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Computational intelligence of GMT and R for modelling seismicity in Cuba

Inteligencia computacional del GMT y R para el modelado de la sismicidad en Cuba

Polina Lemenkova [1,2*], https://orcid.org/0000-0002-5759-1089

[1] Department of Automated Control Systems, College of Computer Sciences, Moscow Institute of Steel and Alloys (MISIS), National University of Science and Technology, Moscow, Russia.
[2] Institute of Geography, Russian Academy of Sciences, Moscow, Russia.

*Autor para la correspondencia. p.lemenkova@misis.ru

ABSTRACT

Data analysis is essential in seismology which integrates cartographic techniques and geophysical information for monitoring seismic events: earthquakes, tsunamis and volcanism. Substantial gaps still persist in this domain which requires developing novel methods for visualization and rapid data processing. Addressing these challenges is imperative to maximize the efficiency of data modelling. Cuba is located in the zone of high seismic risk due to seismotectonic setting. High risk of seismicity in Cuba is caused by its location at the intersection of the two tectonic plates – the North American and Caribbean. Here we propose advanced scripting methods on seismic data processing using GMT and R scripts. The dataset on seismicity in Cuba was collected from the NSF SAGE and USGS and processed to visualize the distribution, frequency and magnitude of earthquakes from 1973 to 2025. The data on tsunami was obtained from the NCEI/WDS to analyse the retrospective occurrence of the events. The results of the data analysis shown that in 2024, significant earthquakes were recorded 35-40 km SSW of Bartolomé Masó with magnitude 5.8 and 6.8 M_L Richter scale, and in 2020, the earthquake with the magnitude of 7.7 struck off the SE coast of Cuba. However, the data analysis shown that the most frequent type of earthquakes in Cuba has a low magnitude (M_L 4.3 R. s.), which is causes no structural damages. This paper contributed to development of seismic hazards prognosis by presenting R and scripting GMT algorithms for seismological data analysis.

Keywords: seismicity; cartography; R programming; statistical analysis; geophysics.

RESUMEN

El análisis de datos es esencial en sismología, ya que integra técnicas cartográficas e información geofísica para el monitoreo de eventos sísmicos: terremotos, tsunamis y vulcanismo. Aún persisten brechas sustanciales en este dominio, lo que requiere el desarrollo de nuevos métodos de visualización y procesamiento rápido de datos. Abordar estos desafíos es imperativo para maximizar la eficiencia del modelado de datos. Cuba se encuentra en una zona de alto riesgo sísmico debido a su entorno sismotectónico. El alto riesgo de sismicidad en Cuba se debe a su ubicación en la intersección de dos placas tectónicas: la Norteamericana y la del Caribe. Aquí proponemos métodos avanzados de scripting para el procesamiento de datos sísmicos utilizando scripts GMT y R. El conjunto de datos sobre sismicidad en Cuba se recopiló de NSF SAGE y USGS y se procesó para visualizar la distribución, frecuencia y magnitud de los terremotos de 1973 a 2025. Los datos sobre tsunamis se obtuvieron de NCEI/WDS para analizar la ocurrencia retrospectiva de los eventos. Los resultados del análisis de datos mostraron que en 2024 se registraron terremotos significativos a 35-40 km al SSO de Bartolomé Masó, con magnitudes de 5.8 y 6.8 en la escala de Richter, y en 2020, un terremoto de magnitud 7.7 golpeó la costa sureste de Cuba. Sin embargo, el análisis de datos mostró que el tipo de terremoto más frecuente en Cuba es de baja magnitud (4.3 en la escala de Richter), lo que no causa daños estructurales. Este trabajo contribuyó al desarrollo del pronóstico de riesgos sísmicos mediante la presentación de algoritmos R y scripting GMT para el análisis de datos sismológicos.

Palabras clave: sismicidad; cartografía; programación R; análisis estadístico; geofísica

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Introduction

Earthquakes are natural hazards with devastating nature. The consequences of earthquakes in the seismically active areas are especially critical for the humanity and environment and include ground shaking and building collapses (Miyamoto et al., 2024), injuries, deaths and displacements, landslides (Clare et al., 2024) and tsunami (Granja-Bruña et al., 2025). Preventing risks of seismic events is based on the advanced monitoring and analysis of seismological datasets, which is one of the important approaches in seismology for identification of earthquakes in seismically active regions. Such approaches utilize the seismicity as a measure of earthquake occurrences, analysis of their mechanisms, focus and magnitude at a given location.

Cuba has a high risk of seismicity, which is caused by its location at the intersection of the two tectonic plates – the North American and Caribbean (Calais et al., 2016, 2023; Escuder-Viruete et al., 2023; Lemenkova, 2020a). The Bartlett-Cayman fault system, stretching along the southeast coast of the island, is the main source of seismic events, which account for about 70% of seismic activity (Moreno et al., 2002). This is the most seismically active area, particularly near Santiago de Cuba, which is the source of most of Cuba's powerful earthquakes (Escuder-Viruete et al., 2024). Recent significant event of the destructive earthquake has experienced in 2020 being the highest magnitude ever recorded in Cuba. Besides the Bartlett-Cayman fault system, other active faults within Cuba also contribute to the seismicity of the country, such as the Cauto-Nipe, Cochinos, and Nortecubana faults (Cotilla Rodriguez et al., 2007).

To prevent the risk of earthquakes, landslides and tsunami, essential measures in seismology have being undertaken to assessment of seismic events (Jessee et al., 2018). The prognosis and forecasting of earthquake risk is strongly related to the progress in data analysis (Lemenkova et al., 2023). Early detection of earthquakes and high seismicity as parts of geophysical monitoring needs a timely recognition of seismic activity and involves data-driven monitoring.

Cuba, a region located in a zone of high seismicity, is also a key player in seismic observations. To foster development in this domain, the country contributes to global operative monitoring of earthquakes through data collected from a national seismic network managed by the National Seismological Service (CENAIS) with at least seismic 21 stations. The CENAIS is processing seismic data to evaluate frequency and magnitude of events using observations obtained from seismometers for prognosis and forecast, https://www.fdsn.org/networks/detail/CW/. However, earthquakes remain the highest hazard for humanity and environment due to the highest devastation level and massive economic damage.

Accurate monitoring and prognosis of seismic risks require novel approaches of computational intelligence to advanced methods of processing Earth observation data. Observation, monitoring, and analysis of seismic activity are among the fundamental approaches of geologic risk prevention and hazard mitigation, where data analysis and methods plays a crucial role. By utilizing geophysical data and seismographs from relevant repositories, the detection of seismic risks enables to visualise earthquake maps, indicate their location and magnitude. Such measures support monitoring seismic dynamics through analysis of data on magnitude, motion, and location of seismic events. In this study, we employ open source data from the geophysical public centers and employ free software Generic Mapping Tools (GMT) and R statistical and programming language to map seismic setting around Cuba.

Materials and Methods

Data

The data were based on the Earthquake Browser from the repository of the Incorporated Research Institutions for Seismology) (IRIS) datasets, EarthScope Consortium which supports the computational geophysical research and education, https://www.earthscope.org/ The seismic data were obtained from the United States Geological Survey (USGS) on the period from 1970-01-01 to 2055-01-01 on the region of Cuba. It includes data on all seismic events with magnitudes, focal depths, location and tim, Table 1.

Table 1 – Seismicity in Cuba: 196 earthquakes (fragment of table with selected 16 rows; original table has 196 rows).

Year	Month	Day	Time	Lat	Lon	Depth	Mag	Region	Timestamp
2025	4	6	14:41:44	19,03	-80,55	10	4,1	66 km ESE of East End, Cayman Islands	1743950504
2024	12	23	06:00:59	19,92	-76,52	22,2	5,9	37 km S of Guisa, Cuba	1734933659
2024	11	25	06:52:49	19,86	-77,06	10	4,3	36 km SSW of Bartolomé Masó, Cuba	1732517569

2024	11	10	21:27:53	19,75	-77,21	10	3,9	49 km SSE of Media Luna, Cuba	1731274073
2024	11	10	18:45:37	19,76	-77,11	15,8	4,6	48 km SSW of Bartolomé Masó, Cuba	1731264337
2024	11	10	18:36:43	19,75	-77,11	16,6	4,3	49 km SSW of Bartolomé Masó, Cuba	1731263803
2024	11	10	16:49:50	19,82	-77,08	14	6,8	40 km SSW of Bartolomé Masó, Cuba	1731257390
2024	11	10	15:50:03	19,85	-76,97	19	5,8	35 km S of Bartolomé Masó, Cuba	1731253803
2024	10	17	14:50:32	19,71	-75,98	17,6	4,6	37 km S of El Cobre, Cuba	1729176632
2024	9	7	23:09:55	19,56	-75,59	10	4,5	57 km SSE of Santiago de Cuba, Cuba	1725750595
The table continues until year 1976 (in total, it contains 196 rows).									
1976	10	17	17:45:08	19,93	-75,37	33	4,9	Cuba region	214422308
1976	10	17	00:09:43	19,68	-75,52	33	4,6	Cuba region	214358983
1976	2	24	11:28:38	19,65	-77,25	33	4,8	Cuba region	194009318
1976	2	23	21:58:50	19,82	-77,2	33	4,9	Cuba region	193960730
1976	2	19	13:59:59	19,89	-76,88	20	5,9	Cuba region	193586399
1973	5	20	03:00:09	19,8	-75,4	33	4,6	Cuba region	106714809

The tsunami source data was analysed using the tsunami database which contains retrospective information on locations where tsunami effects were observed in region of Cuba, Table 2.

Table 2 – Tsunami in Cuba region: A retrospective historical analysis. Data source: NCEI/WDS Global Historical Tsunami Database, existing records from 2100 BC to Present.

Year	**1766**	**1775**	**1852**	**1931**	**1932**	**1939**	**2020**
Month	6	2	9	12	2	8	1
Day	12	11	23	1	3	15	28
Hour	5	N/A	12	N/A	6	3	19
Min	0	N/A	N/A	N/A	16	52	10
Sec	N/A	N/A	N/A	N/A	2	N/A	25
Tsunami Event Validity	-1	4	4	1	2	2	4
Tsunami Cause Code	1	1	1	0	1	1	1
Earthquake Magnitude	6,8	N/A	N/A	N/A	6,7	5.6	7,7
Location	Santiago de Cuba	Santiago de Cuba	Santiago de Cuba	Northern Coast (Las Villas)	Santiago de Cuba	Santa Clara	Off Se Coast Of Cuba
Latitude	19.9	19.9	20.0	19.7	19.7	22.2	19,44

Longitude	-76.100	-76.0	-75.8	-80.4	-75.7	-79.1	-78.7
Maximum Water Height (m)	N/A	N/A	N/A	1	NA	N/A	0,11
Nr. of Runups	1	2	1	2	1	1	2
Total Deaths	40	N/A	N/A	N/A	14	N/A	N/A
Total Injuries	700	N/A	N/A	N/A	300	N/A	N/A

The cartographic data were credited from the public open sources: the administrative data were obtained from the Simplemap project (https://simplemaps.com) which initiatives the interactive maps and data; the topographic grid as a background relief was extracted as a subsets of raster dataset ETOPO Global Relief ModelNCEI's ETOPO 2022: https://www.ncei.noaa.gov/products/etopo-global-relief-model The topographic data was get from the General Bathymetric Chart of the Oceans (GEBCO). GEBCO presents a fine-resolution raster grid for topographic mapping, as reported and used earlier (Lemenkova, 2020b).

Methods

The methodology is based on using open source software: GMT (Wessel et al., 2019) for cartographic data processing and seismic mapping, and R languages for statistical analysis (R Core Team, 2021).

Cartographic scripting

The advances of GMT include scripting algorithms which supports automated data processing (Lemenkova, 2022a). The tabular data were visualised using Generic Mapping Tools (GMT) and QGIS, open source programs. The data were processed in GMT environment using a combination of several modules: 'psbasemap', 'psscale', 'grdcontour', 'pscoast' and 'psxy'. The example of GMT script is shown in Fig. 1. The GMT presents a scripting toolbox for geophysical data analysis which integrates the analytical approach with cartographic data visualization. Such approach facilitates the evaluation of seismic datasets through specially designed modules which excellently visualize shifts in earthquake's magnitude, location and focal depth, offering insights into the risk of seismic hazards.

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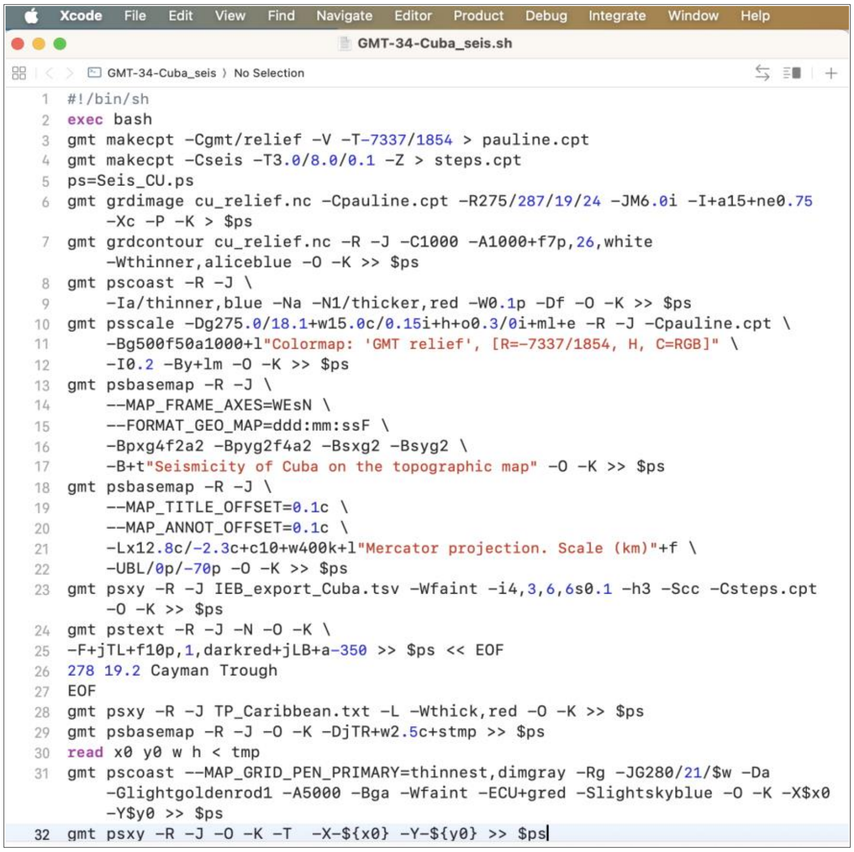


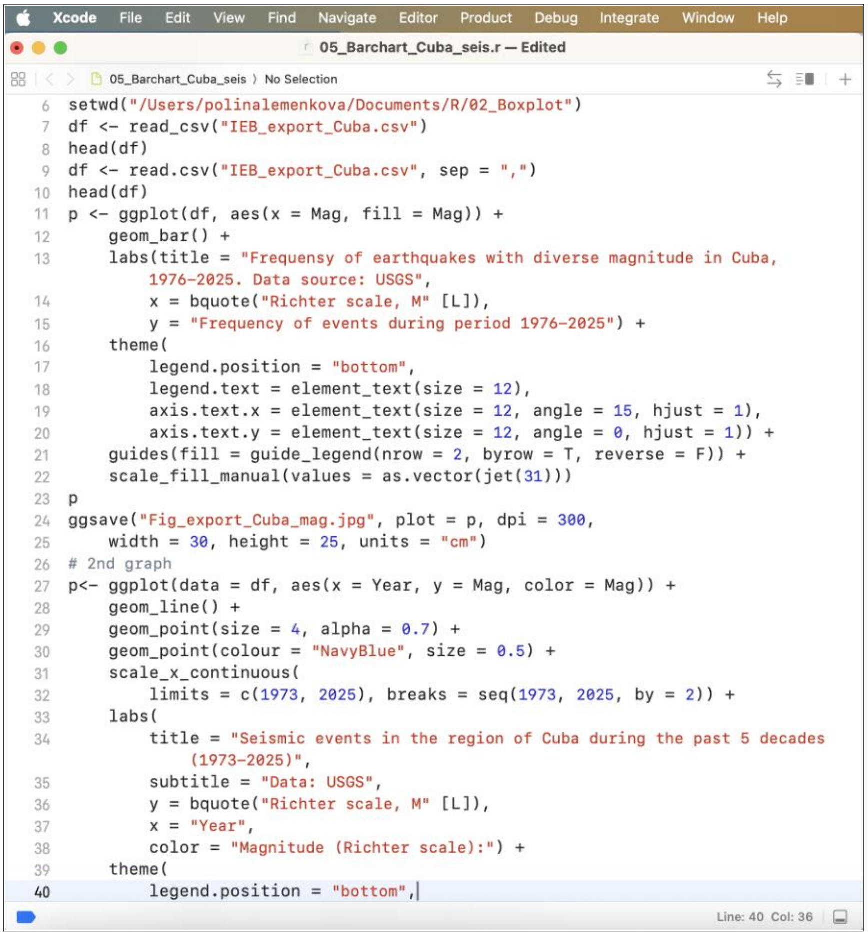

```
#!/bin/sh
exec bash
gmt makecpt -Cgmt/relief -V -T-7337/1854 > pauline.cpt
gmt makecpt -Cseis -T3.0/8.0/0.1 -Z > steps.cpt
ps=Seis_CU.ps
gmt grdimage cu_relief.nc -Cpauline.cpt -R275/287/19/24 -JM6.0i -I+a15+ne0.75
    -Xc -P -K > $ps
gmt grdcontour cu_relief.nc -R -J -C1000 -A1000+f7p,26,white
    -Wthinner,aliceblue -O -K >> $ps
gmt pscoast -R -J \
    -Ia/thinner,blue -Na -N1/thicker,red -W0.1p -Df -O -K >> $ps
gmt psscale -Dg275.0/18.1+w15.0c/0.15i+h+o0.3/0i+ml+e -R -J -Cpauline.cpt \
    -Bg500f50a1000+l"Colormap: 'GMT relief', [R=-7337/1854, H, C=RGB]" \
    -I0.2 -By+lm -O -K >> $ps
gmt psbasemap -R -J \
    --MAP_FRAME_AXES=WEsN \
    --FORMAT_GEO_MAP=ddd:mm:ssF \
    -Bpxg4f2a2 -Bpyg2f4a2 -Bsxg2 -Bsyg2 \
    -B+t"Seismicity of Cuba on the topographic map" -O -K >> $ps
gmt psbasemap -R -J \
    --MAP_TITLE_OFFSET=0.1c \
    --MAP_ANNOT_OFFSET=0.1c \
    -Lx12.8c/-2.3c+c10+w400k+l"Mercator projection. Scale (km)"+f \
    -UBL/0p/-70p -O -K >> $ps
gmt psxy -R -J IEB_export_Cuba.tsv -Wfaint -i4,3,6,6s0.1 -h3 -Scc -Csteps.cpt
    -O -K >> $ps
gmt pstext -R -J -N -O -K \
-F+jTL+f10p,1,darkred+jLB+a-350 >> $ps << EOF
278 19.2 Cayman Trough
EOF
gmt psxy -R -J TP_Caribbean.txt -L -Wthick,red -O -K >> $ps
gmt psbasemap -R -J -O -K -DjTR+w2.5c+stmp >> $ps
read x0 y0 w h < tmp
gmt pscoast --MAP_GRID_PEN_PRIMARY=thinnest,dimgray -Rg -JG280/21/$w -Da
    -Glightgoldenrod1 -A5000 -Bga -Wfaint -ECU+gred -Slightskyblue -O -K -X$x0
    -Y$y0 >> $ps
gmt psxy -R -J -O -K -T  -X-${x0} -Y-${y0} >> $ps
```

Fig. 1 – The snippet of GMT script used for plotting seismicity in Cuba.

R statistical analysis

The statistical analysis of the tabular data as based on R computational software to analyse the frequency and dynamics of earthquakes during 5 decades (1973-2025). Two categories were analysed: the magnitude and repetition of the seismic events on specific focal depths. To this end, the R library "ggplot2" was used for statistical data modelling (Wickham, 2016).The analysis of repeatability of earthquakes with their rate, location and magnitude was performed using R software.

R has advantages in the modelling and visualization performances through scripting, which makes it stand out among the approaches and other statistical software. The example of R script is shown in Fig. 2.The categories of magnitudes were analysed using 'ggplot2' library and its extensive functionality to show the trends in data distribution in temporal extent (recent 5 decades) and by frequency of magnitudes. For graphical analysis, line graphs and bar charts were used as efficient inductive learning algorithms of information extraction from the large dataset (almost 200 rows) of length of the original table.



```
setwd("/Users/polinalemenkova/Documents/R/02_Boxplot")
df <- read_csv("IEB_export_Cuba.csv")
head(df)
df <- read.csv("IEB_export_Cuba.csv", sep = ",")
head(df)
p <- ggplot(df, aes(x = Mag, fill = Mag)) +
    geom_bar() +
    labs(title = "Frequensy of earthquakes with diverse magnitude in Cuba,
        1976-2025. Data source: USGS",
        x = bquote("Richter scale, M" [L]),
        y = "Frequency of events during period 1976-2025") +
    theme(
        legend.position = "bottom",
        legend.text = element_text(size = 12),
        axis.text.x = element_text(size = 12, angle = 15, hjust = 1),
        axis.text.y = element_text(size = 12, angle = 0, hjust = 1)) +
    guides(fill = guide_legend(nrow = 2, byrow = T, reverse = F)) +
    scale_fill_manual(values = as.vector(jet(31)))
p
ggsave("Fig_export_Cuba_mag.jpg", plot = p, dpi = 300,
    width = 30, height = 25, units = "cm")
# 2nd graph
p<- ggplot(data = df, aes(x = Year, y = Mag, color = Mag)) +
    geom_line() +
    geom_point(size = 4, alpha = 0.7) +
    geom_point(colour = "NavyBlue", size = 0.5) +
    scale_x_continuous(
        limits = c(1973, 2025), breaks = seq(1973, 2025, by = 2)) +
    labs(
        title = "Seismic events in the region of Cuba during the past 5 decades
            (1973-2025)",
        subtitle = "Data: USGS",
        y = bquote("Richter scale, M" [L]),
        x = "Year",
        color = "Magnitude (Richter scale):") +
    theme(
        legend.position = "bottom",
```

Fig. 2 – The snippet of R script used for statistical analysis of seismicity in Cuba.

Results and discussion

The cities most vulnerable to earthquakes in Cuba are in the eastern part of the island, particularly Santiago de Cuba, due to their proximity to the North American and Caribbean plate boundary fault. The eastern region, including cities like Holguin and Guantánamo, experiences frequent seismic activity, Fig. 3. The analysis of data shows that the most vulnerable regions of Cuba with high risk of seismicity are southern regions, such as Granma and Guantánamo. For instance, Table 1 shows that in November 2024, the earthquakes magnitudes 5.9 M and 6.8 M respectively, at a depth of 14 km occurred in the proximity of

Bartolomé Masó, at distancces 40 km and 35 km, respectively. The analysed dataset shows that the epicentre was located south-east of Pilon municipality and 40 km south of Bartolomé Masó, Granma province. Other affected locations incldue Holguín and Ciego de Ávila, in south-eastern Cuba, Fig. 3.

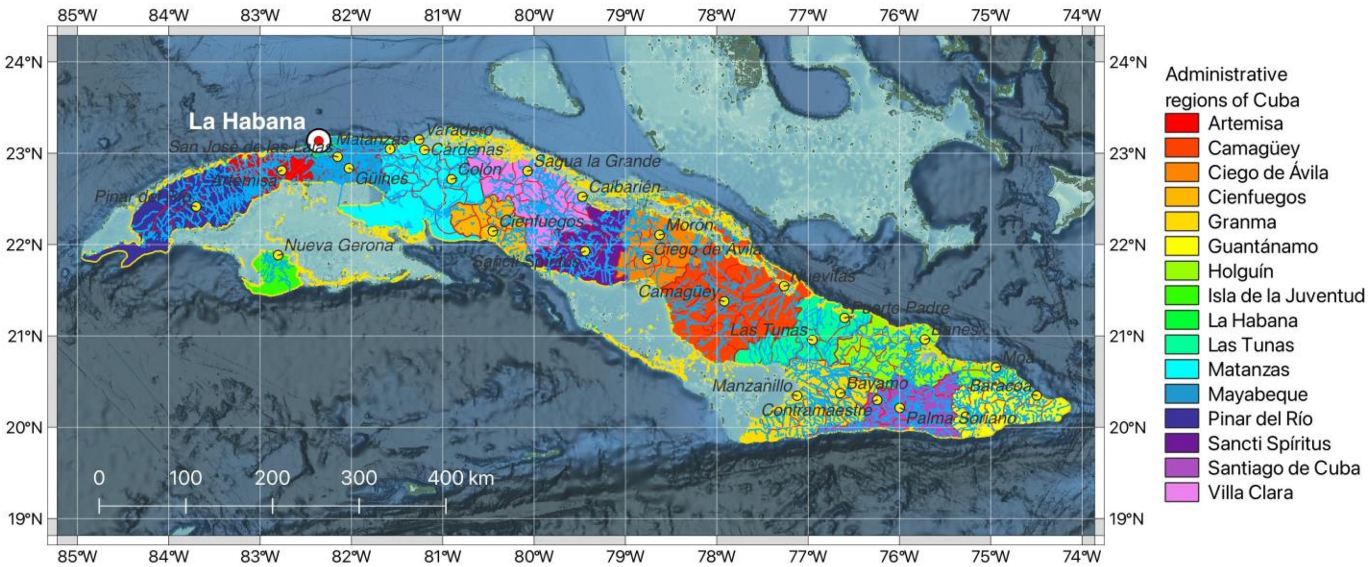


Fig. 3 – General map of Cuba with administrative districts and relief background.

Data: administrative portal of Cuba; ETOPO2022. Software: QGIS. Map source: made by the author.

The analysis of Table 2 shows that the island has been struck by a number of tsunamis as a consequences of destructive earthquakes over the past four centuries (according to the historical records in the archives). Several major quakes hav had a magnitude of 7.0 or above, Table 2. The earthquake with the magnitude of 7.7 struck off the southeast coast of Cuba on January 28, 2020, with epicenter between Cuba and Jamaica.

It primarily shows the distribution of tsunamis in retrospective historical view, since Cuba has a tectonics structure in the southern of the North American plate with possibility of occurrence of tsunamis.

Recent local tsunamis occurred in the Central-Northern region (1931.10. 01, and Nortecubana fault, 1939), the other was a recent tsunami in 2020, Table 2. The tsunamis in 20th century happened in central and northern Cuba. The tsunami in 1939 was triggered by a M_S=5.6 earthquake along the Nortecubana Fault system. The tsunami affected the coast at Cabo Frances, and while wave heights were not specified in the analysed information, earthquakes along this fault system can produce tsunamis. This event was noted in lists of historical tsunamis and is linked as a record to the seismic activity in the region.

The analysis of map in Fig. 4 shows the distribution of the earthquakes with varied magnitude over the region. The majority of earthquakes recorded by the seismological centers are located along the Cayman Trough which indicates the tectonic origin of the events.

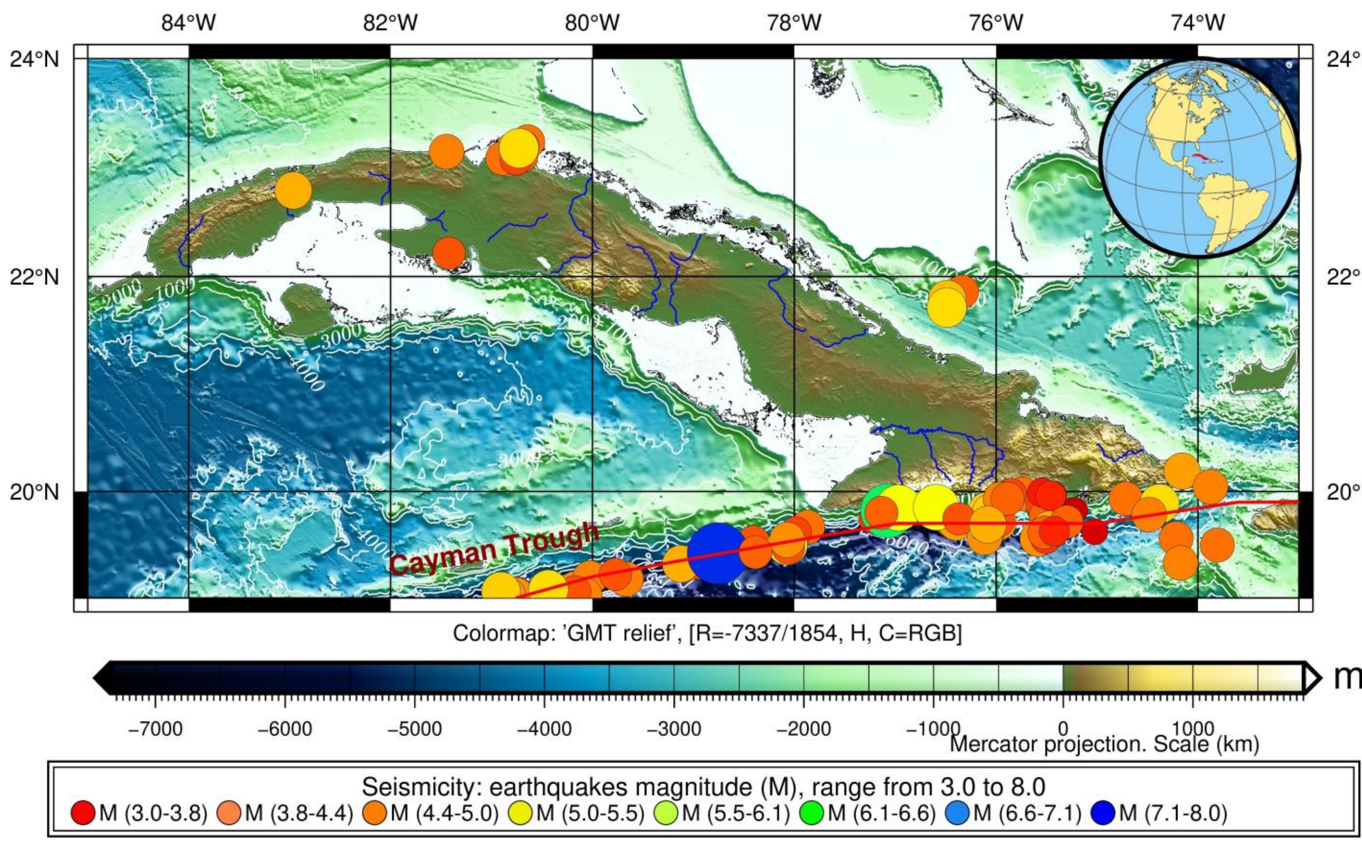


Fig. 4 – Seismicity in Cuba on the topographic map (1976-2025).

Data: NSF SAGE/ USGS. Software: GMT. Map source made by the author.

The Cayman Trough is a seismically active region of south to south-eastern Cuba with earthquakes primarily caused by the left-lateral strike-slip motion along the Oriente fault. The Cayman Trough forms a part of the boundary between the North American and Caribbean plates, Fig. 4. Recent significant seismic activity in this area included a major earthquake (M_L 7.7 Richter scale) on 28/01/2020, which ruptured the Oriente fault and exhibited shear rupture. This earthquake was followed by aftershocks due to the breaking and sliding of rock along a fault, caused by shear stress, which proves general seismotectonic setting of major faulting of southern Cuba. The statistical count showing frequency of earthquakes in Cuba region with diverse magnitudes for the period of 1976-2025 is shown in Fig. 5.

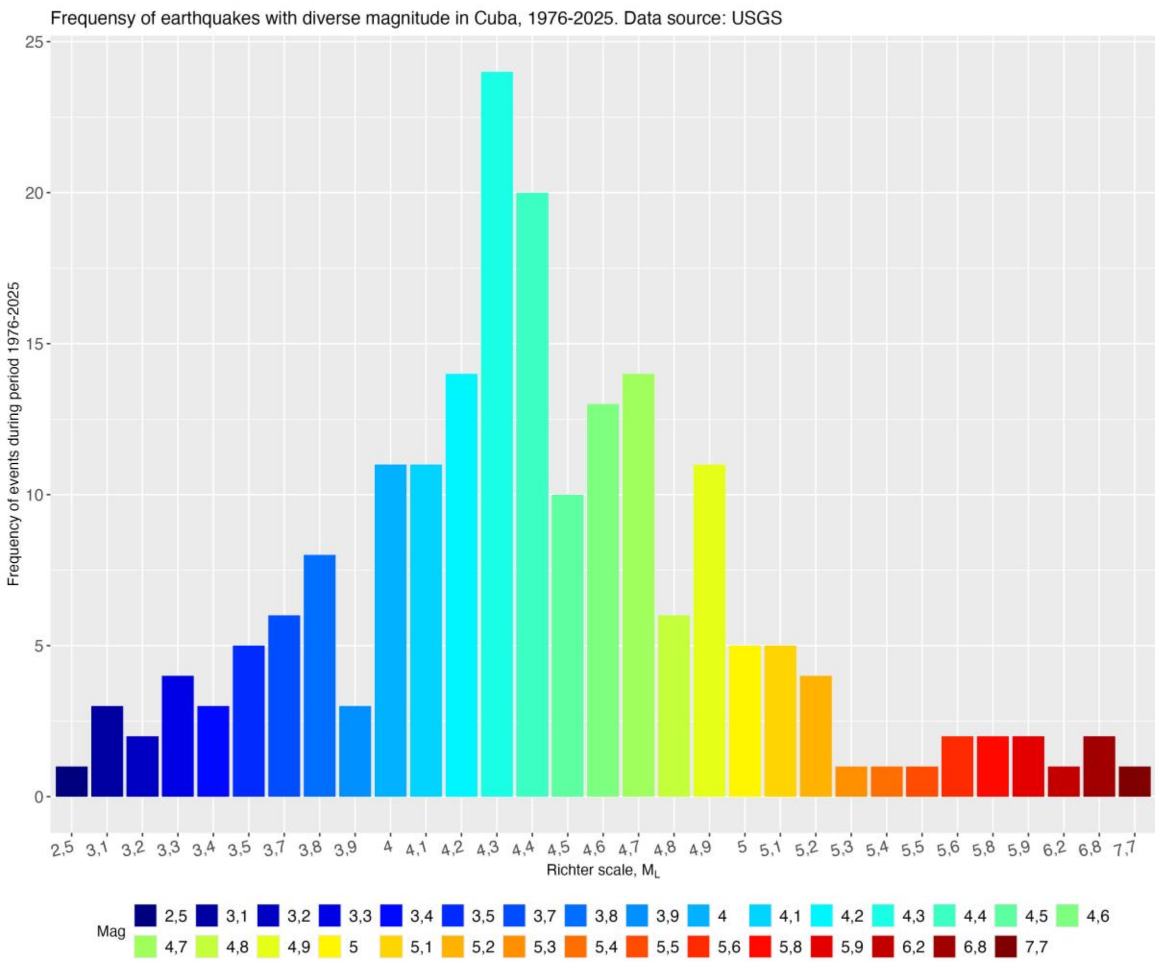


Fig. 5 – Frequency of earthquakes in Cuba region with diverse magnitude (1976-2025).

Data: NSF SAGE, USGS. Software: R. Graph source: made by the author.

It shows that the most frequent earthquake has magnitude of M_L 4.3 Richter scale. The earthquakes with such magnitude often felt, but rarely causes damage. The statistics on retrospective dynamics of seismic events in the region of Cuba in period of 5 decades (1976-2025) is presented in relevant graph, which shows the repetitions of the size of the earthquakes in the given period of 5 decades, Fig. 6.

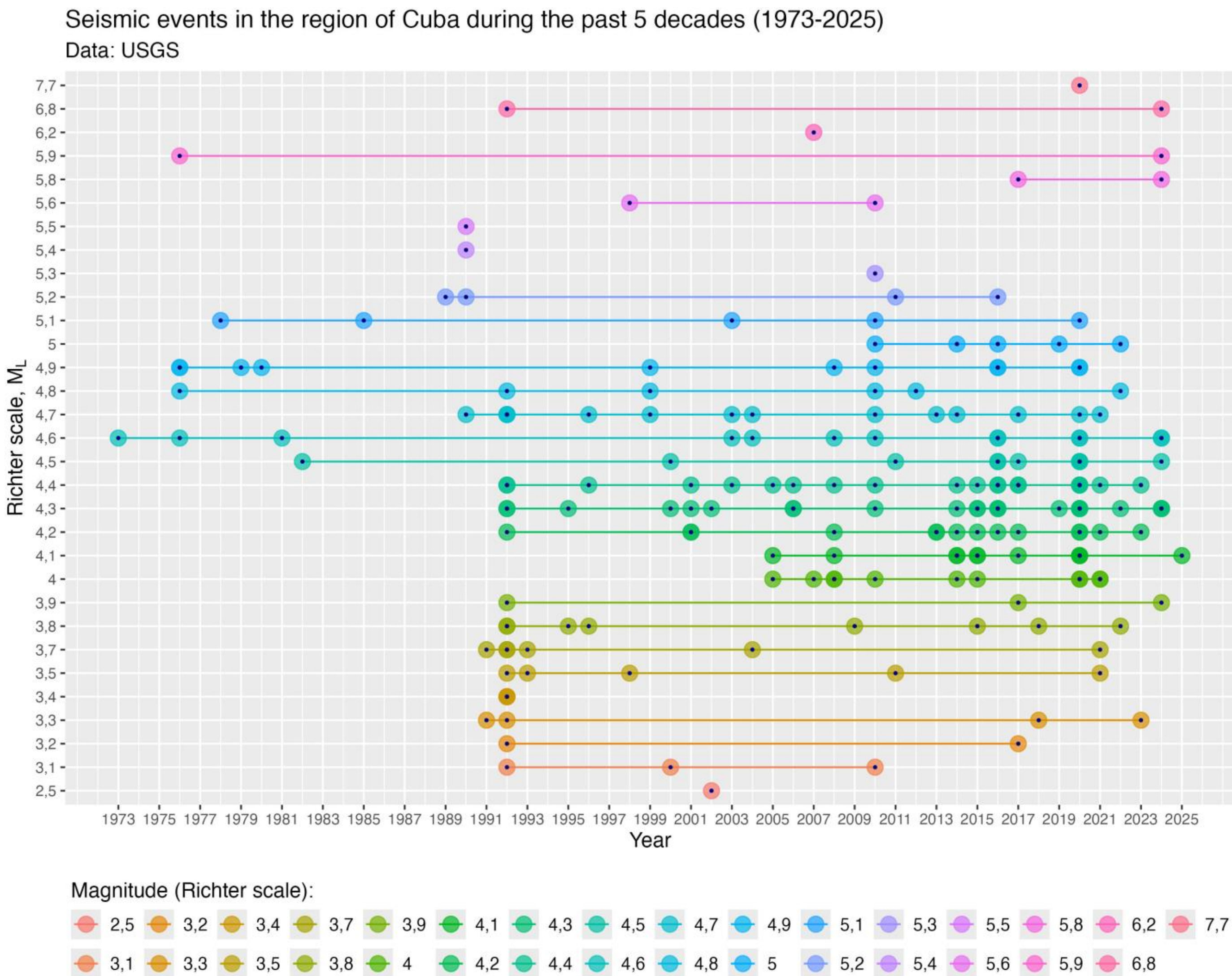


Fig. 6 – Statistics on retrospective dynamics of seismic events in Cuba region in retrospective period of 5 decades (1976-2025).

Data: NSF SAGE, USGS. Software: R. Graph source: made by the author.

The suddenly increased number of events since 1992 indicates the improved accuracy of seismological records on seismic stations and updated instruments that enabled to continue monitoring on a regular basis and with more accurate notations and details of seismic events. The main natural hazard of Cuba is seismicity, which results from the active Bartlett-Cayman fault system bordering the North American and Caribbean plates. Seismic events can potentially cause damaging earthquakes. Nevertheless, in this analysis we demonstrated that the most frequent type of earthquakes has a low magnitude (M_L 4.3 Richter scale), which is considered a light or minor earthquake that is often felt but typically causes no structural damage. Nevertheless, monitoring of seismic events should be updated continuously using open soure data and advanced scripting tools of their processing, such as GMT and R.

Conclusions

The factors that determine risks of geological hazards are fundamental for prognosis of seismically active areas. Understanding reasons of seismic activity in context of geologic history and tectonic formation plays a key role for seismic forecasting and predictive earthquake modelling. In this work, we looked into the feasibility of scripting techniques for evaluating patterns of seismic activity in Cuba. The presented data provide insights on earthquake hazard risks and trends of tsunamis through mapping and visualization of geophysical data. In this way, this paper contributes to the seismic monitoring of Caribbean region in an effort to improve the applicability of advanced scripting instruments of multi-source data analysis to geohazard mapping using spatial data, R libraries and GMT scripting toolset.

Geological hazards threaten both society and environment. The region of Cuba is one of the seismically active areas due to the lithosphere plate subduction. Societal safety require securing infrastructure and building safety in case of seismic events. Cuba is valuable for biodiversity and has high environmental value both for Caribbean region and on global scale. Such endangered and vulnerable region requires accurate and rapid operative monitoring of geophysical data, which often requires processing large volumes of data (big data) for prediction possible geological risks to estimate hazard risk. Such analysis requires advanced tools for modelling, visualization and processing seismic data in quick and accurate way. This is possible using R and GMT scripts, as we demonstrated in this paper.

We investigated novel open data repositories provided by NOAA and USGS and applied integrated methodology that includes both cartographic and statistical approach for seismic data processing. More specifically, we evaluated frequency of seismic events which can be useful for estimating risk probability in future similar studies. In this way, this paper contributed to the interdisciplinary studies on computational seismology and geological hazard monitoring using scripting software GMT and R.

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