

Methods for Determining the Most Dangerous Seismic Areas

Giulio Riga¹, Paolo Balocchi²

¹Independent Researcher, Lamezia Terme, Italy

²Independent Researcher, Modena, Italy

Email: giulio.riga@tin.it

How to cite this paper: Riga, G. and Balocchi, P. (2026) Methods for Determining the Most Dangerous Seismic Areas. *Open Journal of Earthquake Research*, 15, 39-73.
<https://doi.org/10.4236/ojer.2026.153003>

Received: May 20, 2026

Accepted: July 3, 2026

Published: July 6, 2026

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Abstract

For the purposes of this study, we analyzed regional seismicity distributed near the epicenters of numerous major earthquakes that occurred in various regions of the world. In particular, the analysis of clusters near strong earthquakes shows that, prior to major events, seismic activity follows specific spatial patterns, with a high frequency of strong earthquakes near seismic clusters and along the connecting zones between them. In addition to seismic clusters, other patterns were analyzed, such as pre-seismic quiescence in the epicentral area, and various patterns (doughnut-shaped, arc-shaped, arrow-shaped, and epicenter alignments), foreshocks, and seismic belts. The models described show that approximately 98% of the 218 strong earthquakes occur in areas of higher density where seismic belts consist of segments connecting two consecutive epicenters or alignments of three or more epicenters. This represents a statistical feature in the distribution of earthquakes; when correlated with the phenomenon of their local clustering, it allows us to guide the interpretation of epicentral distributions and to assess the significance of alignments along different directions. Therefore, the analysis of the spatio-temporal distribution of clusters and earthquakes using our retrospective models has enabled a better identification of the most hazardous areas where the occurrence of a strong event is most likely.

Keywords

Seismic Cluster, Epicenter, Mainshock, Seismic Sequence, Pattern

1. Introduction

Seismic clusters are groups of small, low-to-moderate-energy tremors occurring

within seismic cycles of varying duration, and they exhibit characteristics distinct from those of aftershock clusters that follow a major earthquake [1].

The spatial distribution of epicenters exhibits characteristics in terms of shape, density, and variable magnitude, and these clusters can continue to develop until a mainshock occurs, generally at the end of the nucleation process [2]. In some cases, they may cease their activity without the development of a strong earthquake [3]. Analysis of the distribution of spatial clusters suggests that earthquakes are not isolated events; on the contrary, an event or a cluster on a given fault can trigger another on structures even many kilometers away.

This phenomenon occurs because a strong earthquake redistributes stress across surrounding faults, promoting their subsequent rupture.

Therefore, seismic activity in some areas can influence the seismicity of other tectonically connected areas as seismic cycles of energy accumulation and release progress.

In the past, it was thought that a fault had only a short-term memory: it “remembers” only the last earthquake and has “forgotten” all the previous ones, but new studies [4] [5] show that faults have a long-term memory.

In fact, the lithospheric deformation accumulated over time is not always completely released during a strong earthquake; rather, a portion remains stored within the lithospheric block affected by the faulting process, highlighting how an earthquake’s energy is closely linked to the volume of the lithospheric block involved in the seismogenic process [6]. Accumulated and undissipated tectonic deformation can stimulate other nearby faults, triggering the initiation of strong earthquakes.

This explains how clusters of strong earthquakes can occur at different times along the same fault, where each earthquake leaves residual strain within the lithospheric block and increases the likelihood of the next earthquake occurring.

The preservation of memory over time allows faults to “remember” those clusters that did not generate any strong earthquakes in the past but contributed to their instability; this leads to a better understanding of why certain current seismic events occur near those clusters that developed in the past.

By combining these observations with a systematic, retrospective analysis of the spatiotemporal distribution of seismic events recorded in a region prior to a major earthquake that has already occurred, it has been possible to develop models that can be used to identify the most hazardous areas—where a seismic event may originate—and to characterize the seismogenic fault at the regional scale [7].

2. Data and Method

2.1. Classification of Seismicity Patterns

Most strong earthquakes are preceded by a seismic sequence that, in some cases, can be interpreted as anomalous. By analyzing this seismicity preceding strong earthquakes, it is possible to identify patterns in the distribution of epicenters,

which are elongated, sometimes even irregular in shape, and vary in density. These characteristics of earthquake distribution are linked to their magnitude [8]-[10]. By analyzing these characteristics, it is possible to obtain important information regarding the prediction of major earthquakes that could occur in the short term.

To identify and classify patterns based on the distribution of seismic activity, a retrospective analysis was conducted of 191 seismic sequences from earthquakes with a magnitude of $M \geq 7$ and 27 with a magnitude of $M = 5.8 - 7.0$ that occurred in various parts of the world, using seismic catalogs from the United States (USGS), Italy (INGV), and Japan (NIED).

The catalog data were not harmonized, as only latitude and longitude data were used for earthquake localization; these provided good results whether from local networks or global-scale networks.

The analysis of seismic activity distribution was performed using: 1) a spatial coverage of data encompassing parts of a region or several countries (ranging from a few tens of kilometers to thousands of kilometers), 2) a magnitude range between 2.0 and 10, 3) a depth range between 1 and 50 km, and a number of foreshocks between 50 and 300 prior to the mainshock. Post-mainshock aftershocks were not considered.

This study describes the patterns identified in the seismic sequences that preceded major earthquakes and that occurred in various regions of the world.

Although many earthquakes are preceded by some of these patterns, their details vary significantly depending on the type of earthquake, their relative positions, and their magnitude [11].

Foreshocks: smaller earthquakes that occur in the same area as a future major earthquake; those of greater magnitude that occur after the energy-building phase are identified as foreshocks [12].

Seismic gap: an area with little or no seismic activity, which often forms years or months before the mainshock.

Seismic clusters: these consist of groups of small-magnitude earthquakes, which may be preceded by a foreshock or energetic tremors before the mainshock.

Doughnut pattern: Seismic activity is distributed around a central zone that had become seismically quiet (seismic gap) [13].

Arc: These are formed by small- and medium-magnitude earthquakes arranged to form an arc.

Alignments: The epicenters of the earthquakes are aligned and converge toward the area that will be affected by the major earthquake.

Vectors: This type of pattern combines arc-shaped and alignment patterns, often along nearly parallel lines. This pattern alone cannot be used as a definitive indicator of a major earthquake.

Among the various seismic patterns identified (Figures 1-8), seismic alignments and clusters are the most common. Alignments were found in 100% of the 218 sequences analyzed, while the frequency of clusters was 59% of the 218, most of which were preceded by one or more higher-magnitude earthquakes.

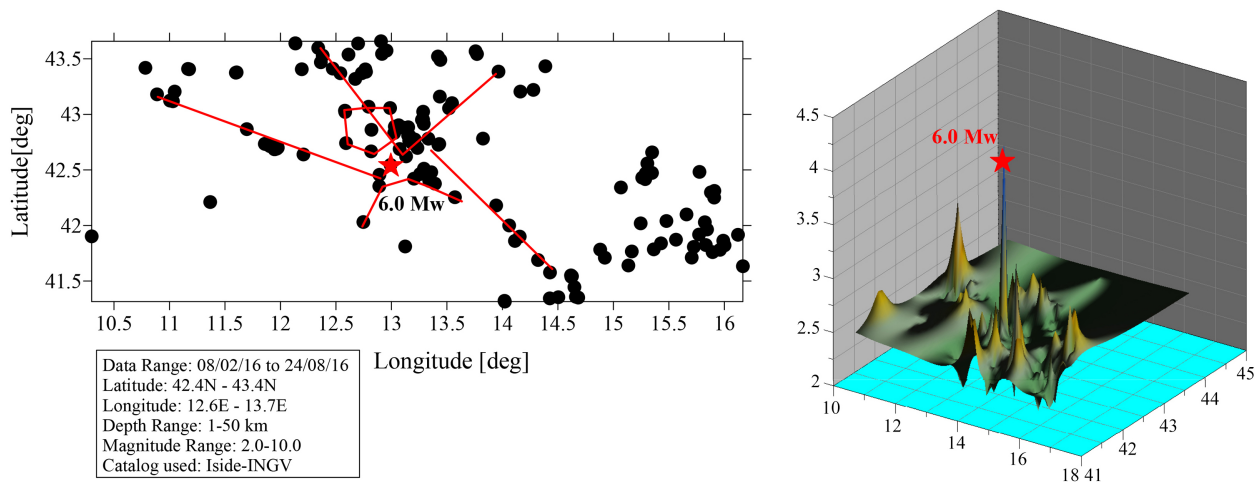


Figure 1. Map of epicenters in Central Italy. Patterns identified in the seismic sequence of the August 24, 2016, earthquake with a magnitude of 6.0 Mw. The distribution of seismic activity reveals several alignments of epicenters (red dashed lines) converging at the point affected by the strong earthquake, as well as a small arc-shaped pattern (green solid line) and a doughnut-shaped pattern (red solid line).

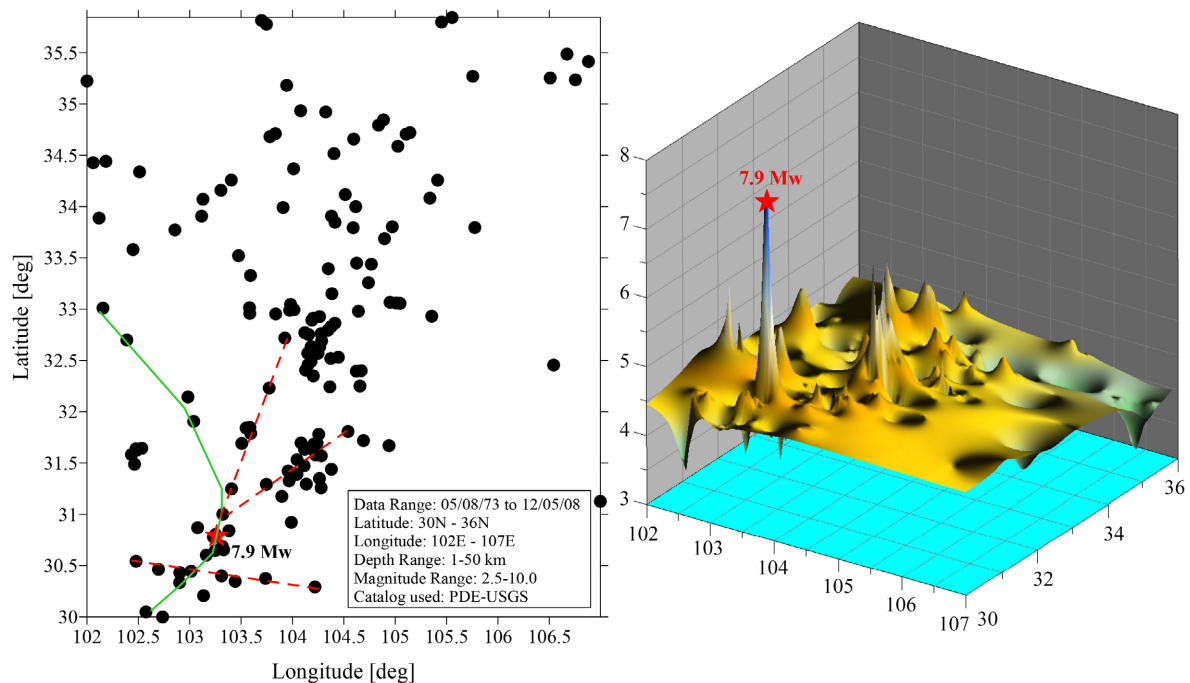


Figure 2. Map of the epicenters in the Sichuan Province, China. Patterns identified in the seismic sequence of the May 12, 2008, Sichuan earthquake, which had a magnitude of 7.9 Mw. The distribution of seismic activity reveals several alignments (red dashed lines) and a broad arc (green solid line).

2.2. Rose Model

This model was developed to identify and locate areas where stress accumulates, which are the areas at greatest risk of a major earthquake occurring.

By analyzing numerous seismic sequences, we have observed that earthquake epicenters often tend to converge toward the area most likely to be affected by a strong earthquake.

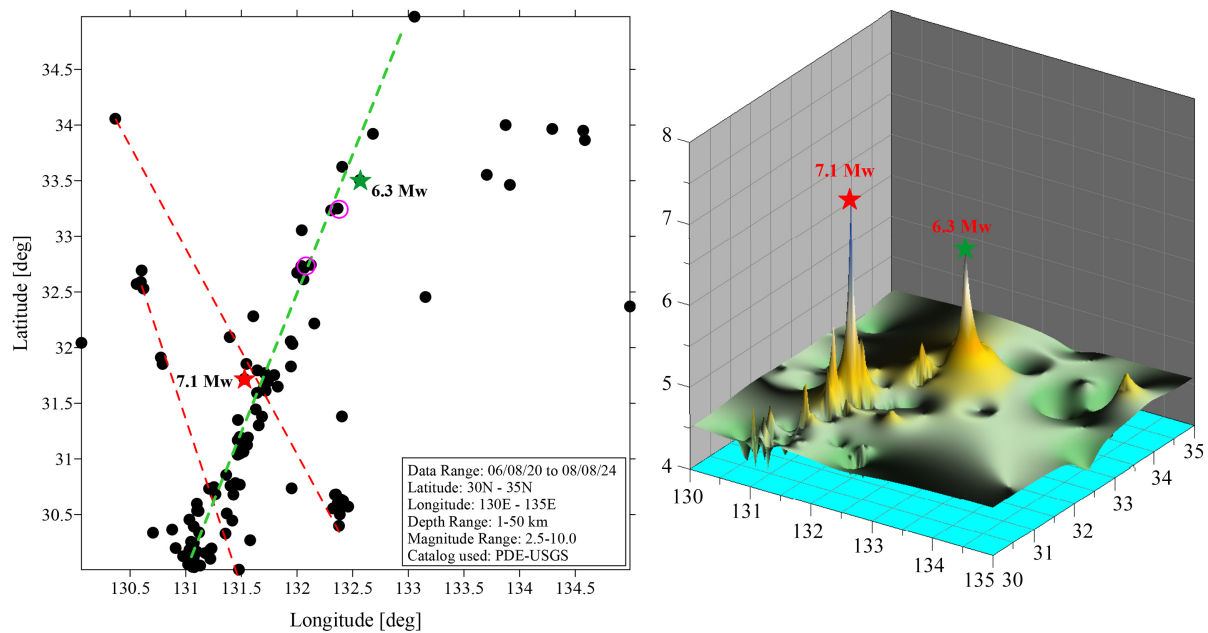


Figure 3. Map of epicenters in the Japanese region. Patterns identified in the seismic sequence of the August 8, 2024, earthquake with a magnitude of 7.1 Mw. The distribution of seismic activity reveals several extensive alignments (red dashed lines), a foreshock of magnitude 6.3 Mw that occurred on 04/17/2004, and clusters associated with high-energy earthquakes (>6.0 Mw) (pink circles) located along the major alignment (green line). The green star indicates the foreshock.

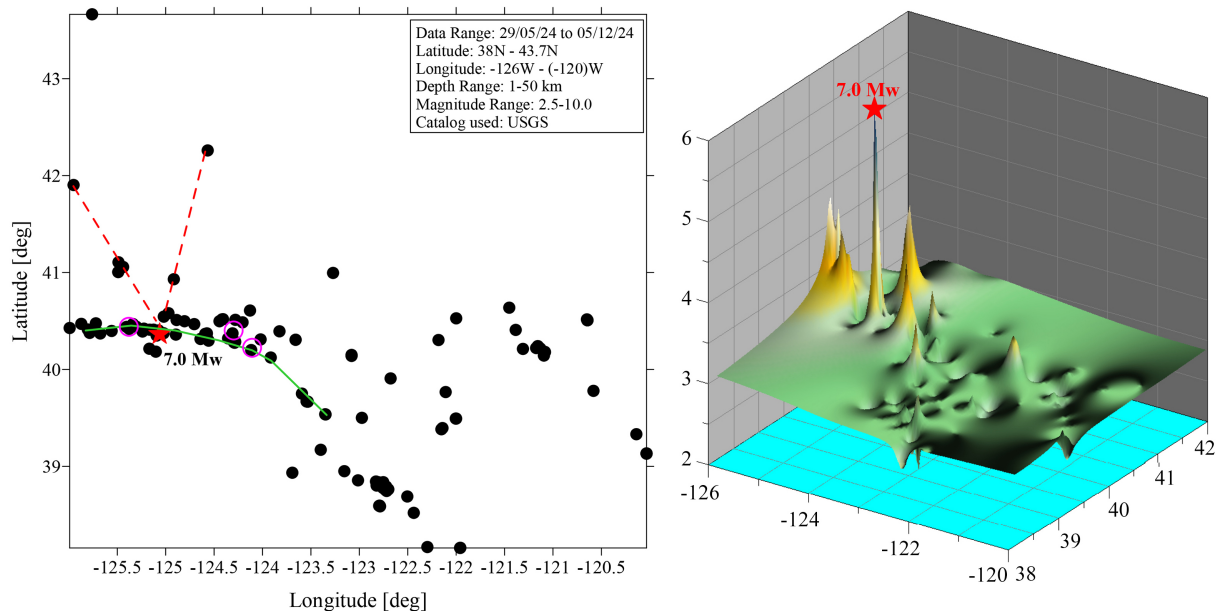


Figure 4. Map of epicenters in the California region. Patterns identified in the seismic sequence of the 7.0 Mw earthquake on December 5, 2024. The distribution of seismicity reveals a broad arc (solid green line), several alignments (dashed red lines), and clusters with associated high-energy earthquakes (>4.5 Mw) located along the major alignment (pink circles).

As can be seen in the seismic sequence of the Mw 6.4 earthquake that occurred in Greece in 2008 (**Figure 9**), the alignments between multiple epicenters form a planimetric pattern that converges toward the area where the mainshock occurred.

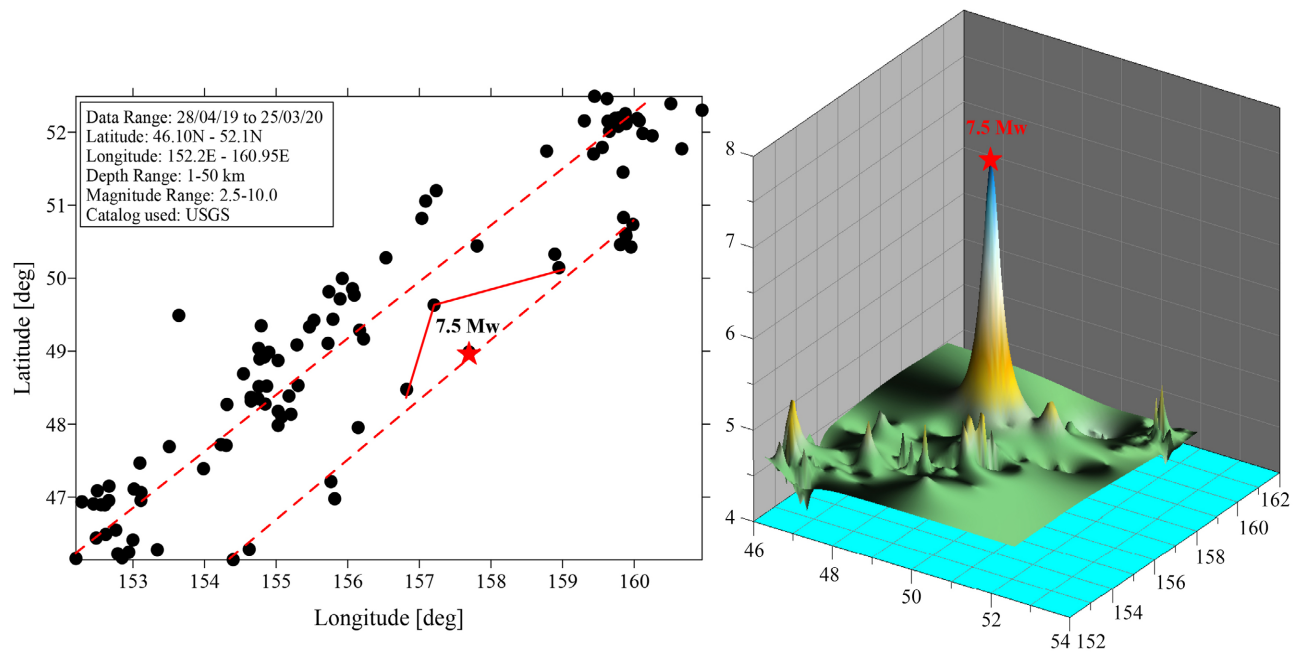


Figure 5. Map of epicenters in the Russian region (Kuril Islands). Patterns identified in the seismic sequence of the March 25, 2020, earthquake with a magnitude of 7.5 Mw. The distribution of seismic activity reveals a gap (solid red lines) and two long alignments (dashed red lines).

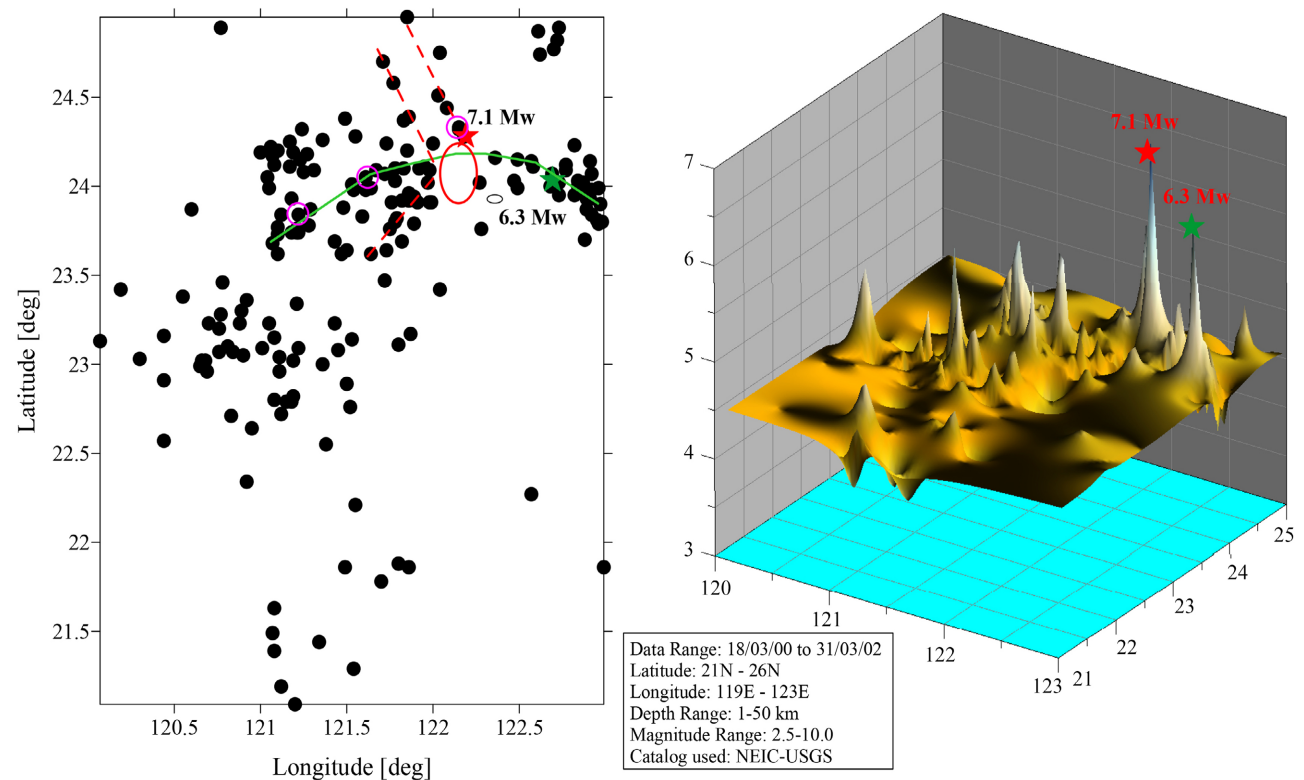


Figure 6. Map of epicenters in the Taiwan region (China). Patterns identified in the seismic sequence of the March 31, 2002, earthquake with a magnitude of 7.1 Mw. The distribution of seismicity reveals a gap (red ellipse), a broad arc (solid green line), several alignments (dashed red lines), and clusters with associated high-energy earthquakes (>5.8 Mw) located along the arc (pink circles). The green star indicates the foreshock of magnitude 6.3 Mw.

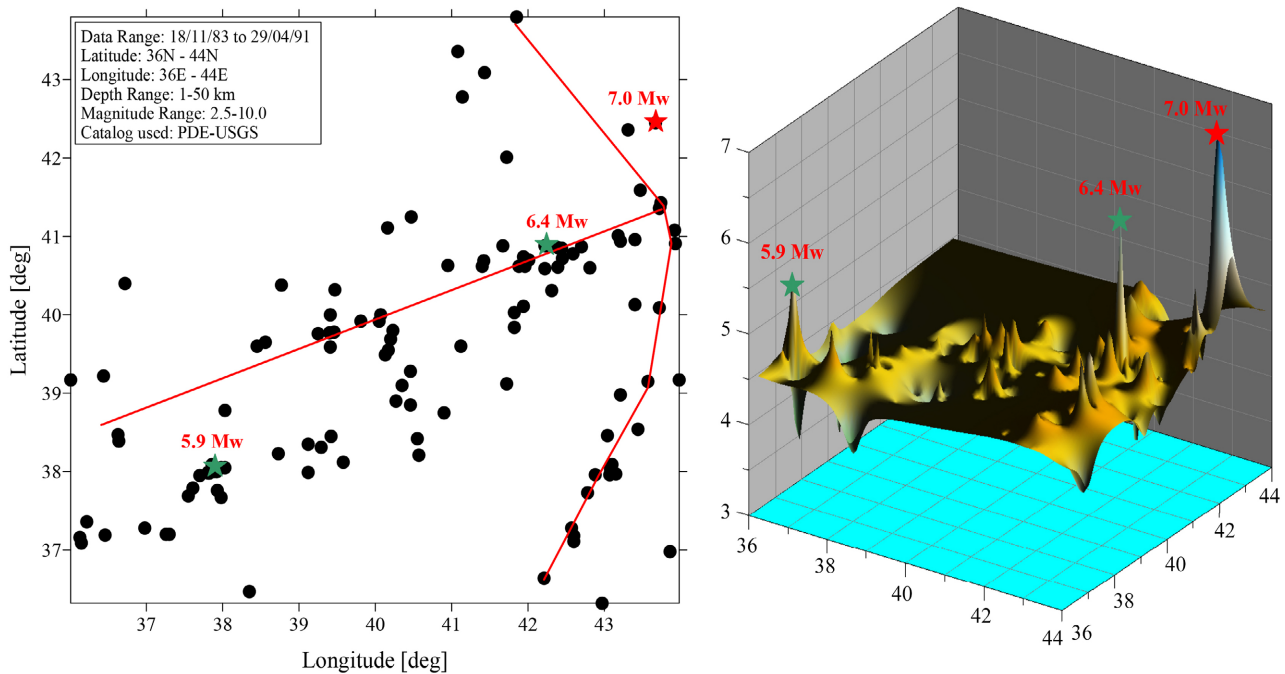


Figure 7. Map of epicenters in the Turkish region. Patterns identified in the seismic sequence of the April 29, 1991, earthquake with a magnitude of 7.0 Mw. The distribution of seismic activity reveals a broad vector represented by an alignment and an arc (red lines). The green star indicates the foreshocks of magnitudes 5.9 Mw and 6.4 Mw.

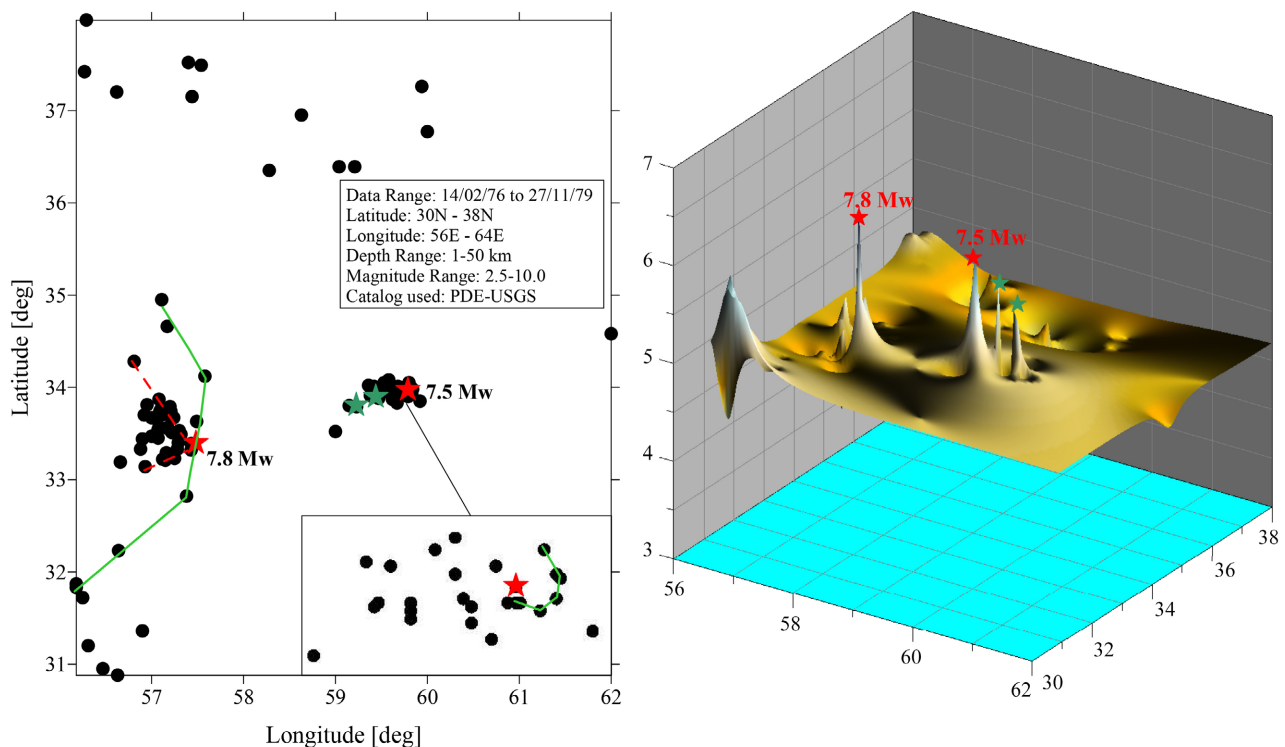


Figure 8. Map of epicenters in the Iranian region. Patterns identified in the seismic sequence of the November 27, 1979, earthquake with a magnitude of 7.5 Mw. The distribution of seismic activity reveals a broad arc (green line) and alignments (red dashed lines). Another arc is present within the cluster where the 7.5 Mw earthquake occurred, which was preceded by two foreshocks of increasing magnitude (green stars).

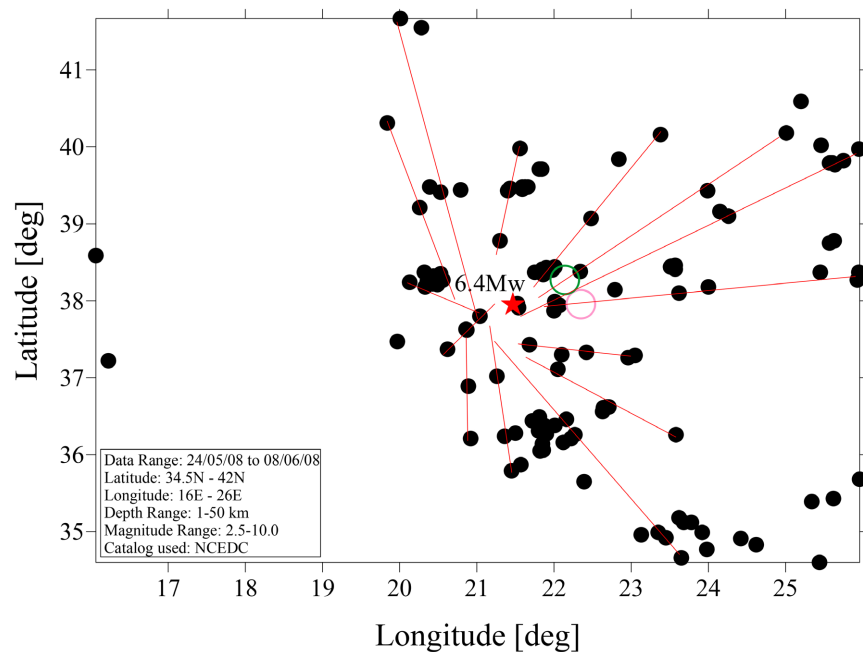


Figure 9. Map of epicenters in the Greek region. Procedure applied to the seismic sequence of the June 8, 2008, earthquake in Greece with a magnitude of 6.4 Mw. The red lines indicate the alignments of epicenters converging toward the mainshock. The pink and green circles indicate the dynamic epicenters calculated using the DEM₁₁ and DEM₂₂ procedures; the red star indicates the location of the mainshock.

In particular, the arrangement of the epicenters shows a central zone, where most of the earthquakes are concentrated, and an outer zone where seismic activity is more widely distributed. The epicenters align to form a radial structure along preferred directions, extending from the central zone toward the outer zone.

The subsequent comparison between the results provided by this model, known as “rose,” and the polynomial function [14] made it possible to identify with greater precision the areas where a major earthquake could occur.

To visualize the areas where the alignments converge, providing an easy-to-read display, we used an algorithm based on the rose diagram, which comprises 16 (Figure 10) or 48 radial sectors with an amplitude of 22.5° or 7.5°, respectively.

The direction and trend of the analyzed epicenters are represented by vectors that provide information on the area where the mainshock may be most likely to occur.

This simple calculation procedure is performed for each epicenter in the analyzed series and includes the following steps:

Step 1. Sort the longitude values $X(1, 2, \dots, Ne)$ and latitude values $Y(1, 2, \dots, Ne)$ in ascending order of longitude (Ne = total number of epicenters in the series to be analyzed).

Step 2. Select the initial value ($d1$) and final value ($d2$) for the first calculation cycle, as well as the increment (i).

Step 3. Start the first calculation cycle (j) from ($d1 = 1$) up to ($Ne - 1$) with an increment ($i = 1$) (the cycle proceeds in ascending order by default).

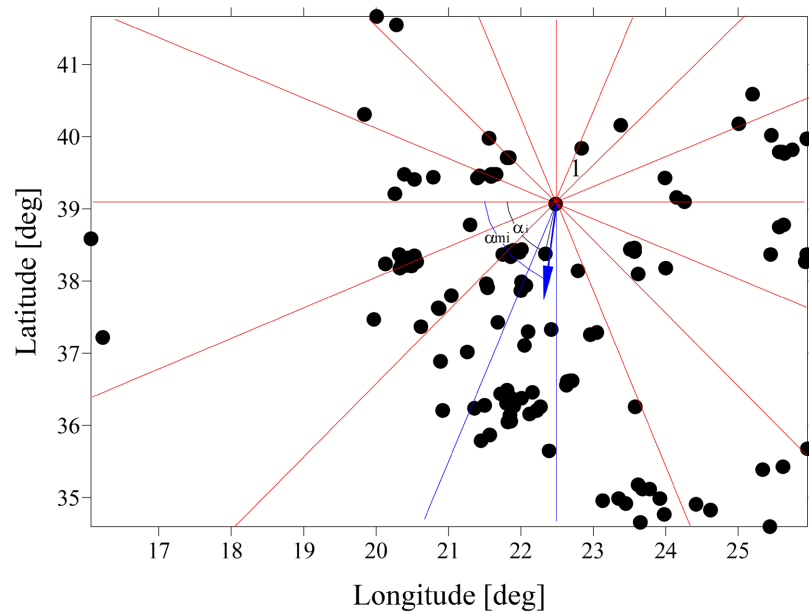


Figure 10. Map of epicenters in the Greek region. Procedure applied to the seismic sequence of the earthquake in Greece on June 8, 2008. The red lines indicate sectors with a width of 22.5° drawn from the first epicenter in the analyzed series. The blue vector indicates the direction and orientation of the most frequent sector; the blue lines indicate the most frequent sector.

Step 4. Start the second calculation cycle (k) from $j + 1$ up to $Ne - 1$.

Step 5. From the first epicenter in the series, draw 16/48 sectors with an amplitude of $22.5^\circ/7.5^\circ$.

Step 6. Identify the sector containing the largest number of epicenters.

Step 7. Calculate the angles α_i of the lines drawn between the first epicenter and all others included in the most frequent sector.

Step 8. Calculate the average angle α_{mi} .

Step 9. Draw the line representing the alignment, which originates at the analyzed epicenter, has an inclination equal to the average angle α_{mi} , and is oriented toward the most frequent sector.

Repeat the same calculation process for all epicenters in the series.

Figure 11, constructed with an X-axis (Longitude) of 12 cm or 1200 pixels and a Y-axis (Latitude) of 6.5 cm or 6500 pixels (these values were used to create the figures for the subsequent models), shows the result obtained at the end of the calculation process using 48 sectors, based on the rose model. It can be observed that many vectors converge toward the area where the mainshock occurred, which is where the greatest accumulation of stress is found.

The figure indicates the most hazardous areas (red boxes) selected through an analysis of the arrangement of the vectors. The identified areas correspond to those where the vectors converge or are closest to each other and in the sectors with the highest frequency of alignments. By analyzing the sequence with additional algorithms, it can be verified that the mainshock falls at an inflection point of the polynomial curve and near the dynamic epicenters DEM_{11} and DEM_{22} [15].

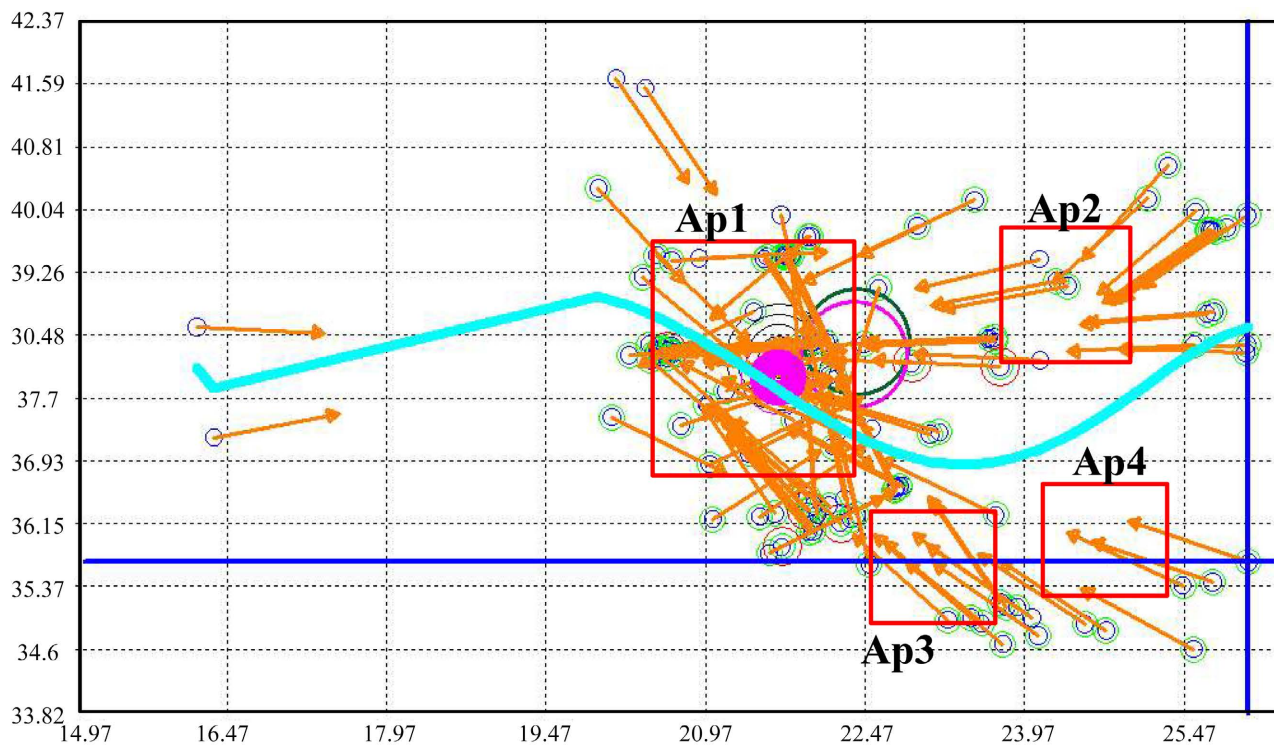


Figure 11. Map of epicenters in the Greek region. Procedure applied to the seismic sequence of the June 8, 2008, earthquake in Greece with a magnitude of 6.4 Mw. The orange vectors, calculated using the Rose model, indicate the direction and orientation of the sectors of greatest hazard, within which lies the solid magenta circle indicating the mainshock. The large purple and green circles indicate the dynamic epicenters DEM₁₁ and DEM₂₂. The blue lines drawn from the last epicenter in the analyzed series divide the area into four quadrants. The light blue line indicates the trace of the polynomial function. The red boxes indicate the areas where hazard is highest. X-axis (longitude), Y-axis (latitude), units (deg).

Analyses performed on many seismic sequences have shown that 97% of 204 analyzed earthquakes indicate an epicenter of the future earthquake near the concavities or inflection points of the calculated polynomial curve [14].

By analyzing the trends of the last 10 or 21 earthquakes and using latitude and longitude values, it is possible to determine, in probabilistic terms, the location of the major earthquake [15]. Back-testing shows that the model is capable of locating 55% of the 153 seismic patterns analyzed in critical areas that may be affected by the epicenter of a strong earthquake.

Figure 12 shows the result obtained at the end of the calculation process using 48 sectors applied to the Sichuan earthquake of May 12, 2008, with a magnitude of 7.9 Mw. It can be observed, even in this earthquake, how many vectors converge toward the zone of greatest hazard where the mainshock occurs. By analyzing the seismic sequence with a polynomial function, it is possible to verify that the mainshock falls just below a concavity in the curve.

Figure 13 shows the epicenters of the strongest earthquakes that occurred in the analyzed area and the line of divergence of the vectors (red line).

One can observe a frontal area (area a) where all the vectors converge and an area (area b) where the vectors fan out in one or two preferred directions.

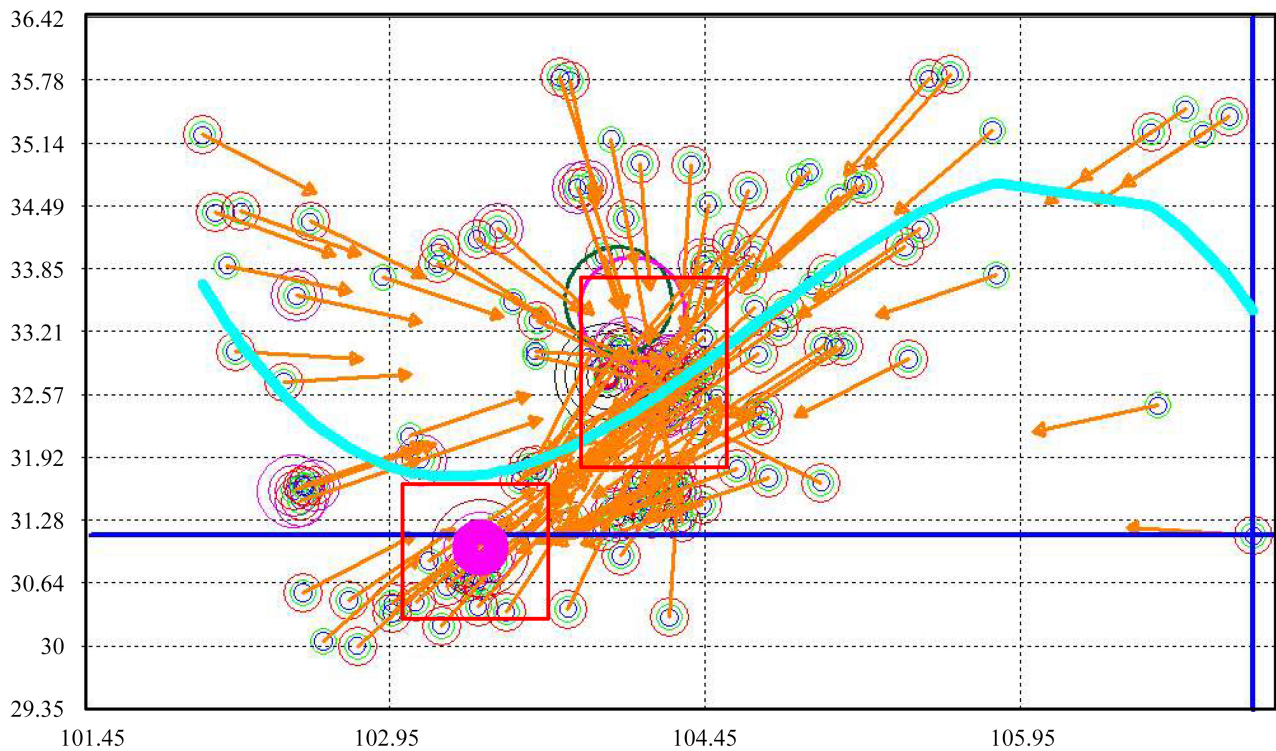


Figure 12. Map of epicenters in the Sichuan Province, China. The distribution of seismic activity preceding the Sichuan earthquake of May 12, 2008, with a magnitude of 7.9 Mw. Areas of highest hazard identified by the rose model are indicated by red boxes, where the orange vectors calculated by the model converge. The light blue line indicates the trace of the polynomial function. X-axis (longitude), Y-axis (latitude), units (deg).

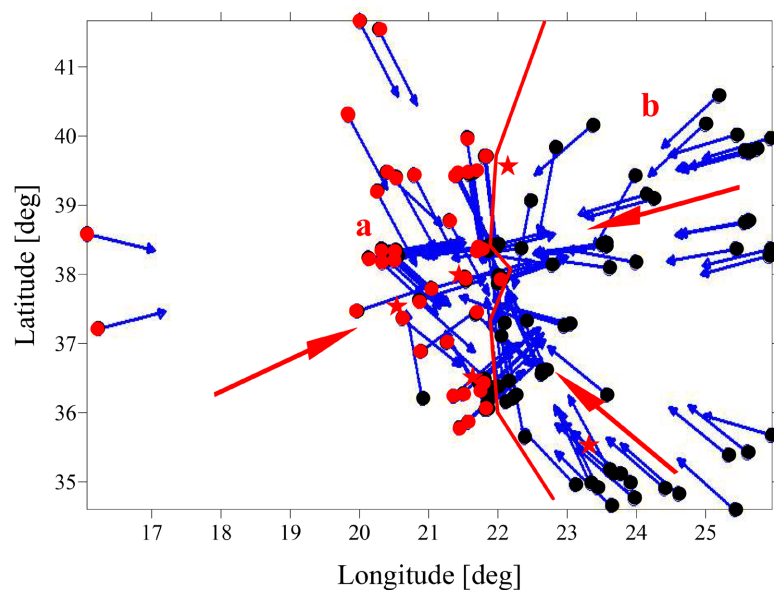


Figure 13. Map of epicenters in the Greek region. Procedure applied to the seismic sequence of the earthquake in Greece on June 8, 2008. The blue vectors indicate the direction and orientation of the most frequent sectors calculated from each epicenter in the analyzed series; the red stars indicate the locations of the strongest earthquakes that occurred in the analyzed area. The red vectors indicate the preferred direction and azimuth; the red line indicates the zone of divergence of the vectors.

Usually, most of the epicenters of strong earthquakes are located in the central part of the frontal area and, less frequently, along the most common sectors of area b.

Figure 14, which pertains to the seismic sequences preceding the earthquakes in Greece on January 29, 2008, and June 8, 2008, indicates the most hazardous areas (red boxes) selected through an analysis of the vectors' arrangement in the plan view. The identified areas correspond to those where the vectors converge or are closest together and within the most frequent sectors. It can be observed that the area affected by the June 8, 2008, earthquake had already been identified by the Rose model applied to the January 29, 2008, earthquake.

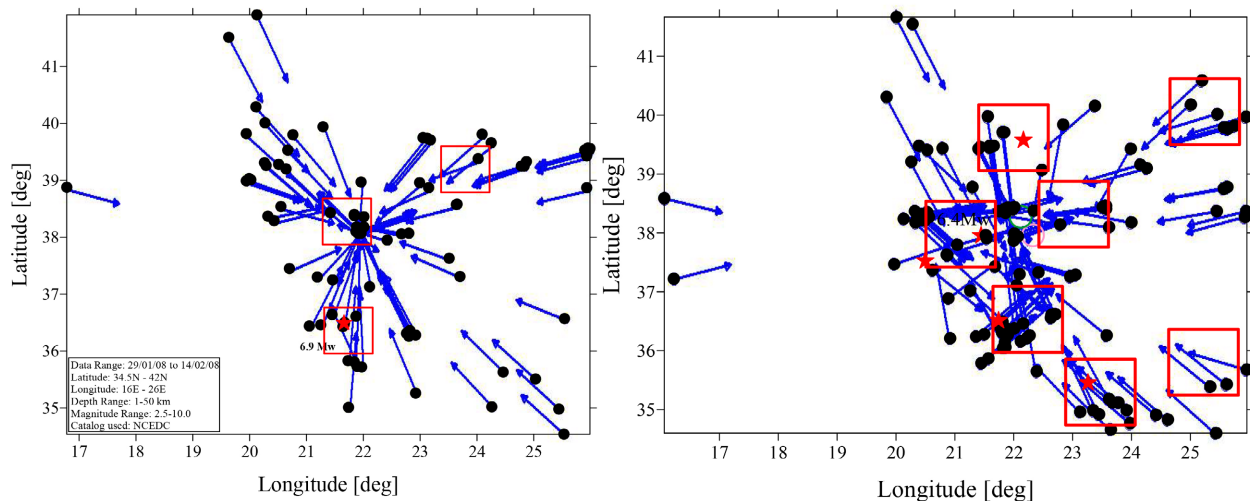


Figure 14. Map of epicenters in the Greek region. Methodology applied to the seismic sequences of the earthquakes in Greece on January 29, 2008, and June 8, 2008. The red boxes indicate the most hazardous areas.

Figure 15 shows the epicenters of the earthquakes in the seismic sequences that preceded the earthquakes in Greece on June 8, 2008 (**Figure 15(a)**), in California on June 28, 1992 (**Figure 15(b)**), in Nicaragua on February 4, 1976 (**Figure 15(c)**), and in Peru on June 23, 2001 (**Figure 15(d)**), the results obtained by applying the Rose model, and the locations of the faults.

2.3. Band Model

This model is used to assess areas that may be affected by a strong earthquake in the future. The analysis is performed by plotting all the segments that progressively connect the epicenters recorded in the analyzed area over a short time period.

Figure 16 shows how the seismic structure of the epicenter distribution, as represented by the segments connecting individual events, is oriented primarily in the SW-NE direction, with a higher frequency of segments in the NW sector.

The geometry of the seismic structure is also clearly visible in the map shown in **Figure 17(a)**, in which only segments with an angle of inclination relative to the horizontal plane less than or equal to 45° are displayed.

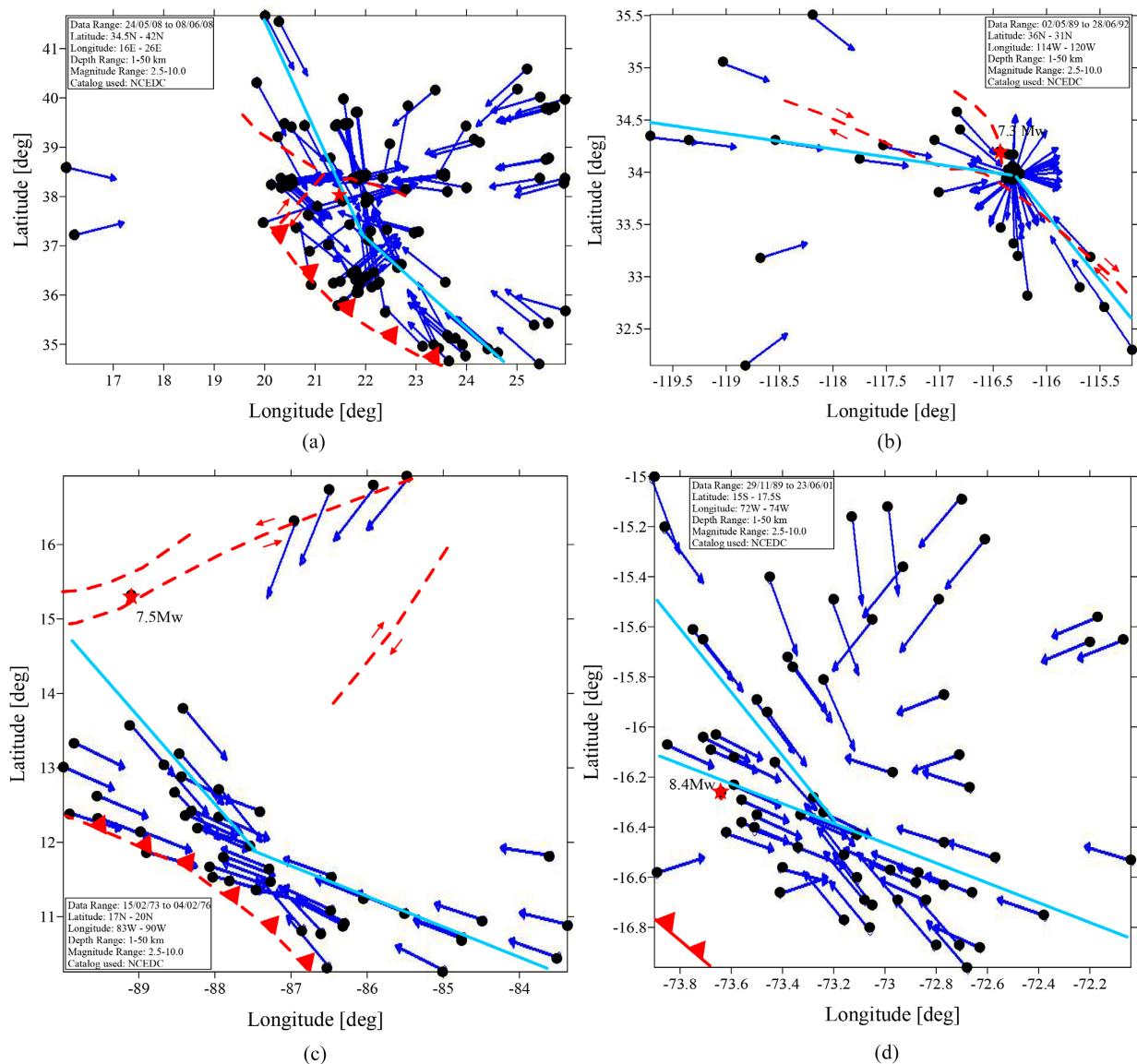


Figure 15. Map of the epicenters of the earthquakes in the seismic sequences preceding the earthquakes in Greece on June 8, 2008 (a), in California on June 28, 1992 (b), in Nicaragua on February 4, 1976 (c), and in Peru on June 23, 2001 (d). The red dashed lines indicate the faults, the triangles indicate the dip direction of the faults, and the light blue lines indicate the direction of the vector alignment. The red star indicates the epicenter of the main.

Figure 17(b) shows only the segments with an inclination angle greater than 45° and two critical areas (A1 and A2), where the segments are closer together or converge.

Figure 17(c) shows segments with angles of inclination both less than or equal to 45° and greater than 45° , while **Figure 17(d)** displays only segments with an angle of inclination greater than or equal to 70° .

Statistically, in 98% of the 218 of the analyzed seismic sequences (N ranging from 50 to 250), the epicenter of the mainshock is located within the densest section of the band formed by multiple segments.

The model's results are easily interpretable, and the model's success rate is high.

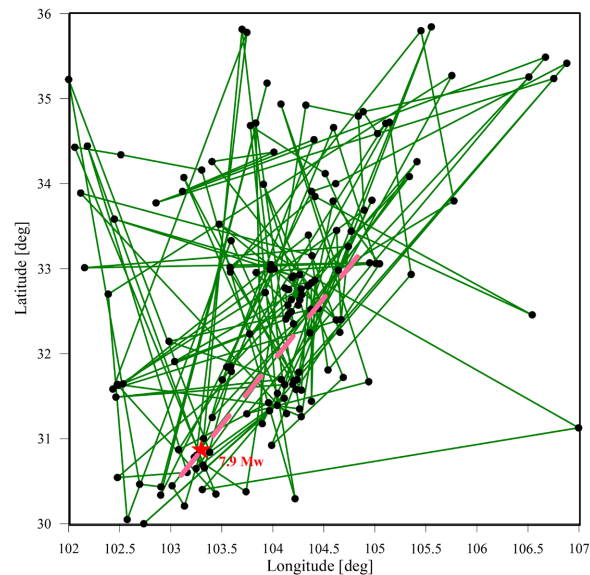


Figure 16. Map of epicenters in the Sichuan region of China. The distribution of seismic activity preceding the Sichuan earthquake of May 12, 2008, with a magnitude of 7.9 Mw, reveals a band of segments oriented approximately SW-NE (magenta dashed line). The red star indicates the location of the epicenter.

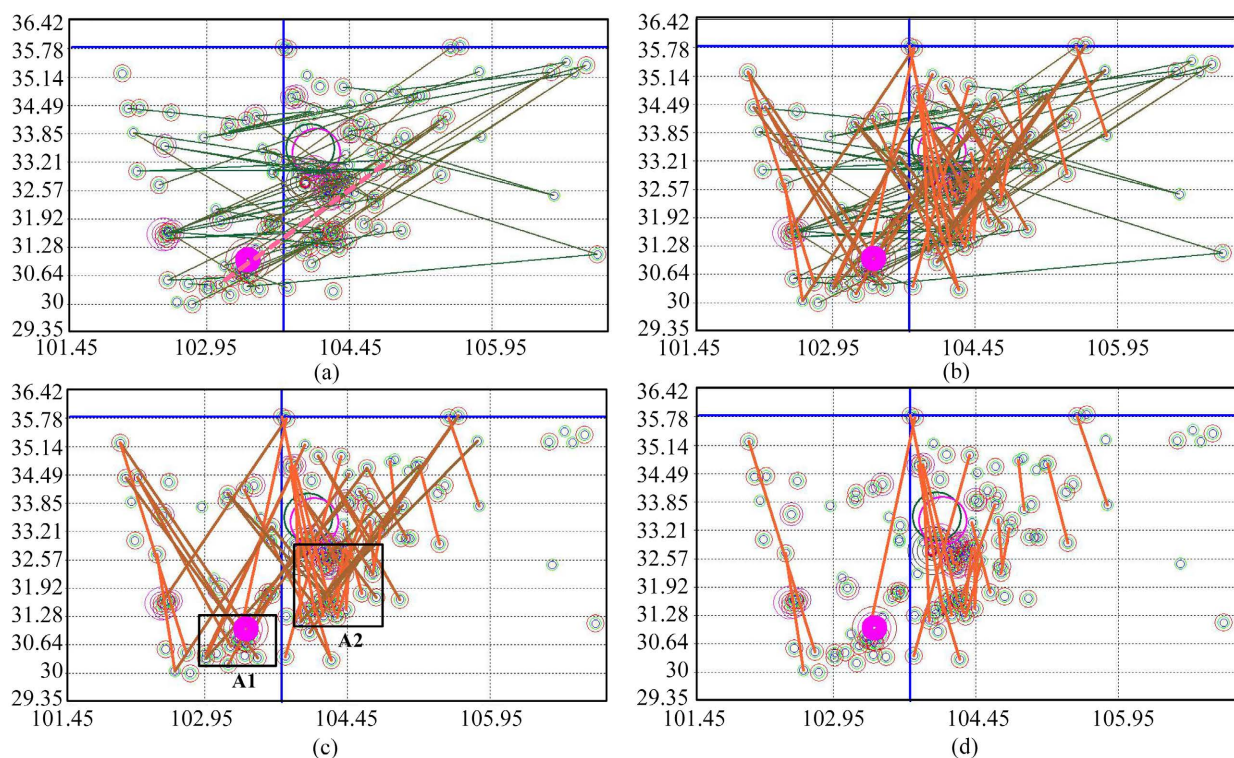


Figure 17. Map of epicenters in the Sichuan Province, China. The distribution of seismic activity preceding the May 12, 2008, Sichuan earthquake with a magnitude of 7.9 Mw. The solid purple circle indicates the location of the mainshock. The black boxes show the critical areas. The large purple and green circles indicate the dynamic epicenters DEM₁₁ and DEM₂₂. The thicker red lines indicate segments with an inclination angle greater than 45°, while the green lines indicate segments with an inclination angle equal to or less than 45°. The deep pink dashed line shows the location of the source region. The blue lines drawn from the last epicenter in the analyzed series divide the area into four quadrants.

2.4. Alignment Model

The algorithm for this model, consisting of three consecutive calculation cycles, uses the alignment patterns between epicenters and their mutual distances to generate diagrams that provide information on the location of the most hazardous areas, where a strong earthquake is most likely to occur.

The calculation procedure is as follows:

Step 1. Sort the longitude values $X(1, 2, \dots, Ne)$ and latitude values $Y(1, 2, \dots, Ne)$ in ascending order of longitude;

Step 2. Select the minimum tolerance value (T) for the alignment calculation between the three epicenters and the distance between the epicenters (d) (default $T = 0.1$; $d = 1000$ pixels) but these can be adjusted manually. In particular, adjusting the d s parameter makes it easier to identify the most hazardous areas; where

T = is the tolerance;

d = is the minimum distance between the coordinates of two epicenters.

Points on the Cartesian plane are aligned by checking whether three points lie on the same line.

The most common method is to verify that the slope between different pairs of points is equal.

Given three epicenters $E_1(x_1, y_1)$, $E_2(x_2, y_2)$, and $E_3(x_3, y_3)$, they are aligned if the slope between E_1 and E_2 is equal to the slope between E_2 and E_3 :

$$\frac{y_2 - y_1}{x_2 - x_1} = \frac{y_3 - y_2}{x_3 - x_2} \quad (1)$$

To avoid division-by-zero errors (vertical lines), the following formula is used:

$$(y_2 - y_1)(x_3 - x_2) = (y_3 - y_2)(x_2 - x_1) \quad (2)$$

Step 3. Start the first calculation cycle (k) from 1 up to $Ne - 2$ with an increment ($i = 1$) (by default, the cycle proceeds in descending order).

Step 4. Start the second calculation cycle (tk) from $k + 1$ up to $Ne - 1$ (**Figure 18**).

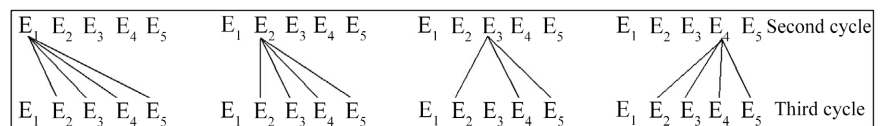


Figure 18. Diagram of the second and third calculation cycles between the epicenters.

where

Ne = total number of epicenters.

Step 5. Activate the third calculation cycle (j) from $tk + 1$ to Ne .

Step 6. Select the epicenters $[Ex(k), Ey(k)]$; $[Ex(j), Ey(j)]$ according to the scheme shown in **Figure 18**.

Step 7. Calculate the distance between the epicenters $E_1(x_1, y_1)$, $E_2(x_2, y_2)$ e $E_3(x_3, y_3)$.

$$D_{1,2} = \left[\text{Abs}(x_2 - x_1)^2 + \text{Abs}(y_2 - y_1)^2 \right]^{0.5} \quad (3)$$

$$D_{2,3} = \left[\text{Abs}(x_3 - x_2)^2 + \text{Abs}(y_3 - y_2)^2 \right]^{0.5} \quad (4)$$

Step 8. Draw the purple line through the epicenters $E_1(x_1, y_1) \in E_3(x_3, y_3)$ if:

$$\text{Abs}[(y_2 - y_1)(x_3 - x_2) - (y_3 - y_2)(x_2 - x_1)] < T \quad \text{e} \quad D_{1,2} \quad \text{e} \quad D_{2,3} > d \quad (5)$$

Step 9. Repeat the calculation procedure until all scheduled cycles have been completed.

Additional diagrams can be generated using the following formula instead of Formula (5).

$$\text{Abs}[(y_2 - y_1)(x_3 - x_2) - (y_3 - y_2)(x_2 - x_1)] < Tl \quad \text{e} \quad D_{1,2} \quad \text{e} \quad D_{2,3} < d \quad (6)$$

Figure 19 shows the various patterns obtained by analyzing the seismic activity preceding the earthquake in Japan on August 8, 2024, while varying the model parameters. It can be seen that most of the seismic structure is oriented in a SW-NE direction, with a higher frequency in the NW block (higher frequency of alignments).

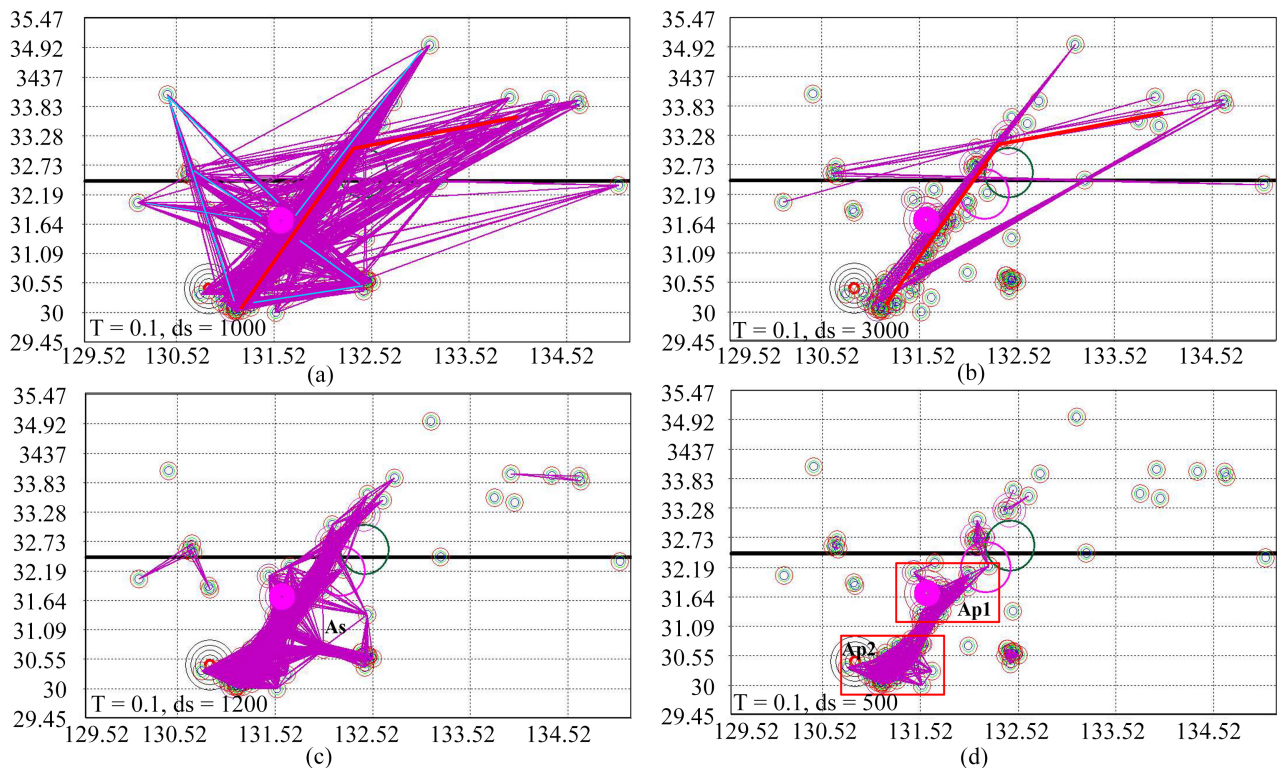


Figure 19. Map of epicenters in the Japanese region showing the seismic activity that preceded the 7.1 Mw magnitude earthquake on August 8, 2024. The solid purple circle indicates the location of the earthquake's epicenter. The red line indicates the seismic structure. The black horizontal line indicates the presence of a cluster of earthquakes with similar latitudes at the end of the seismic sequence. The magenta lines indicate alignments between three epicenters. The red boxes show the most dangerous areas. The large purple and green circles indicate the dynamic epicenters DEM₁₁ and DEM₂₂. The light blue lines indicate the zones where the alignments are most concentrated. The aseismic area is indicated by As.

Figure 19(a) and **Figure 19(b)**, obtained using Formula (5), highlight the structure responsible for the mainshock, which is oriented approximately SW-NE, while **Figure 19(c)** and **Figure 19(d)**, obtained using Formula (6), show an aseismic zone (As) near the earthquake's epicenter, along the perimeter of which the mainshock epicenter is located, as well as two hazardous areas (the identified areas correspond to those where the alignments converge or intersect). This characteristic, where the main event is located near an aseismic zone, has been observed in many past earthquake sequences.

Further information on the location of the hazardous areas or the mainshock can be obtained by plotting the mean lines of each alignment bundle (light blue lines). The convergence of the mean lines indicates a possible location of the mainshock's epicenter or the hazardous area.

Figure 20(a), concerning the magnitude 6.5 earthquake in central Italy on October 30, 2016, obtained using Formula (5), shows that most segments are oriented in a NW-SE direction, indicating the preferred orientation of the seismogenic fault, and a higher frequency of earthquakes in the SW block, indicating its presumed dip direction.

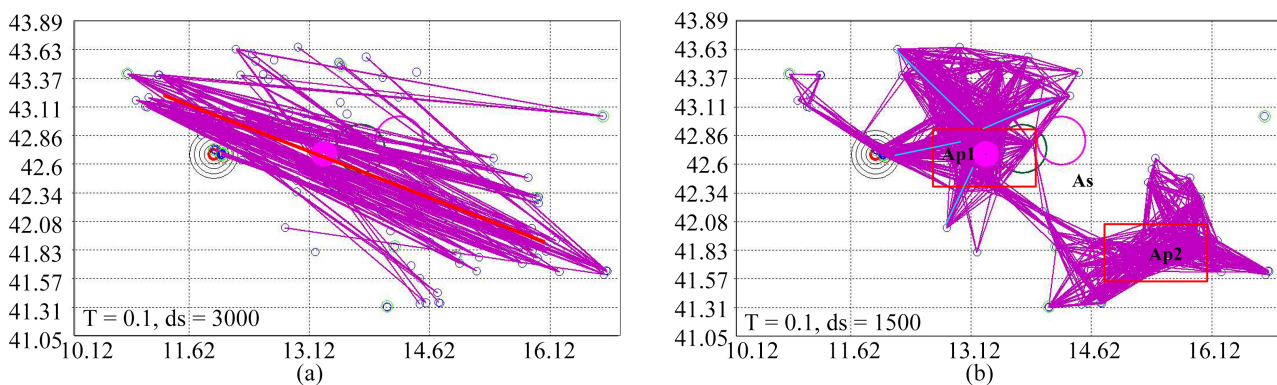


Figure 20. Map of epicenters in the Italian region. The distribution of seismic activity preceding the 6.5 Mw earthquake on October 30, 2016. The solid purple circle indicates the location of the earthquake's epicenter. The red line indicates the seismic structure. The magenta lines indicate the alignments between the epicenters. The red boxes show the most dangerous areas. The large purple and green circles indicate the dynamic epicenters DEM₁₁ and DEM₂₂. The light blue lines indicate the zones where the alignments are most concentrated. The aseismic area is indicated by As.

Figure 20(b), obtained using Formula (6), shows an aseismic area As, where the epicenter of the main earthquake is located along its perimeter, along with two hazard zones.

2.5. Sector Model

Epicenters often exhibit a distribution in bands of varying lengths and widths, which frequently coincide with seismogenic structures [16]. Typically, examining the distribution of earthquakes at increasingly smaller scales reveals these bands, which are most likely associated with seismogenic faults.

This model analyzes the distance between pairs of epicenters and generates di-

agrams that provide information on the sectors within a given area that are most likely to be affected by a strong earthquake, on the location of clusters, and on the seismogenic structures that may generate the strong earthquake.

The calculation procedure is as follows:

Step 1. Sort the longitude values $X(1, 2, \dots, N)$ and latitude values $Y(1, 2, \dots, N)$ in ascending order of longitude.

Step 2. Select the initial value ($d1$), the final value ($d2$), and the increment (i) for the first cycle, (default values: $d1 = 6$ degrees, $d2 = 0.30$ degrees, $i = -0.30$ degrees);

where

$d1$ = is the maximum distance between the coordinates of two epicenters;

$d2$ = is the minimum distance between the coordinates of two epicenters;

i = is the calculation increment between ($d1$) and ($d2$).

Step 4. Activate the first calculation cycle (kk) from ($d1$) to ($d2$) with an increment ($-i$) (the cycle proceeds in descending order by default).

Step 3. Activate the second calculation cycle (k) from 1 to Ne

where Ne = total number of epicenters;

Step 4. Activate the third calculation cycle (j) from 2 to Ne .

Step 5. Select the epicenters $[Ex(k), Ey(k)]$; $[Ex(j), Ey(j)]$ according to the diagram shown in **Figure 18**.

Step 6. Perform the calculation if:

$$\left[X(k) - X(j) \right] \leq kk \quad \text{or} \quad \left[Y(k) - Y(j) \right] \leq kk \quad (7)$$

Step 7. Calculate

$Sx = X(j) + Sx$ (sum of the longitudes of the epicenters of the third cycle);

$Sy = Y(j) + Sy$ (sum of the latitudes of the epicenters of the third cycle);

$Ns = Ns + 1$ (sum of the epicenters selected in the third cycle).

Step 8. At the end of the third cycle, calculate the average values of longitude and latitude

$$X(Sx) = (Sx)/Ns \quad (8)$$

$$Y(Sy) = (Sy)/Ns \quad (9)$$

Step 9. Draw the blue line using the coordinates $[Ex(k), Ey(k)]$; $[X(Sx), Y(Sy)]$.

Step 10. Draw the light blue circle using the coordinates $X(Sx), Y(Sy)$.

Step 11. Repeat the calculation procedure until all planned cycles are completed.

Figure 21 shows the graphical results based on data processed by the computational model, applied to the distribution of earthquakes that preceded the March 31, 2002, earthquake in Taiwan region (China) with a magnitude of 7.1 Mw. **Figure 21(a)** shows a rose diagram of the average latitude and longitude values of the epicenter pairs, in which a main direction with a SW-NE orientation can be clearly observed, linked to the seismogenic fault with probable SE dip. The graph was generated using an initial distance (start of calculation cycle) of 6° , a final distance of 5° (end of calculation cycle), and a calculation interval of 1 degree.

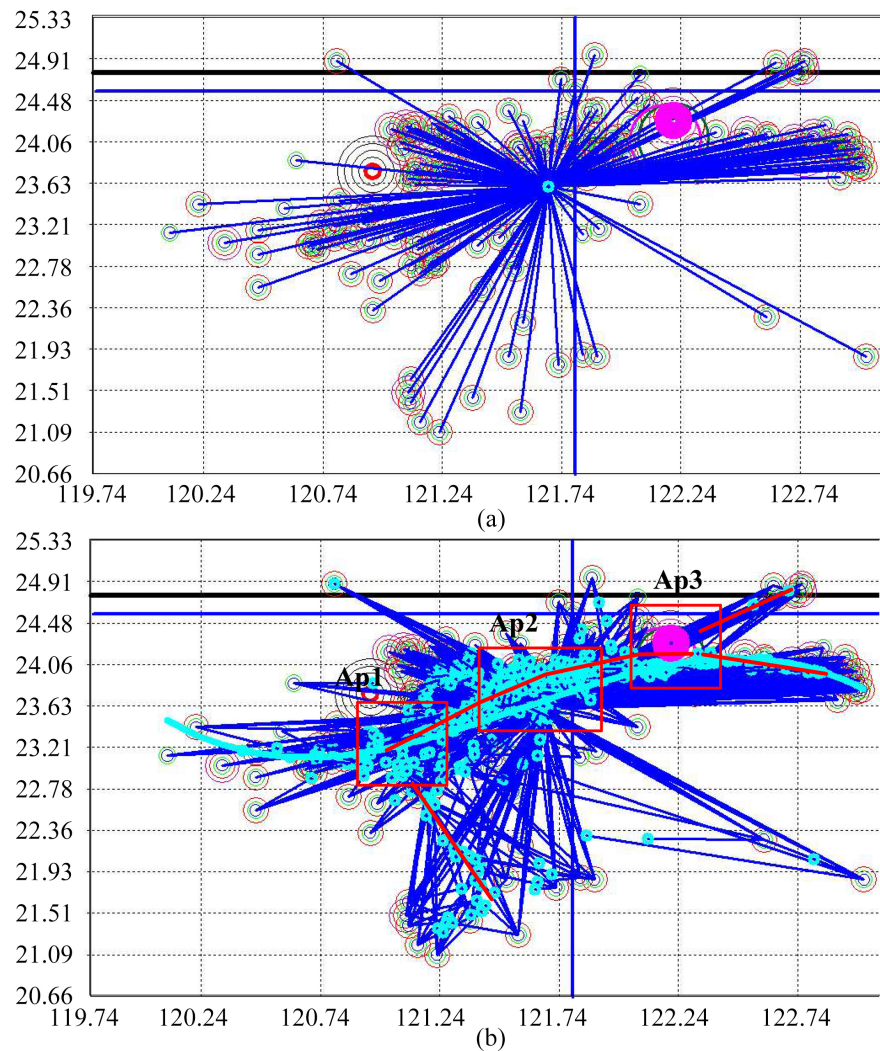


Figure 21. Map of epicenters in the Taiwan region (China). The distribution of seismic activity preceding the March 31, 2002, earthquake with a magnitude of 7.1 Mw. The solid purple circle indicates the location of the epicenter. The blue lines indicate alignments between three epicenters. The red boxes show areas of greatest hazard. The large purple and green circles indicate the dynamic epicenters DEM₁₁ and DEM₂₂. The red line indicates the possible seismic structure. The light blue circles indicate the midpoints. The black horizontal line indicates the presence of a cluster of earthquakes with similar latitudes at the end of the seismic sequence. The light blue line indicates the trace of the polynomial function.

Figure 21(b) shows the distribution of all mean longitude and latitude values for the pairs of epicenters, using an initial distance (start of the calculation cycle) of 8°, a final distance of 0.5° (end of the calculation cycle), and a calculation interval of 0.5 degrees in step 8. It can be observed that the bands of straight lines drawn from the outer points converge into three areas (indicated by a red box) where the mean points (light blue circles) are concentrated and also coincide with the concavities and the inflection point of the polynomial function (light blue line).

The convergence of the curve segments, the clustering of the midpoints, the

concavities, and the inflection point are the elements that make it possible to visually identify the hazardous areas.

In the central part of the graph, there is a band of light blue epicenters that partially coincides with the seismogenic fault and the polynomial function. Transversely to the straight line of the polynomial function, alignments of mean epicenters (thick red lines) are observed, converging in the critical areas indicated by the red boxes. These alignments may represent secondary seismogenic faults.

2.6. Histogram Model

The underlying assumption of this model is that earthquakes, when sorted in ascending order by longitude, latitude, and magnitude, tend to form specific patterns and alignments near the areas where the strongest earthquakes occur.

The model generates a diagram of event pairs, selected based on the chosen calculation distance, and is represented by horizontal bars of different colors.

The ends of the bars are connected by vertical lines, making it easy to identify areas that typically correspond to seismic gaps.

Analysis of numerous seismic sequences has revealed significant spatial patterns. Large earthquakes, in fact, often occur near the convergence of epicenter alignments or along the vertical bands that delimit aseismic zones. Other preferred locations include the vertices of concave or convex epicenter distributions and the quadrant containing the dynamic epicenters DEM_{11} and DEM_{22} . Finally, a significant correlation has been observed in the horizontal bands characterized by bars of greater width and where the seismogenic source intersects these bands.

There is, however, a small number of major earthquakes that cannot be explained by this model, but the resulting geometric configuration is consistent with the methods described above. This model nevertheless allows us to obtain further information on the location of areas with the highest probability of a major event.

The calculation procedure is as follows:

Step 1. Sort the latitude, longitude, and magnitude values in ascending order of latitude.

Step 2. Draw the blue bars (thick horizontal lines) using the coordinates $[Ex(1), Ey(1)]$; $[Ex(2), Ey(1)]$.

Step 3. Draw the red bars (thick horizontal lines) using the coordinates $[Ex(2), Ey(2)]$; $[Ex(1), Ey(2)]$.

Step 4. Draw the blue vertical lines (thin lines) between two consecutive epicenters $[Ex(1), Ey(1)]$; $[Ex(2), Ey(2)]$.

Step 5. Calculate the dynamic epicenters DEM_{11} and DEM_{22} .

Figure 22(a) and **Figure 22(b)** show the results obtained by applying the model to the epicenters of the earthquakes that preceded, respectively, the major earthquake that occurred in Iran on November 27, 1979, with a magnitude of 7.8 Mw and the earthquake in central Italy on August 26, 2016, with a magnitude of 6.0 Mw, respectively, while **Figure 22(c)** and **Figure 22(d)** present the interpretation of the graphs.

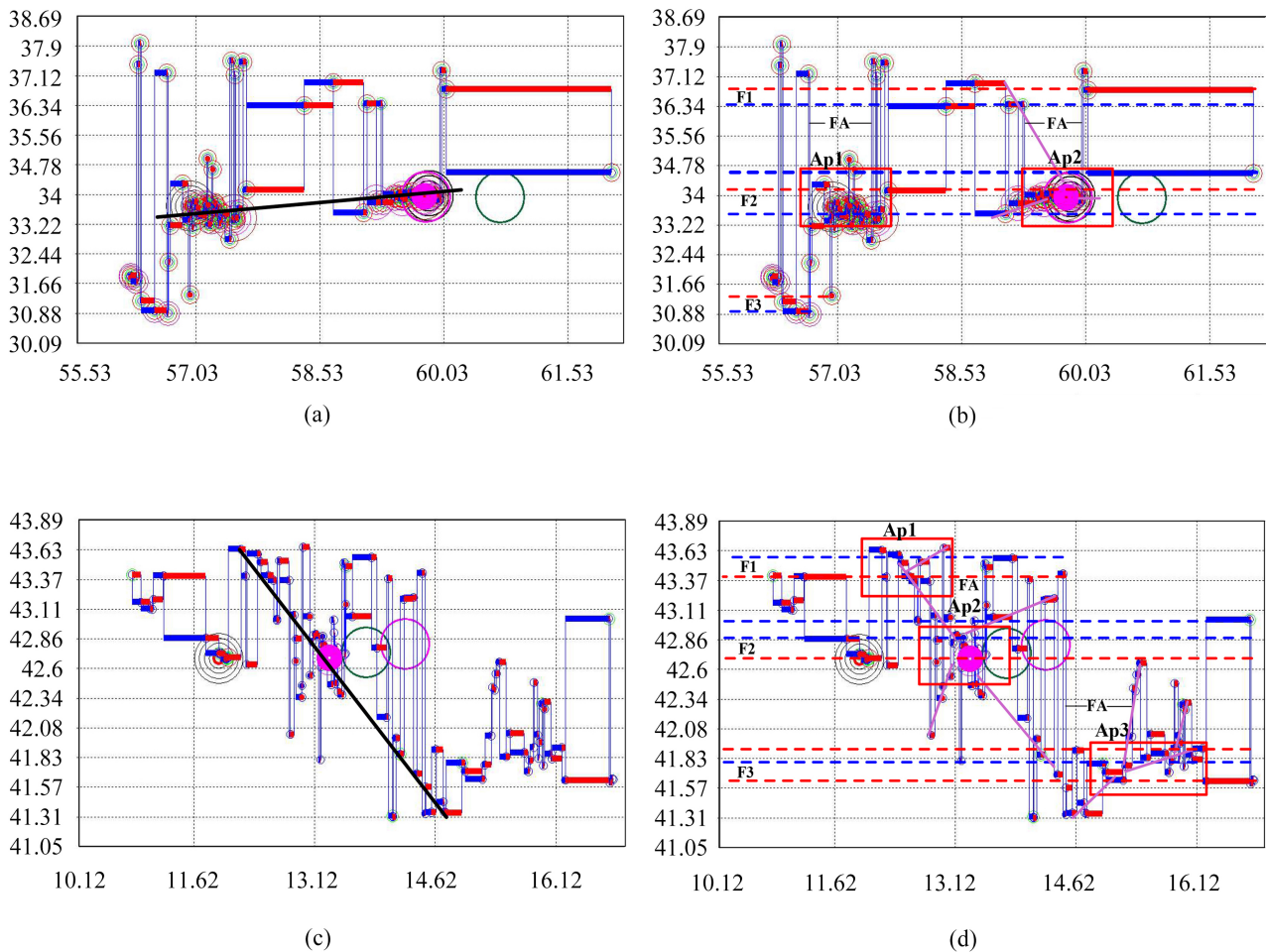


Figure 22. Map of epicenters in the regions of Iran and central Italy. The distribution of seismic activity preceding the major earthquakes that occurred in Iran on November 27, 1979 (Mw 7.8) and in central Italy on August 26, 2016 (Mw 6.0). The solid purple circle indicates the location of the epicenter. The red and blue bars indicate the horizontal distance between two epicenters, ordered by longitude. The thin blue lines indicate the vertical distance between two epicenters. The red and blue dashed horizontal lines indicate the critical seismic zones (F). The magenta lines indicate the alignments between the epicenters. The red boxes (Ap) show the areas where the hazard is high. The large purple and green circles indicate the dynamic epicenters DEM₁₁ and DEM₂₂. The black line indicates the trace of the seismogenic source ((a) and (b)).

The two graphs show three critical seismic zones (F1, F2, and F3) marked by the red and blue bars that are widest in the longitudinal direction. Each critical zone must include at least one or more red and blue bars located toward the right side of the graph.

Furthermore, the vertical blue lines drawn in Step 2 show the aseismic zones (FA) that delimit, in the lower part, areas where the distribution of epicenters is denser (clusters) and are usually affected by strong earthquakes.

Finally, alignments between bars often indicate the presence of seismogenic faults, while their convergence identifies the most hazardous area.

Typically, the epicenters of expected strong earthquakes are located within the broader critical seismic zones, at the convergence points of the alignments, and where the seismogenic source intersects the zones.

Based on the width of the seismic zone and the locations of the dynamic epicenters DEM_{11} and DEM_{22} , it is possible to determine the hazard level of the zone. The widest zones closest to the dynamic epicenters are the most hazardous. Based on the two parameters described above, the most hazardous zones shown in **Figure 22(c)** are, in order of hazard, zones F2, F1, and F3, while in **Figure 22(d)** they are zones F2, F3, and F1; the most hazardous areas are Ap1 and Ap2 (the most hazardous) in **Figure 22(c)** and Ap1 and Ap2 (the most hazardous) in **Figure 22(d)**.

2.7. Model of Horizontal Seismic Belts

The region contains several seismic belts and active seismotectonic zones where large shallow earthquakes are most likely to occur [17].

A simple method is described for identifying these seismic belts, with hazard levels decreasing in proportion to their longitudinal extent. It provides promising clues for selecting sites where strong earthquakes can be predicted.

The final result is a map of the epicenters of earthquakes that occurred prior to the mainshock, on which several horizontal zones selected through a simple interactive process are depicted.

In fact, to trace the zones, it is necessary to perform a series of consecutive calculations (**Figure 23**), where in each cycle the distance between two epicenters and the angle they form are calculated, and subsequently certain conditions are verified.

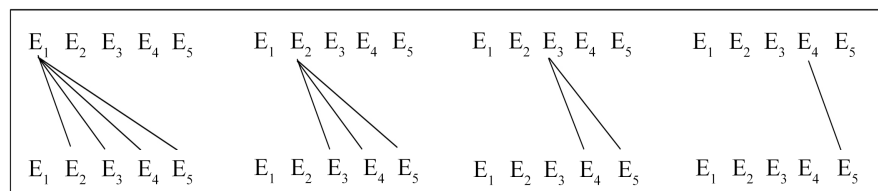


Figure 23. Calculation cycles between epicenters.

The calculation begins by setting the angle and distance between two epicenters to zero (the default value), and then increments them simultaneously or individually with each calculation cycle, until the entire series of epicenters has been processed.

The values of the angle αD and the distance (ΔD), 5° and 1 (pixel), respectively, are optimal for calculating the widest zones, where a strong earthquake is most likely to occur (increasing the value of the angle αD increases the width of the bands, while increasing the value of ΔD decreases the width of the bands).

The analysis process is repeated several times with different inputs, stopping the checks only after four seismic zones of decreasing width have been identified.

Considering two epicenters on the Cartesian plane, each identified by a pair of coordinates of the form (longitude, latitude), to calculate the seismic zones, proceed as follows:

Step 1. Calculate the distance between two epicenters E_1 and E_2 , whose value is given by the square root of the sum of the square of the difference in longitudes and the square of the difference in latitudes of the two epicenters.

$$\Delta(E_1, E_2) = \text{ABS} \sqrt{(\lambda_2 - \lambda_1)^2 + (\Phi_2 - \Phi_1)^2} \quad (10)$$

where

$\Delta(E_1, E_2)$ = distance between the epicenters;

λ = longitude of the epicenter;

Φ = latitude of the epicenter.

By definition, the distance between two points is non-negative; therefore, it is either positive or zero if the two epicenters coincide.

Step 2. Calculate the angle α of the line passing through the two epicenters with respect to the horizontal axis using the following formula:

$$\alpha = \frac{\Phi_2 - \Phi_1}{\lambda_2 - \lambda_1} \cdot 180/\pi \quad (11)$$

Step 3. Check whether the two epicenters satisfy the following condition:

Se $\Delta(E_1, E_2) \geq \Delta D$ and $\text{abs}(\alpha) \leq \alpha D$ a band or box must be drawn between the two epicenters;

where

ΔD = default value;

αD = default angle.

The calculation is repeated for all epicenters in the series.

The analyses show that the majority of strong earthquakes occur in the widest (from the origin of the latitude axis) and densest (presence of multiple aligned clusters) bands.

By analyzing 218 strong earthquakes that occurred globally, the model revealed that 95% of the epicenters were located within the three widest and densest bands, while 99% of the epicenters were within the four widest and densest bands.

The number of failures is very low (11 earthquakes out of 218 when considering three zones). This model can be used to obtain information about areas that may be affected by a strong earthquake in the short to medium term.

In this model as well, a significant correlation was observed where the seismogenic source intersects the bands.

Figure 24 shows the horizontal seismic zones identified by the model for the California earthquake of December 5, 2024, with a magnitude of 7.0 Mw.

The following initial values were used in the example:

Figure 24(a), $\Delta D = 1$ and $\alpha D = 0^\circ$;

Figure 24(b), $\Delta D = 0.01$ and $\alpha D = 0^\circ$;

Figure 24(c), $\Delta D = 1$ and $\alpha D = 1^\circ$;

Figure 24(d), $\Delta D = 1$ and $\alpha D = 5^\circ$.

As can be seen, the epicenter of the 7.0 Mw earthquake was located within the widest and densest seismic zone, shown in red (F1).

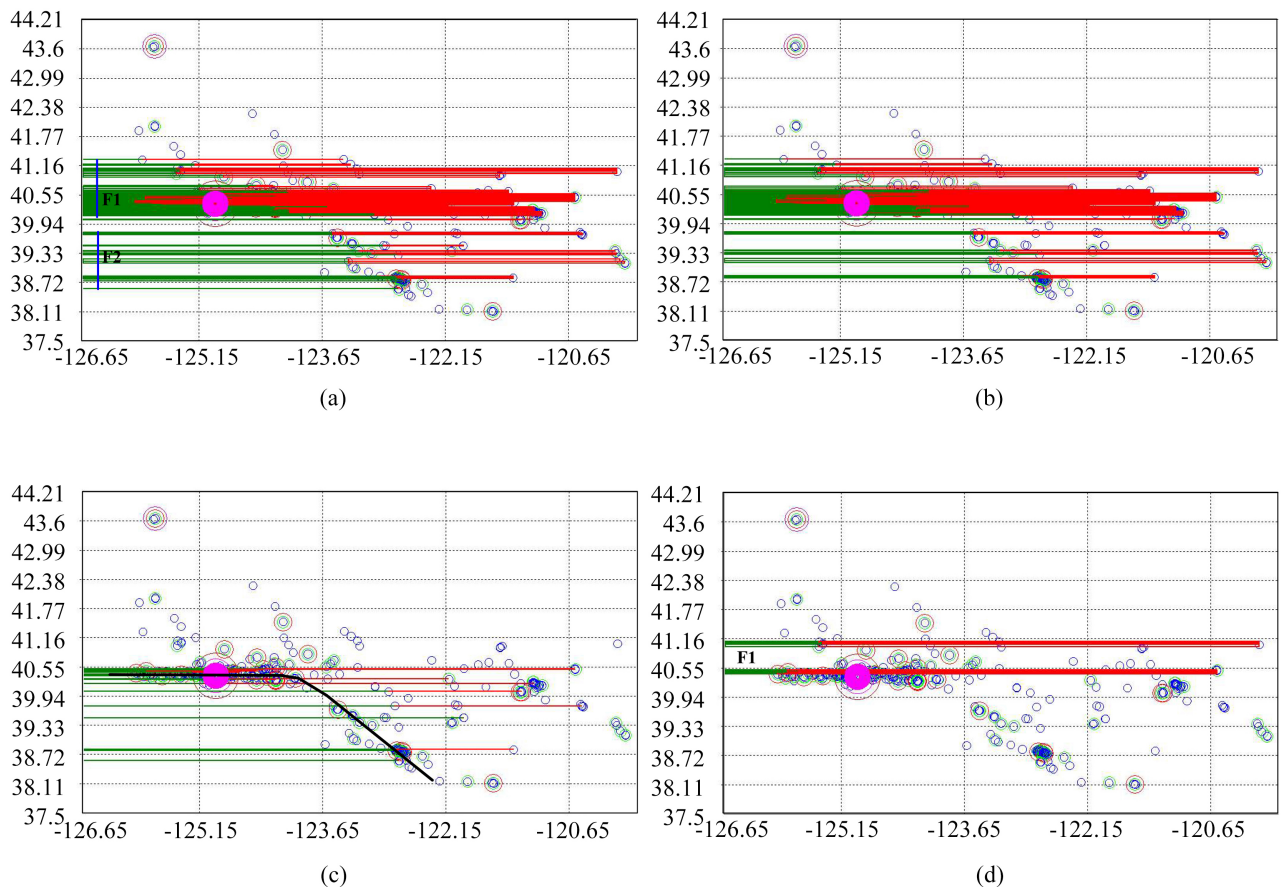


Figure 24. Model of horizontal seismic zones obtained by analyzing the earthquake in California on December 5, 2024, with a magnitude of 7.0 Mw. Initial values: a) $\Delta D = 1$ and $\alpha D = 0^\circ$, b) $\Delta D = 0.01$ and $\alpha D = 0^\circ$, c) $\Delta D = 1$ and $\alpha D = 1^\circ$, d) $\Delta D = 1$ and $\alpha D = 5^\circ$. The wider and denser green and red lines indicate the most hazardous zones (F1 and F2), respectively. The solid purple circle indicates the location of the earthquake's epicenter. The black line (b) indicates the trace of the seismic source.

2.8. Seismic Network Model

The output of this model displays seismic points in the form of a dendrogram, which provides a visual representation of clusters and isolated epicenters arranged to form a linear, branching pattern on the map, similar to the patterns of river networks.

This method begins by treating each epicenter as an individual cluster and merging the nearest epicenters until a predefined criterion is met, which stops the calculation procedure.

The calculation procedure is as follows:

Step 1. Sort the longitude values $X(1, 2, \dots, Ne)$ and latitude values $Y(1, 2, \dots, Ne)$ in ascending order of longitude;

Step 2. Start the first calculation cycle (k) from 1 up to $Ne - 1$

where Ne = total number of epicenters.

Step 3. Start the second calculation cycle (j) from $k + 1$ to Ne .

Step 4. Select the epicenters $[Ex(k), Ey(k)]$; $[Ex(j), Ey(j)]$ according to the scheme shown in **Figure 25**.

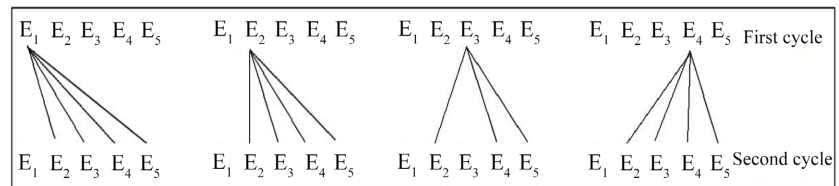


Figure 25. Diagram of the first and second calculation cycles between the epicenters.

Step 5. Calculate the distance between two epicenters.

$$D = \left[\text{Abs}[Ex(k) - Ex(j)]^2 + \text{Abs}[Ey(k) - Ey(j)]^2 \right]^{0.5} \quad (12)$$

$D1 = 20,000$ pixels is the initial radius value (default).

Step 6. Perform the calculation if:

$D < D1$ then $Xf = Ex(j)$;

$D < D1$ then $Yf = Ey(j)$;

$D < D1$ then $D1 = D$.

where

Xf and Yf are the coordinates of the second point of each branch of the lattice;

$D1$ is the updated radius.

Step 7. Draw the black line (seismic branch) using the coordinates $(Ex(k), Ey(k))$; Xf, Yf ;

Step 8. Repeat the calculation for all epicenters in the series until both calculation cycles are complete.

The final result implies that the seismic points in the grid are arranged to form a linear pattern on the map, analogous to the traces of major river channels represented by lines oriented in different directions.

Seismic grids can be described based on their geometry (pattern), which varies depending on the lithology and tectonic structure of the area.

The main types of seismic networks are the sub-dendritic and sub-rectangular networks, which develop along fractures or faults in the subsurface and affect areas with rocks of varying strength and homogeneity.

In the sub-dendritic pattern, some seismic branches have preferred directions, thus highlighting the presence of fractures. In the sub-rectangular pattern, the seismic branches are more regular, with angles between the main and secondary branches that are nearly right angles, thus highlighting the presence of fractures or faults in the subsurface.

Therefore, this model provides information on the main directions of seismogenic faults.

Usually, the epicenters of strong earthquakes are located along the longest segments of the seismic network and often near the convergence of two seismic branches forming angles greater than 60° , and after the formation of the second-order branch.

Figure 26 and **Figure 27** show the seismic networks generated by the model for some earthquakes on a global scale.

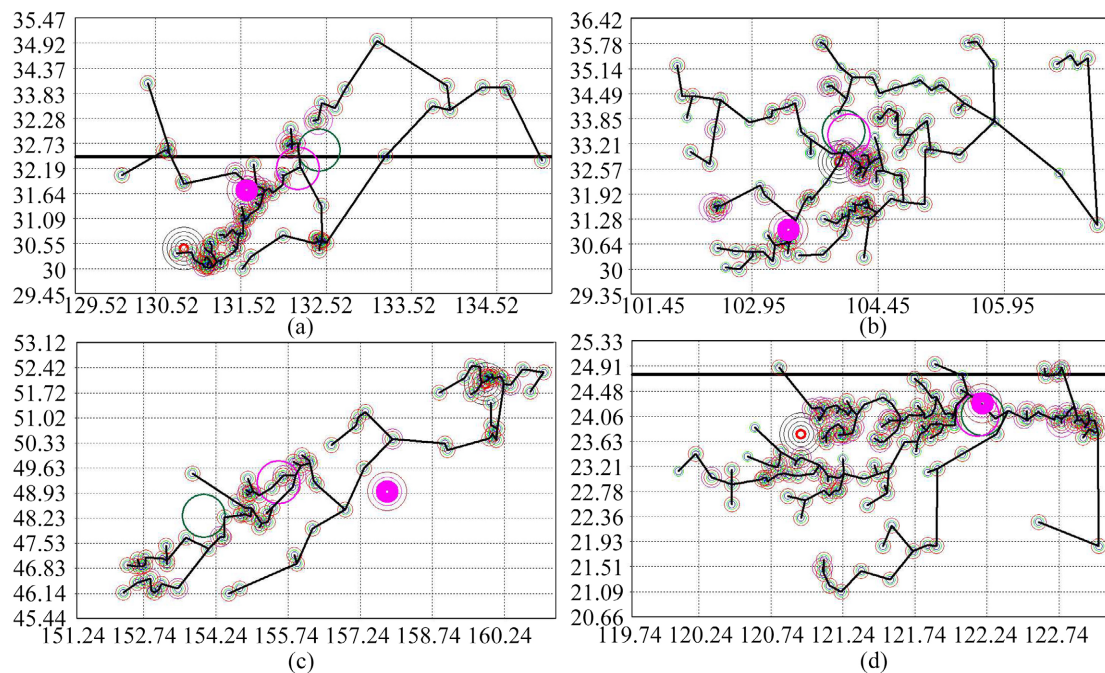


Figure 26. Map of epicenters showing the results of seismicity analysis using the seismic network model. (a) Japan earthquake on 08/08/2024 with a magnitude of 7.1 Mw; (b) China earthquake on 12/05/2008 with a magnitude of 7.9 Mw; (c) Russia earthquake on 25/03/2020 with a magnitude of 7.5 Mw; (d) the earthquake in Taiwan region (China) of March 31, 2002, with a magnitude of 7.1 Mw. The solid magenta circle indicates the mainshock. The large green and magenta circles indicate the dynamic epicenters DEM₁₁ and DEM₂₂. The black lines indicate the seismic grids.

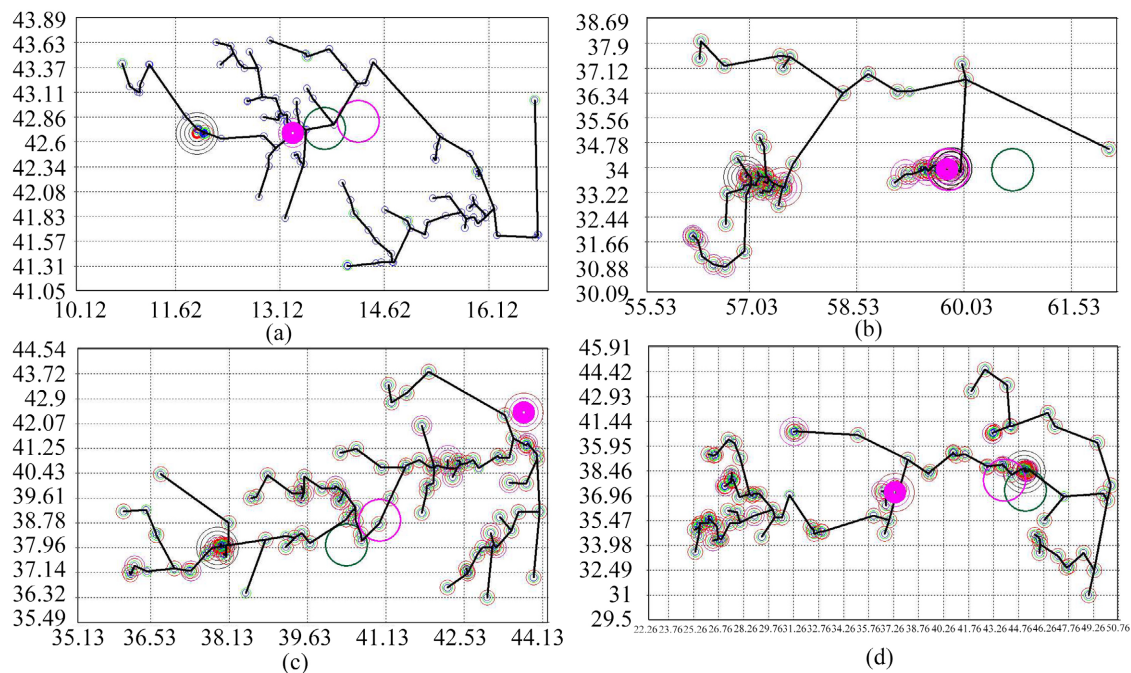


Figure 27. Map of epicenters showing the results of seismicity analysis using the seismic network model. (a) earthquake in central Italy on 08/26/2016 with a magnitude of 6.0 Mw; (b) earthquake in Iran on 11/27/1979 with a magnitude of 7.8 Mw; (c) earthquake in Turkish region on 04/29/1991 with a magnitude of 7.3 Mw; (d) the earthquake in Turkish region on February 6, 2023, with a magnitude of 7.8 Mw. The large green and magenta circles indicate the dynamic epicenters DEM₁₁ and DEM₂₂. The black lines indicate the seismic grids.

2.9. Cluster Model

This model, based on the decreasing distance between pairs of epicentres, takes into account both the spatial information and the density of the lines connecting the pairs of points to the most recent earthquake that occurred during the seismic sequence.

In the first phase of the algorithm's application, using a distance of $\Delta\varphi = 0.30$ degrees (by default) between pairs of epicentres, it generates a diagram providing information on the areas of the map that may be affected by the formation of clusters and a strong earthquake.

In the second phase, by reducing the distance between pairs of epicentres and after eliminating the earthquakes not used in the first phase, a new spatial representation is obtained of only the seismic events selected in the previous phase, with a new distribution of epicentres.

The results of this model provide information for identifying areas that may be affected by a strong earthquake.

The calculation procedure is as follows:

Step 1. Select the distance value between the coordinates of the epicentre pairs $\Delta\varphi = 0.30$ degrees(default).

Step 2. Run the first calculation cycle (k) from 1 to $Ne - 1$, with an increment ($i = 1$),

where Ne = total number of epicenters.

Step 3. Activate the second calculation cycle (j) from 2 up to Ne with an increment ($i = 1$).

Step 4. Calculate the epicentres $[Ex(k), Ey(k)]; [Ex(j), Ey(j)]$.

Step 7. Continue the calculation procedure if:

$$Abs[X(k) - X(j)] \leq \Delta\varphi \text{ or } Abs[Y(k) - Y(j)] \leq \Delta\varphi \quad (13)$$

Step 8. Calculate

$Sx = X(k) + Sx$ (sum of the longitudes of the epicentres in the second cycle);

$Sy = Y(k) + Sy$ (sum of the latitudes of the epicentres in the second cycle);

$Ns = Ns + 1$ (sum of the epicentres selected in the second cycle);

$Sx = X(j) + Sx$ (sum of the longitudes of the epicentres of the second cycle);

$Sy = Y(j) + Sy$ (sum of the latitudes of the epicentres of the second cycle);

$Ns = Ns + 1$ (sum of the epicentres selected in the second cycle).

Step 10. At the end of the cycle, calculate the average values of longitude and latitude

$$X(Sx) = (Sx)/Ns \quad (14)$$

$$Y(Sy) = (Sy)/Ns \quad (15)$$

Step 11. Plot the red line using the coordinates $[Ex(Ne), Ey(Ne)]; [X(Sx), Y(Sy)]$,

where $Ex(Ne)$ and $Ey(Ne)$ are the coordinates of the most recent earthquake.

Step 12. Draw the blue circle using the coordinates $X(Sx), Y(Sy)$.

Step 13. Repeat the calculation procedure until all cycles are closed.

Step 14. Store the coordinates of the calculated blue circles $X(Sx)$, $Y(Sy)$.

Step 15. Construct a new map using the epicentres stored in the previous step.

Step 16. Apply the model again to the new map of epicenters.

Step 17. Repeat the procedure described in steps 13 and 14 until a new reduced map of epicentres is obtained.

By analysing the seismic sequence preceding the 2008 earthquake in China with a magnitude of 7.8 Mw, it is possible to describe the model.

In the first analysis cycle, the variable “number” starts at 1 and is subsequently increased by one for each iteration of the cycle. The calculation ends when the value of ‘number’ reaches $Ne - 1$.

In the second cycle, the variable “number” from the first cycle starts at 2 and is increased by one for each iteration of the cycle. In this case, the calculation ends when the value of “number” reaches Ne .

The value of $\Delta\phi$ can be decreased or increased to produce maps with varying levels of detail.

The distance value between the coordinates of the epicentrepairs used is $\Delta\phi = 0.30$ degrees (this can be reduced or increased to obtain maps with varying levels of detail).

Figure 28(a) shows the results obtained using the cluster model, whilst **Figures 28(b)-(d)** show the results obtained using the procedure described in steps 12 - 14.

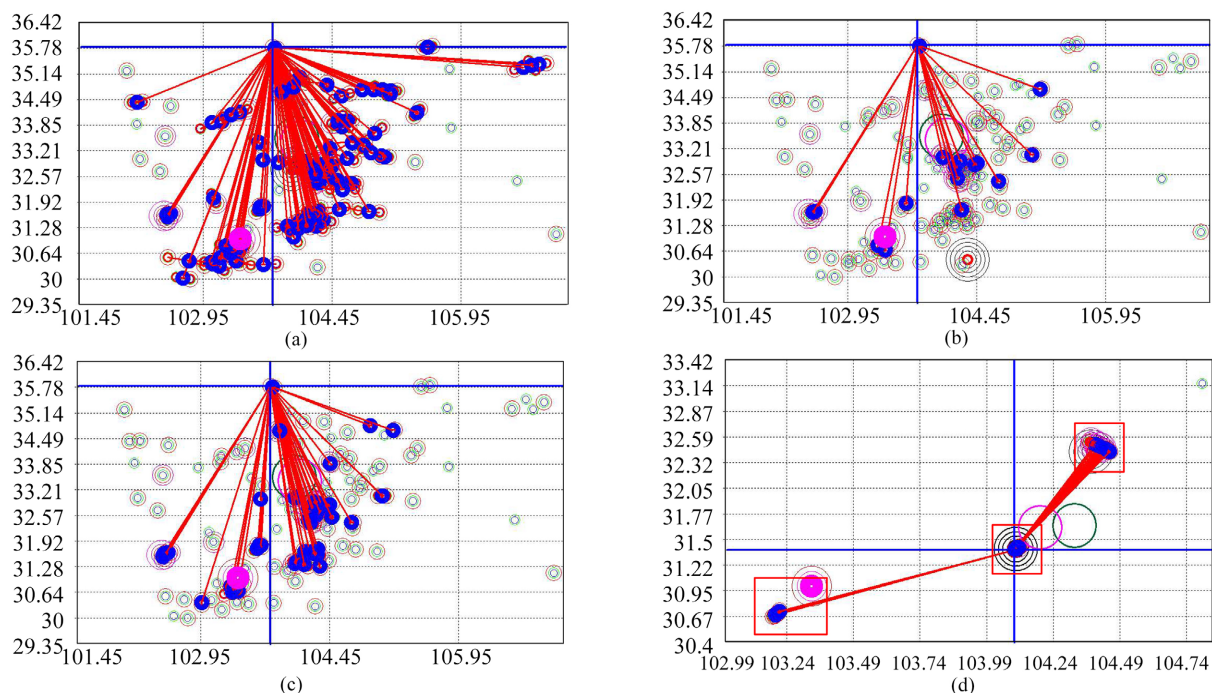


Figure 28. Map of the epicentres of the earthquake in China on 12 May 2008, showing the results of the clustering model (a). The blue horizontal and vertical lines are the axes drawn from the last epicentre in the analysed series. The blue circles indicate the positions of the average epicentres (step 10). The red lines indicate the distance between the last point in the analysed series and the mean points. The solid magenta circle indicates the mainshock. The large green and magenta circles indicate the dynamic epicentres DEM_{11} and DEM_{22} . The red boxes indicate the areas that may be affected by a strong earthquake.

In particular, **Figure 28(d)**, obtained after several cycles of training and applying the cluster model, shows the areas likely to be affected by a strong earthquake, whilst **Figure 28(b)** and **Figure 28(c)** indicate the most hazardous sectors.

Figure 29(a) shows the map of the epicentres of the 7.8 Mw earthquake obtained using a distance $\Delta\varphi = 0.30$ degrees, whilst **Figure 29(b)** shows the results obtained after several iteration cycles, with the distance d_s between pairs of epicentres decreasing with each iteration.

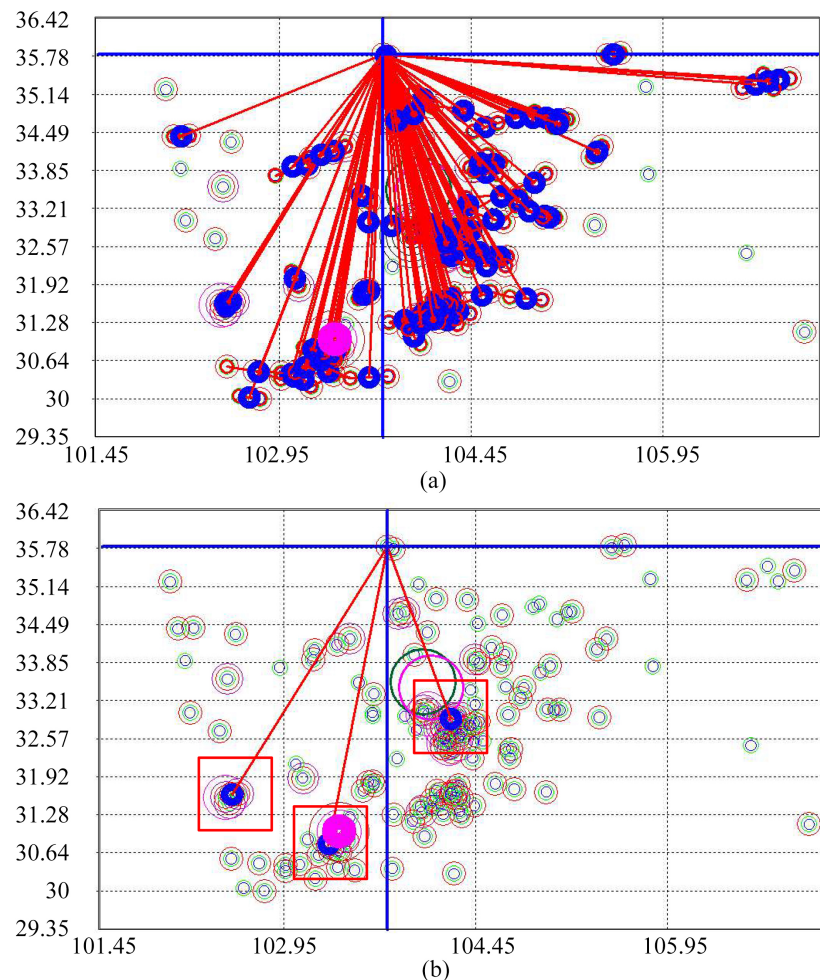


Figure 29. Map of the epicentres of the earthquake in China on 12 May 2008, showing the results of the cluster model ((a) $\Delta\varphi = 0.30$ degrees, (b) $\Delta\varphi = 0.03$ degrees). The red boxes indicate areas that may be affected by a strong earthquake.

The calculation procedure was halted when the distance reached a value of $\Delta\varphi = 0.03$ degrees, which led to the identification of three areas likely to be affected by a strong earthquake in the future. The analysis presented regarding seismic clusters is reliable in locating the epicentre of the expected earthquake, provided it falls in the vicinity of clusters of active earthquakes or those that occurred in the past. **Figures 30-33** show the results obtained using the cluster model applied to certain earthquakes that occurred in other parts of the world.

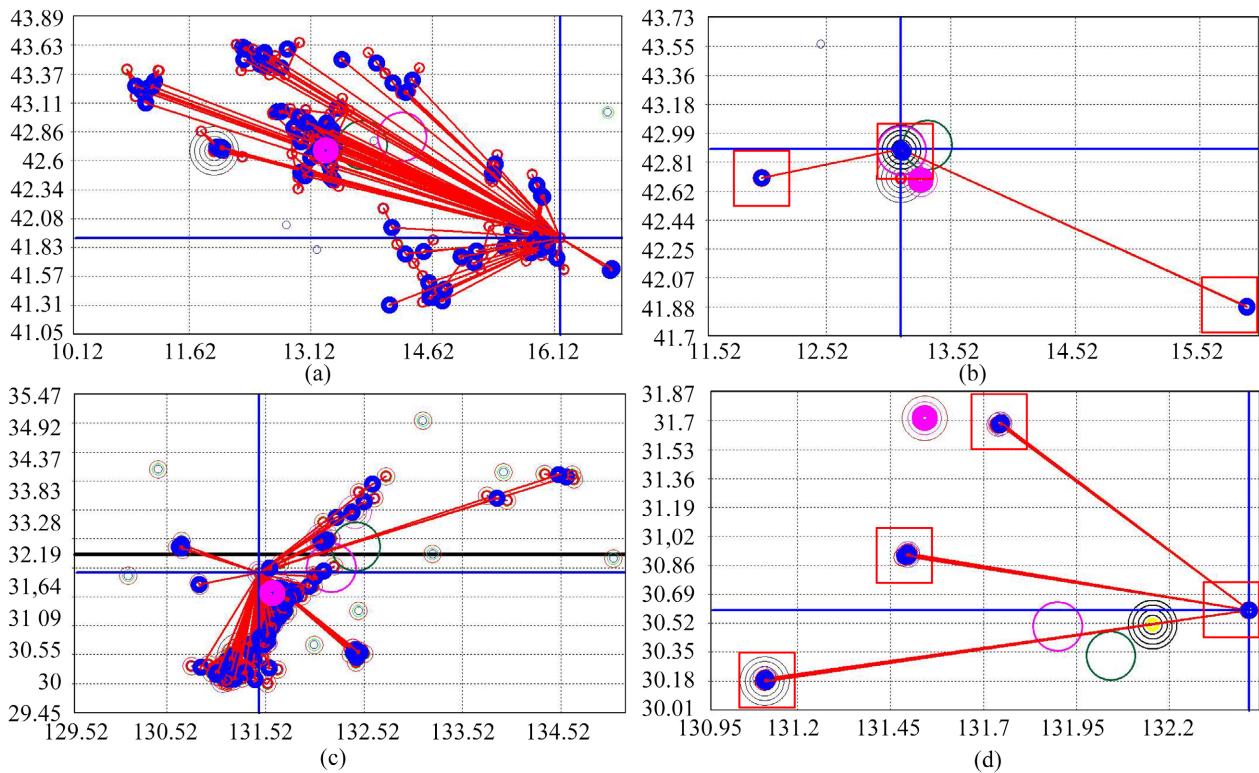


Figure 30. Map showing the epicentres of the earthquake in central Italy on 30 October 2016 ((a) and (b)) and in Japan on 8 August 2024 ((c) and (d)).

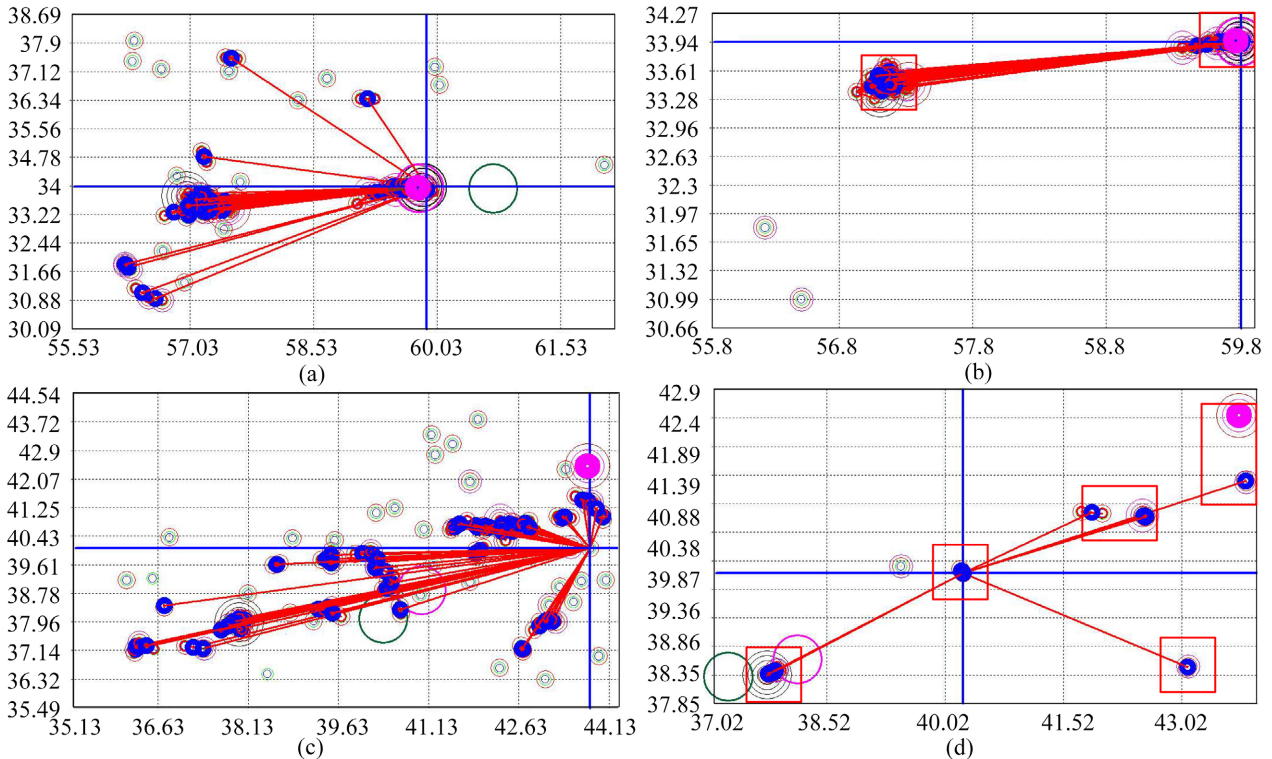


Figure 31. Map showing the epicentres of the earthquake in Iran on 27 November 1979 ((a) and (b)) and in Turkish region on 27 November 1991 ((c) and (d)).

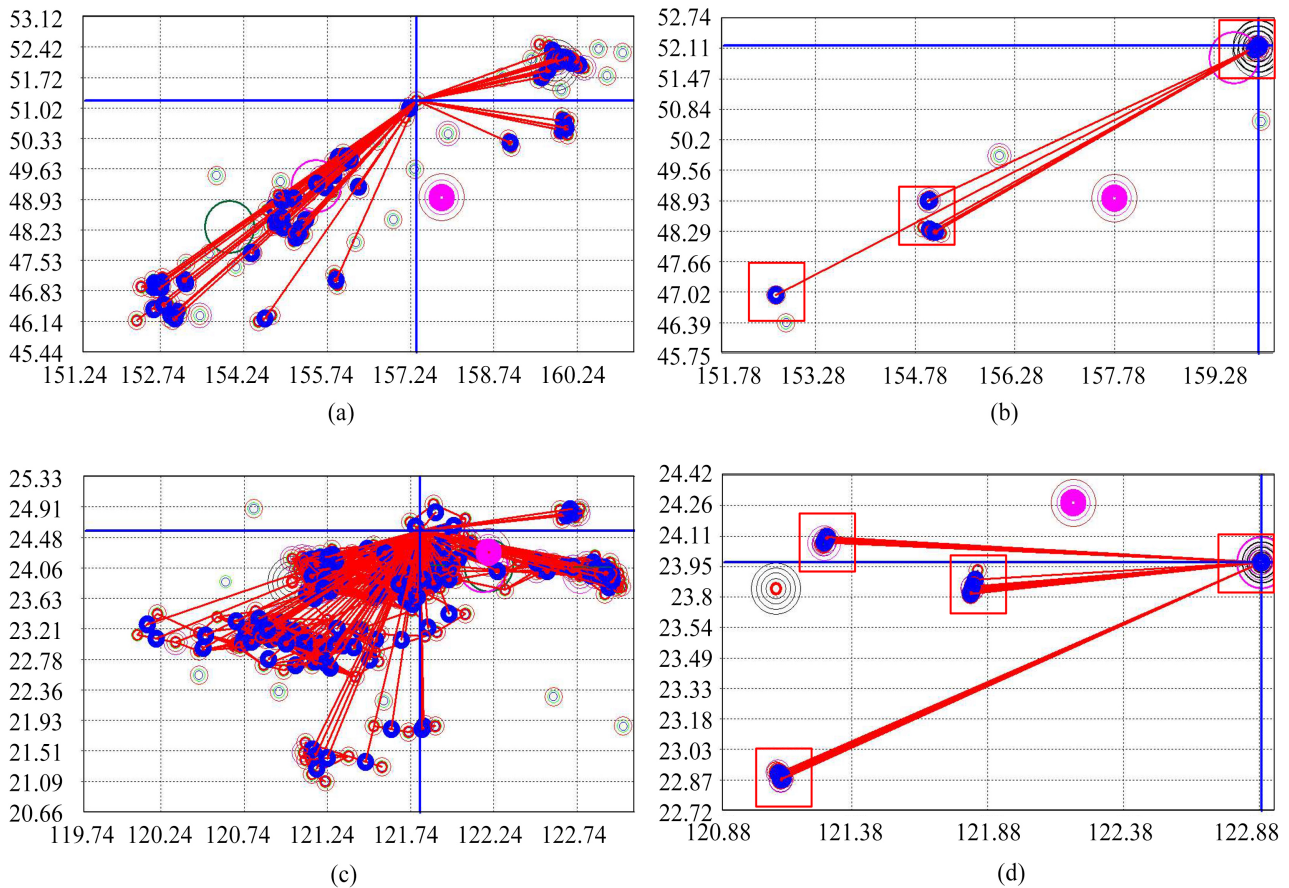


Figure 32. Map showing the epicentres of the earthquake in Russia on 25 March 2020 ((a) and (b)) and in Taiwan region (China) on 31 March 2002 ((c) and (d)).

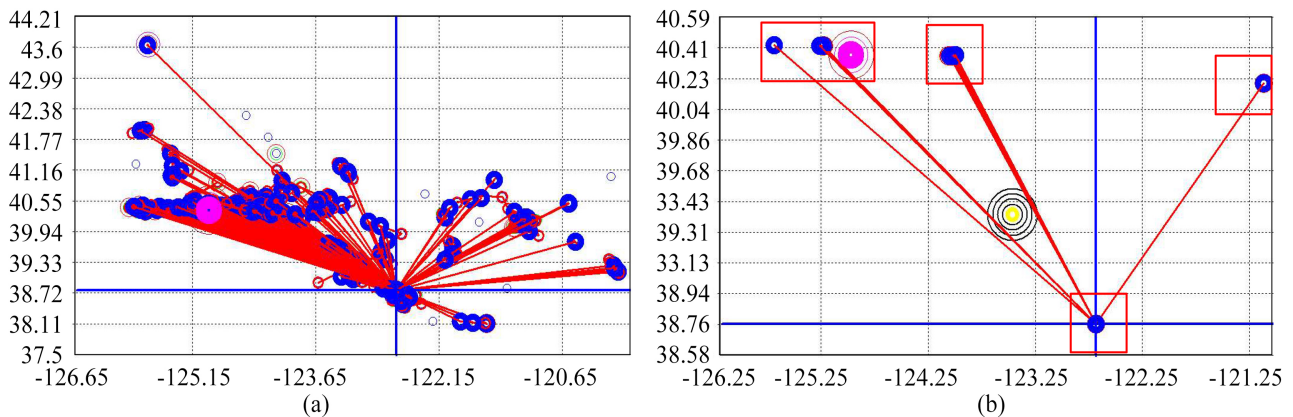


Figure 33. Map of the epicentres of the California earthquake on 5 December 2024 ((a) and (b)).

2.10. Multi-Cycle Model

The algorithm for this model consists of three nested calculation cycles and uses the distance between pairs of epicenters. This model generates diagrams that provide information on the location of clusters and on seismic sources capable of generating a strong earthquake.

The calculation procedure is as follows:

Step 1. Sort the longitude values $X(1, 2, \dots, Ne)$ and latitude values $Y(1, 2, \dots, Ne)$ in ascending order of longitude.

Step 2. Choose the initial calculation value ($d1$), the final value ($d2$), and the increment (i) for the first cycle (default values: $d1 = 6$ degrees, $d2 = 0.50$ degrees, $i = -0.50$ degrees);

where

$d1$ = is the maximum distance between the coordinates of two epicenters;

$d2$ = is the minimum distance between the coordinates of two epicenters;

i = the calculation increment between ($d1$) and ($d2$).

Step 3. Activate the first calculation cycle (kk) from ($d1$) to ($d2$) with an increment ($-i$) (the cycle proceeds in descending order by default).

Step 4. Activate the second calculation cycle (k) from 1 to $Ne - 1$;
where Ne = total number of epicenters.

Step 5. Activate the third calculation cycle (j) from 2 to Ne .

Step 6. Select the epicenters $[Ex(k), Ey(k)]$; $[Ex(j), Ey(j)]$ according to the scheme shown in **Figure 18**.

Step 7. Perform the calculation if:

$$[X(k) - X(j)] \leq kk \text{ or } [Y(k) - Y(j)] \leq kk \quad (16)$$

Step 8. Calculate

$Sx = X(j) + Sx$ (sum of the longitudes of the epicenters in the third cycle);

$Sy = Y(j) + Sy$ (sum of the latitudes of the epicenters in the third cycle);

$Ns = Ns + 1$ (sum of the epicenters selected in the third cycle);

Step 9. At the end of the third cycle, calculate the average values of longitude and latitude.

$$X(Sx) = (Sx)/Ns \quad (17)$$

$$Y(Sy) = (Sy)/Ns \quad (18)$$

Step 10. Assign colors to the circles for each calculation cycle, starting with yellow and progressing to dark red in the final calculation cycle.

Step 11. Draw the blue circle using the center coordinates $X(Sx)$, $Y(Sy)$.

Step 12. Repeat the calculation procedure until all planned cycles k and kk are completed.

Figure 34 shows the results obtained using the multi-cycle model applied to the earthquakes in central Italy on October 30, 2016 (**Figure 34(a)**), in Japan on August 8, 2024 (**Figure 34(b)**), the earthquake in Iran on November 27, 1979 (**Figure 34(c)**), and the earthquake in Taiwan region (China) on March 31, 2002 (**Figure 34(d)**). The main seismogenic structures and the alignments of the epicenters calculated by the model, which converge in the area affected by the mainshock, are clearly evident.

The figures were generated by assigning the following parameters to the first calculation cycle: $d1 = 6$ degrees; $d2 = 0.5$ degrees; $i = -0.5$ degrees.

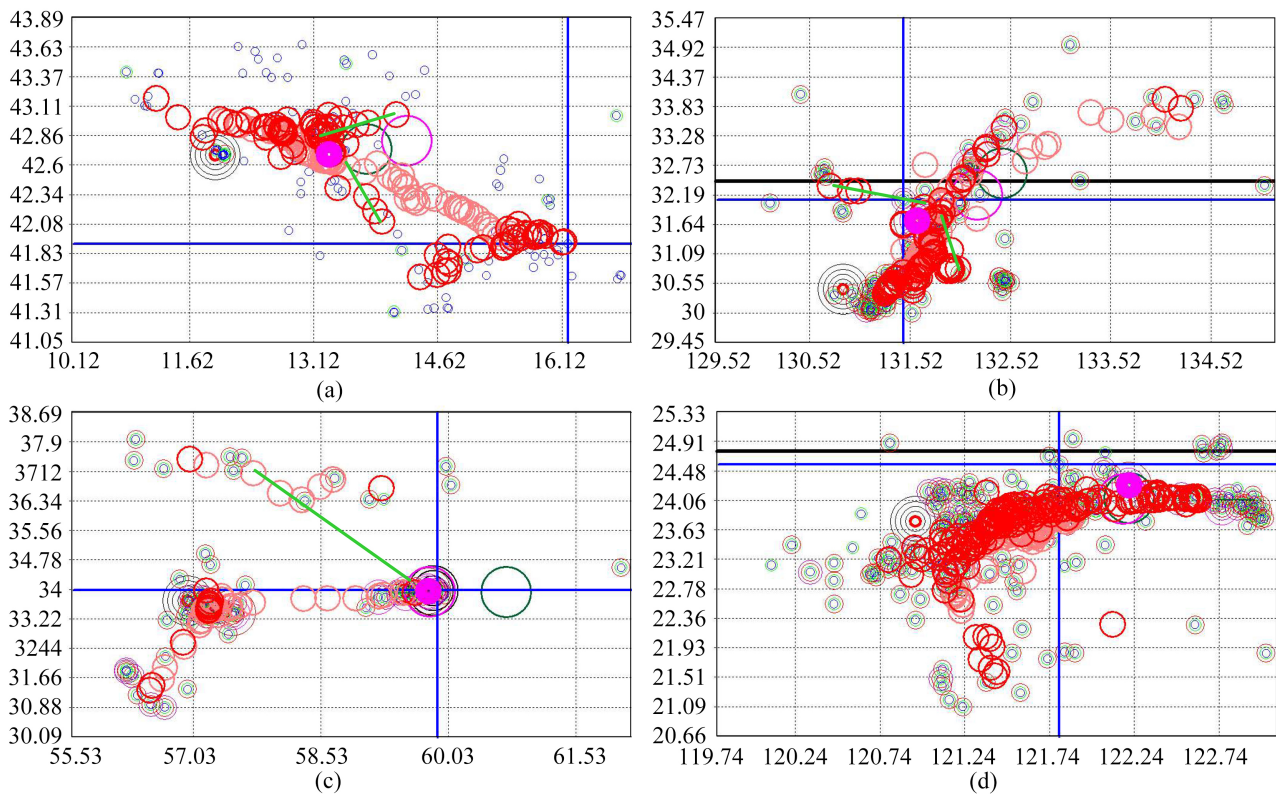


Figure 34. Map of the epicenters of the earthquakes in central Italy on October 30, 2016 (a), in Japan on August 8, 2024 (b), in Iran on November 27, 1979 (c), and in Taiwan region (China) on March 31, 2002 (d). The red circles indicate the epicenters calculated by the multi-cycle model. The green lines indicate the alignments between the epicenters calculated by the model. The solid magenta circle indicates the mainshock. The large green and magenta circles indicate the dynamic epicenters DEM_{11} and DEM_{22} .

3. Conclusions

Seismic sequences do not occur randomly, but follow a temporal and spatial pattern correlated with the system of seismogenic faults, which over time can lead to the initiation of a major earthquake.

By observing the locations of earthquake epicenters in a region over the short to medium term, a strong tendency emerges to form clusters of varying sizes and irregular shapes, often intersected by other clusters or arranged in alignments when they are directly related to a specific seismogenic fault or adjacent secondary faults.

Based on the position of the clusters, we have observed that earthquakes are often interconnected, and it is possible that an earthquake or a cluster on a seismogenic fault may stress a fault located even many kilometers away, which in turn can generate a seismic event (the occurrence of a major earthquake can stress surrounding faults, which may generate other earthquakes).

This could stem from the fact that a major earthquake does not always allow the lithospheric block to dissipate the stress accumulated over time; rather, some of it remains stored and can trigger an earthquake in an area different from the epicenter.

Statistically, only 59% of the 218 epicenters of strong earthquakes that oc-

curred worldwide were located near clusters that became active shortly before the mainshock (21% of 218) or gradually over time (38% of 218); the others occurred in the inter-cluster space and, to a lesser extent, in aseismic areas.

51% of the 218 strong earthquakes that occurred near clusters were preceded in the past by one or more foreshocks with a magnitude slightly lower than that of the mainshock.

Using these observations and information, together with the analysis of 218 strong earthquakes, we have developed retrospective models that can be used to identify and locate the most hazardous areas, where a strong earthquake is most likely to occur in the short term. The models also provide information on the seismogenic source and also allow for the interpretation of the various seismicity patterns that emerge prior to major earthquakes and provide valuable insights for short-term earthquake forecasting.

Verifications performed on many seismic sequences that preceded strong earthquakes demonstrate a good overlap between clusters, epicenter alignments, and the seismogenic source, also making it possible to identify the most hazardous areas that may be affected by a strong earthquake in the short term. The best results in terms of defining a seismically hazardous area are obtained by overlaying the information obtained using multiple models simultaneously.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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