & Farnaghi, M. 2021, 'Spatiotemporally explicit earthquake prediction using deep neural network'. *Soil Dynamics and Earthquake Engineering*, *144*. https://doi.org/10.1016/j.soildyn.2021.106663

Zhang, L., Ma, Z., & Guo, L. 2009, 'An evaluation of spatial autocorrelation and heterogeneity in the residuals of six regression models'. *Forest Science*, *55*(6), 533–548. https://doi.org/https://doi.org/10.1093/forestscience/55.6.533

GIS software references

Blue Marble Geographics. 2018, Global Mapper v18.0.0. Hallowell, Maine 04347 U.S.A.

Environmental Systems Research Institute (ESRI). 2017, ArcGIS Release 10.6. Redlands, CA.

