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Mapping seismogenic structures through earthquake waveform similarity clustering: an application to La Palma volcano, Spain

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ABSTRACT

High-resolution earthquake catalogs provide valuable information to illuminate fault structures and track their temporal evolution. We propose a multi-stage approach that combines seismicity clustering and fault imaging to reconstruct seismogenic structures based on hypocenters, moment tensors, and full waveforms. We reprocess the volcano-tectonic seismicity during the 2021 Tajogaite volcanic eruption, that took place on the western flank of the Cumbre Vieja volcanic ridge, La Palma island, Spain. The first stage is a waveform-based clustering across variable frequency bands. Next, we use the spatial distribution of hypocenters and focal mechanisms to investigate the geometry of active structures at the most active seismogenic volumes, at ~10-14 and ~33-39 km depth, which have been interpreted as magma accumulation volumes along the rise path. Our approach suggests using a clustering-based outlier removal procedure and a bootstrap-PCA analysis of hypocenter locations. Several earthquake families were identified and their geometries and temporal evolution reconstructed. In the deeper volume, earthquake families located at slightly greater depths reflect sustained seismicity, controlled by compressional tectonic and magmatic-induced stresses, in response to upward magma intrusions. In contrast, shallower families, with opposite focal mechanisms, are interpreted as the result of short-lasting, tensional stress transients at the tip of rising magma batches. The coexistence of rotated focal mechanisms is also found at the shallow reservoir. Our work demonstrates how dense seismic catalogs can be used to reconstruct the geometry of fault networks in response to magma transfer.

KEYWORDS: Clustering; Seismicity; Moment tensor; Repeaters; Fault geometry; Volcano seismology.

1 INTRODUCTION

1.1 Background

The spatial distribution of seismicity is tightly connected to the underlying tectonic and volcanic processes [Isacks et al. 1968] and to the geometry of active seismogenic structures. Studying the spatiotemporal distribution of seismicity helps towards the assessment of regional seismotectonic settings and earthquake recurrence intervals, that are both used in hazard models. Seismicity is thus of first importance to improve hazard maps and preparedness strategies, even in regions with limited historical data. While seismic hazard assessments predominantly focus on tectonic earthquakes, integrating volcano-related

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seismicity is crucial for comprehensive risk evaluations, especially in regions with active volcanoes [Azzaro et al. 2016]. The spatial distribution of earthquakes' hypocentral locations can be used to identify active faults [Ouillon and Sornette 2011; Truttmann et al. 2023; Petersen et al. 2025]. Seismicity is often the unique source of information to unveil the geometry and extent of faults at depth and to assess their seismogenic potential, particularly in the case of blind faults or in lack of other geological evidence. Previous attempts for automated fault imaging illustrated how to reconstruct fault network geometries from the spatial distribution of aftershock hypocenters, e.g., with an application to the 1992 Landers earthquake, southern California [Ouillon et al. 2008] or the 2018 Zakynthos sequence [Petersen et al. 2021]. Further developing and improving these methods can help achieve a more detailed fault mapping. Previous applications focused on the spatial reconstruction of tectonic faults [e.g., Ouillon et al. 2008; Ouillon and Sornette 2011], as well as on the investigation of volcano-related activity [Vogfjord et al. 2005; Carmona et al. 2010; Alparone et al. 2013; Afnimar et al. 2022]. Among the most relevant outcomes of these studies are: the confirmation of strike-slip faults at the Sinabung volcano [Afnimar et al. 2022], the resolution of the geometry of deep seismogenic structures at Mt. Etna despite the lack of any surface evidence [Alparone et al. 2013], and the mapping of geometry and extent of magma dikes [Cesca et al. 2022; Isken et al. 2025].

Clustering algorithms are used to identify classes of objects with similar properties out of large object sets [Xu and WunschII 2005]. Seismicity clustering offers a powerful tool to analyze the spatial distribution of earthquakes [Cesca 2020; Petersen et al. 2021; Vijay et al. 2025]. They can further be used to classify seismicity upon different earthquake characteristics, such as the temporal evolution, moment tensor geometry and waveform similarity [Cesca 2020]. Temporal clustering has helped to identify earthquake bursts, distinguish among mainshock-aftershock sequences and swarms [Passarelli et al. 2026], or to identify and remove aftershocks from seismic catalogs [Zaliapin and Ben-Zion 2022]. Focal mechanism and moment tensor clustering has been used to identify the occurrence of similar rupture processes, even when occurring at different locations or at different times [Cesca et al. 2014]. Finally, waveform-based event classification has been extensively investigated in the frame of studies focusing on repeaters, i.e. earthquakes that re-rupture the same fault patch with nearly identical waveforms [Uchida and Bürgmann 2019; Gao and Kao 2020; Hatch et al. 2020; Sheng et al. 2021; Cabrera et al. 2026]. The analysis of repeaters, identified upon their high waveform similarity and supported by accurate locations and moment tensors, improved our understanding of the temporal evolution of fault slip [Nadeau and McEvilly 1999; Chen and Lapusta 2009; Uchida and Bürgmann 2019]. In contrast to repeaters, a recently recognized class of (quasi) anti-repeaters comprises event pairs that exhibit high waveform anti-correlation, thus suggesting similar locations and opposite source mechanisms [Cesca et al. 2024; 2026]. In general, using clusters of similar events instead of single earthquakes can provide more robust results and can potentially identify and resolve large fault structures.

This paper presents a multi-stage workflow that first exploits high-resolution waveform cross-correlation to identify clusters of similar earthquakes, hereafter called families, and then uses the distribution of hypocenters and source mechanisms among the waveform-similarity-based earthquake families to infer fault-plane structures. The approach extends upon the waveform clustering approach presented in [Petersen et al. 2021] and is here demonstrated using a recent volcano-seismology case study: The seismicity at La Palma island, Canary Islands, Spain, during its recent eruption episode in 2021 [Longpré 2021; Carracedo et al. 2022; D'Auria et al. 2022; Global Volcanism Program 2022; González 2022].

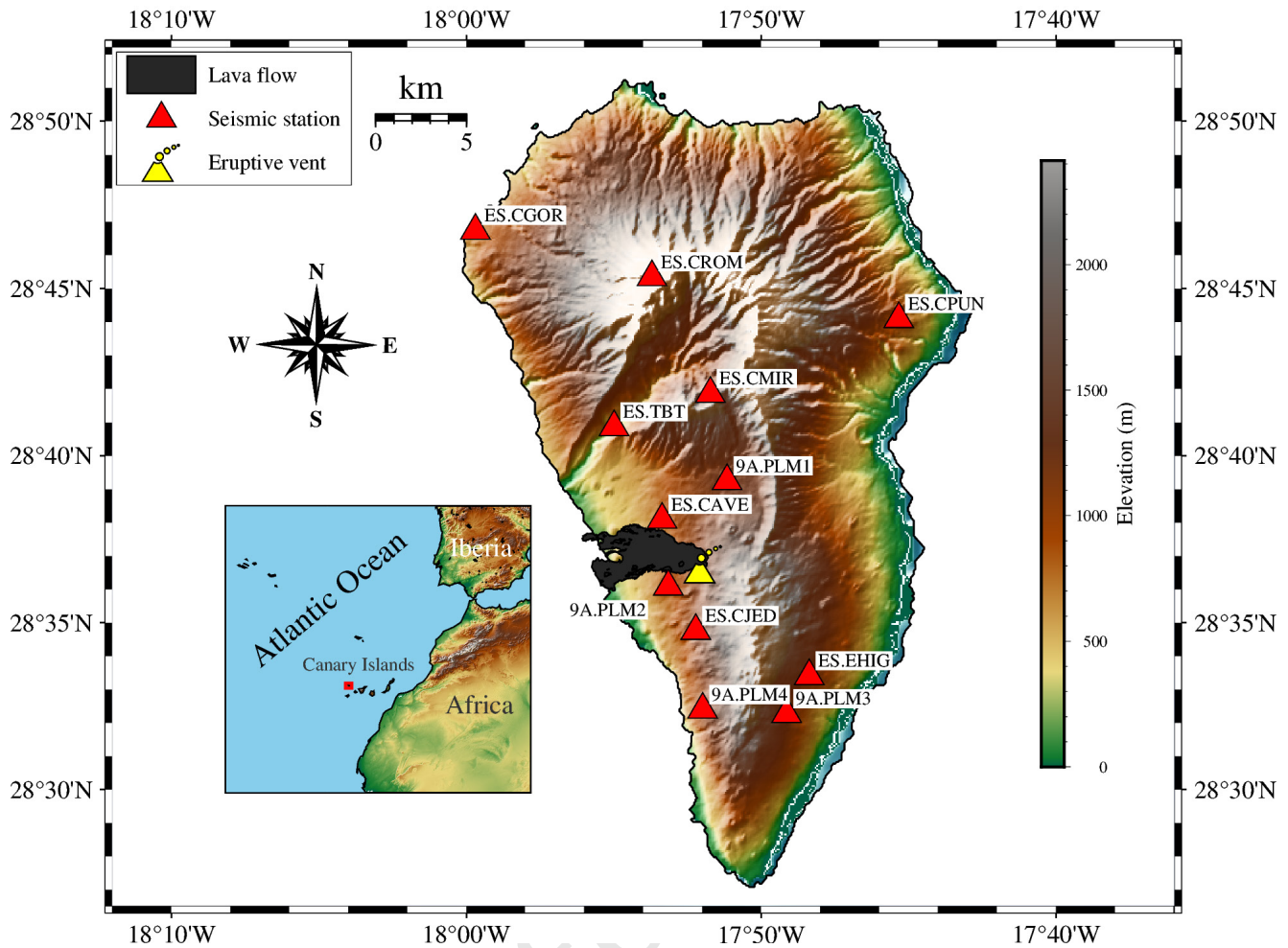


Figure 1: Location (inset) and topographic map of La Palma Island, Canary Islands archipelago, Spain. The map displays seismic stations (red triangles) that were operational during all or part of the 2021 eruption and were utilized to analyze co-eruptive seismicity [Del Fresno et al. 2023]. The lava flow is plotted accordingly to the [Copernicus Emergency Management Service 2021].

In this study we develop and validate a workflow to reconstruct fault geometry using weak volcano-tectonic seismicity. Applying it to La Palma, we investigate how fault activation reflects tectonic and magmatic stress perturbations and track the spatiotemporal evolution of seismicity. The approach is generalizable to both tectonic and volcanic settings and can support seismic hazard assessment.

1.2 La Palma sequence

La Palma is located at the Northeastern part of the Canary Islands (Figure 1) and it is the second youngest island of the volcano origin archipelago [Carracedo et al. 2001].

La Palma experienced mainly volcano-tectonic (VT) seismicity and was rather active in the pre-instrumentation era, with at least 6 historical eruptions [Longpré and Felpeto 2021]. In the 5 years preceding the 2021 eruption, seismicity rates have been low and characterized by a number of weak seismic swarms within 15 - 35 km depth [Del Fresno et al. 2023]. The 2021 sequence represents the island's most significant recorded seismic unrest. The seismic unrest accompanying the 2021 eruption started on September 11 and lasted more than 3 months. The pre-eruptive phase included two stages [Del Fresno et al. 2023].

80 The first one, from October 2017 to August 2021, can be described as the system destabilization. In this phase, the seismicity mostly occurred in the form of swarm episodes in the uppermost mantle at depths of 20 - 30 km, a region which remained almost aseismic during the 2021 eruption. The second stage, from 11 to 19 September 2021, shortly preceding the eruption, concerns the volcano pressurization, when the magma system built excess stress in response to magma accumulation, and shallow dike ascent, accompanied by shallow seismicity at less than 12 km depth [Suarez et al. 2023]. The total volume of the magmatic intrusion has been estimated at 4.6 million m³ [Suarez et al. 2023]. The eruption started on September 19. Over the 85 following 85 days, until December 13, lava covered an area of 12.19 km² [Del Fresno et al. 2023].

The seismicity clustered spatially within two highly active seismogenic volumes, located along the supposed magma ascent path at ~11 km, below the island's summit area, and at ~35 km depth (Figure 2). These dominant clusters, which host 85% of all earthquakes, have been attributed to two magma storage systems, most likely characterized by mushy volumes or distributed magma reservoirs, where the magma is temporarily stored during its ascent to the surface [Del Fresno et al. 2023]. Models linking the geometry of seismically active structures to magma storage and magma transfer can help understand the observed spatial and temporal evolution of the seismo-volcanic seismicity.

Previous studies characterized the primary seismicity patterns including hypocentral locations and moment tensors and provided seismological support for interpreting co-eruptive processes [Del Fresno et al. 2023; Suarez et al. 2023]. Del Fresno et al. 2023 used density based clustering of event pair-wise full waveform cross correlation with the bandpass filter from 6 to 16 Hz and a cross-correlation threshold of 0.7. Despite a similar approach to our first analysis step, several questions remain unanswered. First of all, Del Fresno et al. 2023 noted a discrepancy: spatial and focal mechanism clustering identifies only a few earthquake families at both shallow and deep depths, while waveform similarity analysis reveals many more small-scale families. Another peculiar observation concerned the presence of heterogeneous focal mechanisms at neighboring families, suggesting the presence of strong, localized stress heterogeneities. Although several families have been identified, the geometry of the activated faults and the shape of the magma reservoirs remain poorly constrained.

2 DATA AND METHODS

2.1 Dataset

Our study is based on the seismic catalog provided by Del Fresno et al. 2023 for the 2021 Tajogaite eruption, La Palma island, that includes 8488 relocated earthquakes observed over 3.3 months, beginning with the shallow dike intrusion that preceded the eruption and continuing throughout the eruptive period. The catalog is based on the Spanish National Earthquake bulletin [Instituto Geográfico Nacional 2022]. Relative relocations of event hypocenters were derived by Del Fresno et al. 2023 using HypoDD [Waldhauser and Ellsworth 2000; Waldhauser 2001] with cross-correlation derived differential travel times and a local velocity model [Dañoibeitia 1980]. We focus on the period between September and December 2021. This specific time period includes the seismicity during the last days before the eruption and the following, early eruption phase. Shortly before the eruption, the seismicity migrated from ~8 km depth to the surface along a curved path marked the intrusion of an ascending magma dike, which led to the surface eruption [D'Auria et al. 2022; Suarez et al. 2023; Przeor et al. 2024]. However, this very shallow seismicity was weak in magnitude and lacked moment tensor solutions, thus limiting the possibility of reconstructing

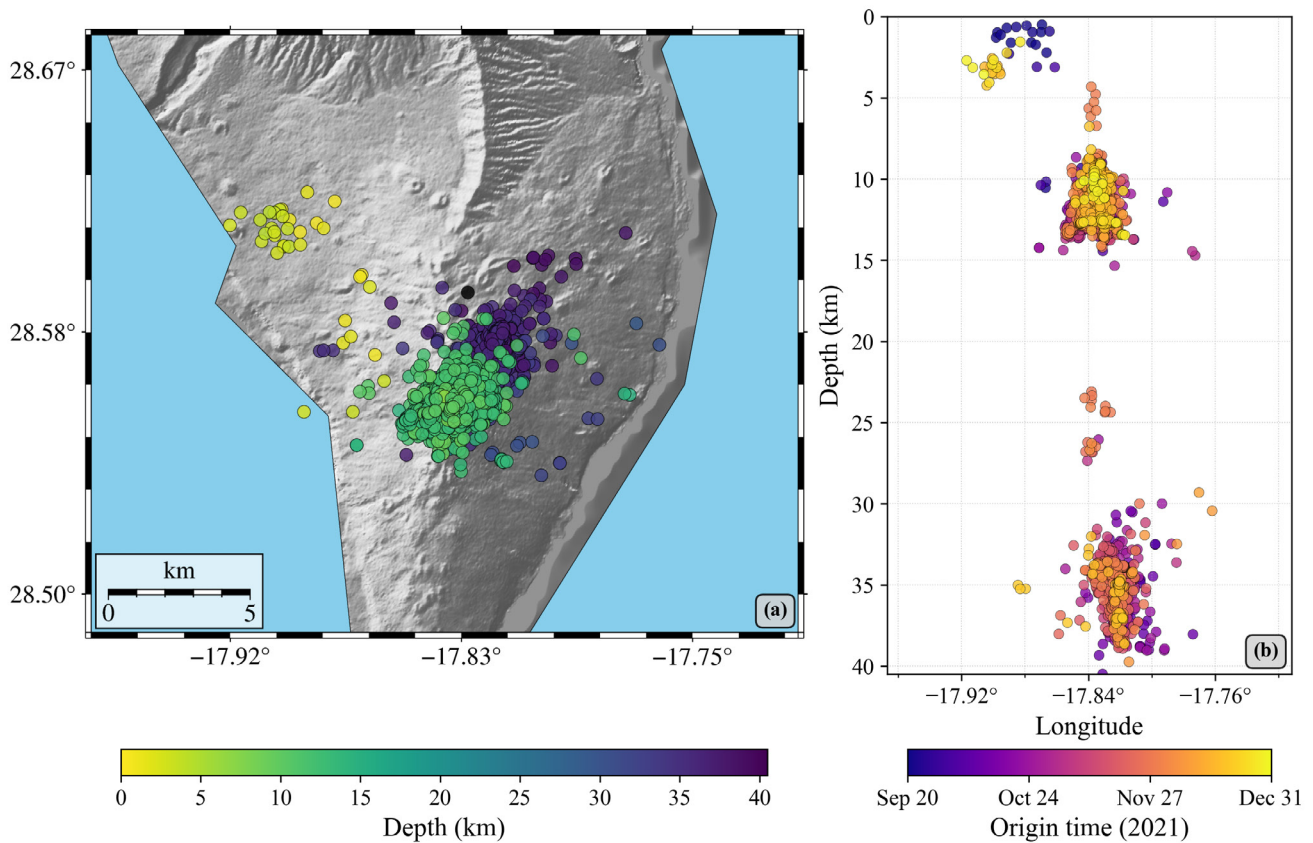


Figure 2: Earthquakes during the 2021 La Palma sequence shown in map view (a) and east-west cross-section (b) highlighting seismicity concentration at a shallow (10-14 km depth) and a deep cluster (33-39 km depth).

fault geometries along the dike path. During the analyzed time period the largest earthquakes, reaching magnitude M_L 4.2, occurred at larger depths. The spatial distribution of such deeper seismicity marks a discontinuous magma path (Fig. 2), suggesting part of the magma ascent was aseismic. This is most pronounced at depths between ~ 15 and ~ 32 km. While this volume was almost aseismic during the eruption, it was repeatedly activated by swarm episodes between 2017 and 2021. These swarms, comprising 800 weak earthquakes with magnitudes ranging from 1.0 to 2.6 [Del Fresno et al. 2023], have been attributed to the process of progressive opening of a magma pathway from the deeper to the shallower reservoirs, creating a region of partial melt, or mushy reservoir [Del Fresno et al. 2023].

The co-eruptive seismicity clustered at two main volumes (Figure 2): a shallower one, located between ~ 10 and ~ 14 km, and a deeper one between ~ 33 and ~ 39 km depth [Del Fresno et al. 2023]. It is believed that these two clusters mark the location of two intermediate magmatic reservoirs [Del Fresno et al. 2023], where magma may be temporarily stored while propagating toward the surface. The deeper cluster dataset contains 1054 events, with 81 of them having moment tensor solutions. The shallow cluster dataset is much more populated, with 6142 events, including 72 with moment tensor solutions. Overall the complex, spatiotemporal evolution of the seismicity suggests a complex geometry of the magma reservoir and the path of magmatic intrusions, providing snapshots of the complex plumbing system over ~ 40 km depths at different stages of volcanic development described in detail within the discussion. Del Fresno et al. 2023 identified four spatial clusters at both the deep and the shallow cluster based on their focal mechanism.

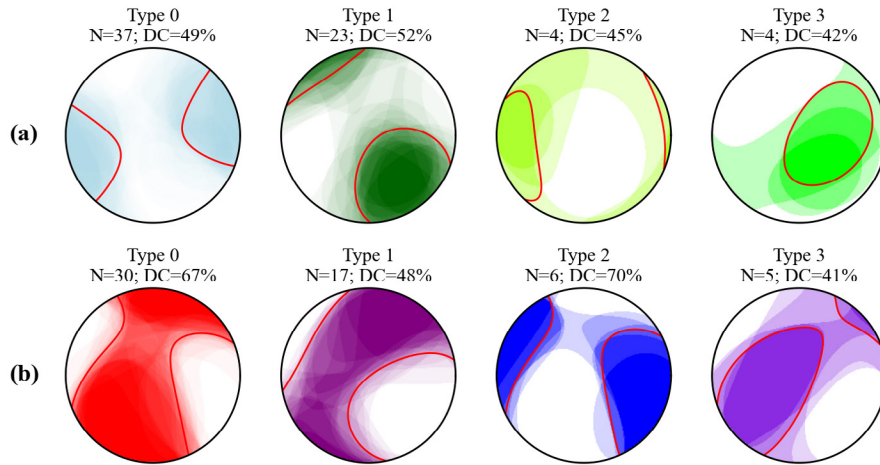


Figure 3: Fuzzy moment tensor representations for the moment tensor types identified at the shallow (a) and deep (b) clusters in Del Fresno et al. 2023. Fuzzy moment tensors show overlay of deviatoric moment tensor solutions pertaining to a moment tensor type. The most representative moment tensor is shown using a red line; above each focal sphere, the number of overlay moment tensor solutions and mean double couple component percentage are reported. A similar figure, showing the overlay of double couple components is provided as Suppl. Fig. 1.

At the shallow cluster, moment tensors show variable mechanisms, with a majority of strike-slip to oblique DC components (Figure 3a). Non-DC components are present, including CLVD (compensated linear vector dipoles) and isotropic components with different polarities, but scattered and showing large uncertainties. Moment tensors have been grouped in four types (Figure 3): the two largest (Type 0 and 1) show different DC components, characterized by strike-slip mechanisms with pressure and tension axes oriented NNW-SSE and ENE-WSW [Del Fresno et al. 2023].

At the deep cluster, four moment tensor types were found (Figure 3b). Three of them (Types 0, 1, 3) have similar, NW-SE oriented, pressure axes, but different tension axes, so that their mechanisms vary from strike-slip (Type 1), to oblique (Type 0) to reverse (Type 3). The fourth type (Type 2) is notably different, with focal mechanisms almost reversed to those of Type 0 (Figure 3). Non-DC components are less scattered at the deep cluster, compared to the shallow one, showing that also the non-DC part has a reversed polarity: for Type 0 this is consistent with a negative, closing tensile crack source, and for Type 2 with an opening crack with the same orientation.

Hereafter, the terms *shallow* and *deep spatial clusters* denote seismicity at ~10–14 km and ~33–39 km depth, respectively, whereas (*earthquake/event*) *families* refer to waveform similarity-based subclusters within each cluster.

2.2 Methods

We design and apply a multi-stage approach to gain insight into activated fault structures at depth. The first step corresponds to a waveform-based clustering of the seismic activity. Next (step 2) we optimize and choose the frequency band and main waveform based DBSCAN parameters: ϵ and N_{min} [Ester et al. 1996]. ϵ is the maximum distance between two points to be connected and N_{min} is the minimum number of connections for a point to be considered a core-point, i.e. to form a dense volume. Finally, we perform an active structure analysis based on probabilistic PCA analysis (step 3) and the last step is the analysis of the obtained fault planes and their comparison with the moment tensor derived ones (step 4). The whole

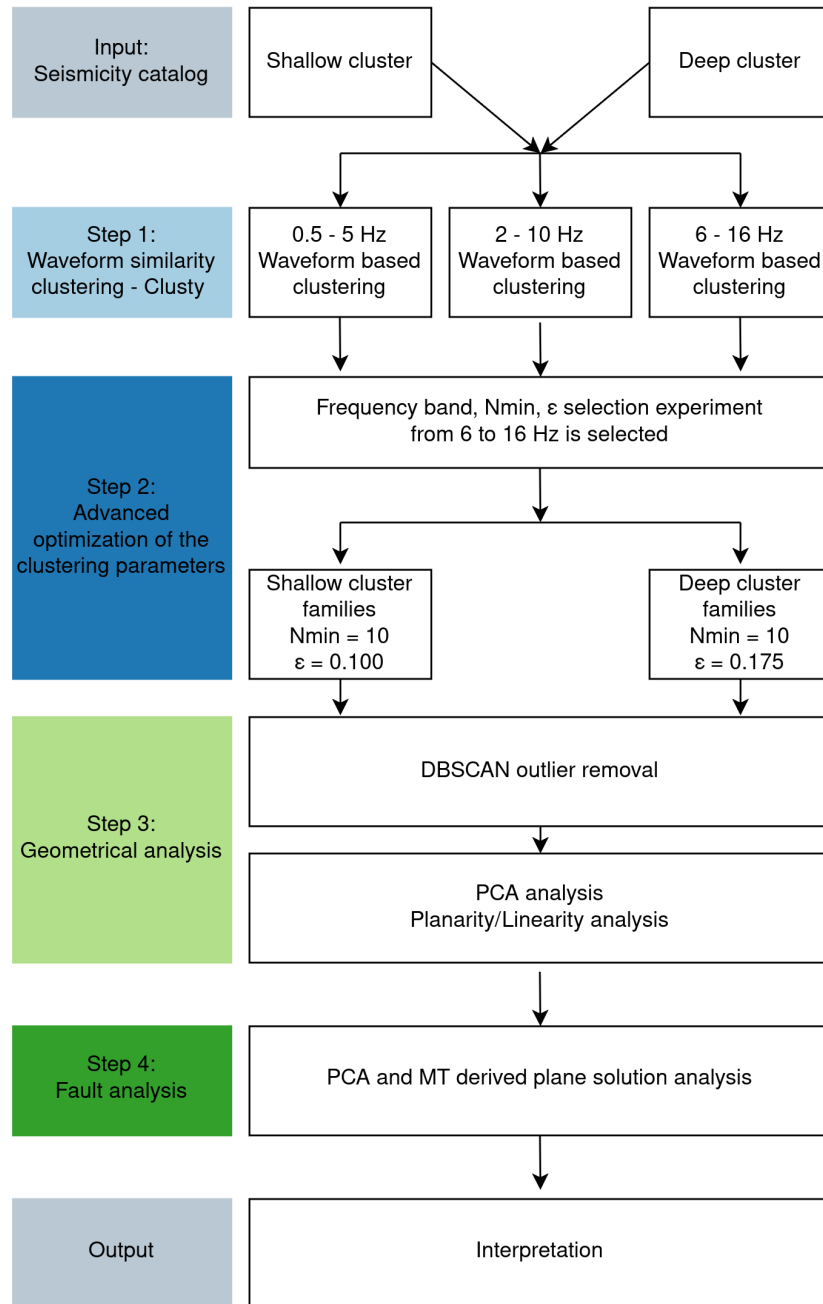


Figure 4: Experiment workflow covering all steps from input seismicity catalogs to the interpretation of derived fault planes.

experiment workflow is shown in Figure 4. From a methodological perspective, the new approach builds on Clusty [Petersen et al. 2021] for the clustering (steps 1-2), but now includes the newly developed structure imaging (steps 3-4), extending the workflow (Figure 4) towards reliable, bootstrap-based fault plane fitting incorporating the information of MT inversion results.

2.2.1 Waveform similarity clustering - and selection of clustering parameters

Out of the many available clustering algorithms [Vijay et al. 2025], DBSCAN [Ester et al. 1996] is chosen because of two major advantages: (1) it offers a robust handling of noise and outliers and (2) it relies on density-based connectivity and thus performs a transitive clustering. Indeed, DBSCAN effectively identifies and treats noise in large seismological catalogs, such as background seismicity, poorly located earthquakes or even false detections, by marking them as unclustered events.

This allows for focused analysis of meaningful event families without manual filtering, aligning with the goal of isolating seismic structures or repeating earthquake families. Furthermore, DBSCAN's ability to link earthquakes through intermediate neighbors enables the identification of irregularly shaped earthquake families, which may sample segmented faults or fracture zones. This transitivity property of clustering is well-suited for reconstructing complex fault structures by connecting distant but density-connected events, tracking extended fault segments. The performance of density based clustering is controlled by two main parameters: ϵ and N_{min} . All points reachable (distance less than ϵ) from a core point will be considered border points but only those that have N_{min} neighbors are considered core points in order to elongate the family.

DBSCAN has often been used in two main ways: clustering events by spatial location [Ansari et al. 2009; Cesca 2020; Piegari et al. 2022] or by waveform similarity [Petersen et al. 2021]. In the first case, earthquakes are grouped based on their epicentral or hypocentral coordinates to identify seismologically active geographical regions or earth volumes. This approach is useful e.g. for detecting spatial clusters, such as aftershock zones or fault segments, and is based on Euclidean distances between earthquake locations. In this case, the ϵ parameter represents a spatial distance threshold. In waveform-based clustering, the procedure does not operate in source parameter domains, but rather use a pairwise distance matrix derived from earthquake waveform features—typically using cross-correlation, spectral similarity, or dynamic time warping. Here, ϵ refers to a waveform similarity threshold. This method is capable of identifying repeating earthquakes and similar source processes without precise event locations, accounting for large location errors. In this study, we apply the Clustly software [Petersen et al. 2021] which was developed to implement this approach; there, the waveform similarity is actually computed using simultaneously multiple stations and/or components.

Clustly allows for testing variable ranges for the ϵ and N_{min} parameters. We perform the clustering for ϵ between 0.05 and 0.30 and N_{min} between 5 and 100. In addition, we test here several different bandpass filters (from 0.5 to 5 Hz; from 2 to 10 Hz and from 6 to 16 Hz) in order to understand the connectivity among events and sub-structures. Combining or comparing clustering results obtained from different frequency ranges helps to include events across a larger magnitude range, resulting in different corner frequencies, frequency contents and thus experiencing variable degrees of attenuation and scattering [Petersen et al. 2021]. Cross-correlation-based similarity values for each event pair were derived on all three-component seismometers, then the three components were combined using an equal weighting of $\frac{1}{3}$. Next, all stations were combined using a trimmed mean value of 0.6 for the shallow and 0.7 for the deep clusters, removing the worst 60 and 70 % (respectfully for the shallow and deep clusters) of similarity values while requiring a minimum of 2 stations to enter the clustering stage [Petersen et al. 2021]. While a larger number of stations is beneficial, the high noise conditions during the eruptions resulted in this rather small minimum number of stations to be used for clustering. The minimal required cross-correlation similarity value for an event pair to enter the clustering procedure was kept consistently at 0.7. This was mostly done in order to overcome the poor SNR (signal-to-noise ratio) not requiring an additional SNR threshold. Overall 13 stations were used from 2 networks. ES: CADE, CAVE, CGOR, CJED, CMIR, CPUN, CROM, EHIG, TBT [Instituto Geografico Nacional, Spain 1999] and temporary 9A: PLM1, PLM2, PLM3, PLM4 [Walter et al. 2021] for both shallow and deep clusters. We used both P and S waves in the windows of 2 seconds (from t_P-1 s to t_P+1 s) and 3 seconds (from t_S-1 s to t_S+2 s) windows, respectively, for P and S waves

with no SNR threshold, based on P and S arrival times (t_P , t_S). The cross-correlation result is divided by the product of the Euclidean norms of both input signals, scaling the coefficients uniformly.

2.2.2 Geometrical analysis

The next part leverages the spatial distribution of the waveform-based families to reconstruct fault segments in three dimensions. By treating each family centroid as a point of slip release, we fit planar and non-planar surfaces that capture the underlying fault geometry. This reconstruction allows us to map previously unrecognized fault strands. Incorporating the information provided by moment tensors, we further estimate slip vectors for individual families, and evaluate the connectivity between adjacent slip patches.

After assigning events to families based on their waveform similarity, we assess the spatial distribution of their hypocenters. In the presence of heterogeneous location uncertainties due to challenging noise conditions beneath the active volcano, the hypocenters of the clustered earthquakes may not always be confined within compact seismogenic volumes. The presence of outliers in the spatial distribution may hinder the accuracy of fault reconstruction. Therefore, we implement a procedure to detect and filter those outliers. We use a spatial DBSCAN method implemented in scikit-learn python library [Buitinck et al. 2013] to find core events, which are highly connected to the cluster, and then use their spatial distribution to remove outliers. Specifically, outliers are identified as those hypocenters located outside a distance for each axis of one standard deviation in the standardized space. The outlier removal step is necessary if location uncertainties are similar or larger than the event family size: in those cases, the approach allows to consistently filter outliers, while maintaining the originally obtained family shape.

We end up with 1269 clustered events for the shallow cluster and 402 for the deep one that contained 30.3% and 24.2% of seismic moment respectively. For both the deep and shallow cluster families we used $N_{min} = 5$ for the outlier removal and this resulted in 290 (22.9%) and 100 (24.9%) events removed, respectively, for shallow and deep clusters. The experiment is very sensitive to the outlier removal and therefore we used ϵ equal to one standard deviation in the standardized space, which preserves the geometry of the family. Consequently, only spatially consistent events are later used for the estimation of the fault geometry. Additional discussion about the outlier removal is provided in the section Section 4.1. Overviews of removed events are provided in Suppl. Fig. 2 and Suppl. Fig. 3.

Principal Component Analysis (PCA) is an effective, validated approach to infer the orientation of a fault plane from the 3D spatial distribution of earthquake hypocenters [Ocaña et al. 2008; Roden et al. 2015; Truttmann et al. 2023]. Therefore, after outlier removal, the PCA is applied to the 3D spatial coordinates of the earthquakes within each family: PCA identifies the directions of maximum variance among these points by computing the orthogonal axes, known as the principal components. The third principal component (the one with the smallest variance) is assumed to be the normal vector to the best-fitting plane for the family, whose strike and dip can then be derived by trigonometric transformations. Hypocenters may align along planar structures corresponding e.g. to a fault or fault segment. To proof such hypothesis, a planarity coefficient (from here on referred to as φ) is calculated as $\varphi = \frac{\lambda_2 - \lambda_3}{\lambda_1}$, where λ_1 , λ_2 , λ_3 are the eigenvalues [Weinmann et al. 2013]. In the context of volcano seismicity, seismicity may also organize into linear families, e.g. along conduits, propagation of narrow cracks and dikes, or shear faulting along narrow, confined fracture zones. Therefore, a linearity coefficient $\mathcal{L}$ is also calculated,

as $\mathcal{L} = \frac{\lambda_1 - \lambda_2}{\lambda_1}$ [Weinmann et al. 2013]. For linear clusters the geometry is dominated by a single elongation axis rather than a planar distribution. In such cases, the first principal component corresponding to the direction of maximum variance represents the elongation vector of the clustered events trend. Finally, we calculate the ratio of $\frac{\varphi}{\mathcal{L}}$ and treat it as a criterion to decide the family geometry state: planar or linear. Since both φ and $\mathcal{L}$ represent the amount of planarity and linearity from 0 to 1, their ratio shows the dominant geometry of the event family. Values above 1 represent planar families as the planarity dominates over the linearity, and values below 1 linear families. In conclusion, in this second step we use only geometric data-driven information, based on the waveform similarity clustering, to estimate the geometry and orientation of seismogenic faults and volumes.

Even after the removal of outliers, the fault reconstruction procedure may still be affected by the hypocentral location uncertainties. We use a bootstrap approach to quantify the uncertainty of the inferred plane orientation: the family is resampled 1000 times with replacement, and PCA is applied to each resampled dataset to extract strike and dip values. The resulting distributions of strike and dip are then used to compute standard deviations and confidence intervals (e.g., 95% CI), providing statistical bounds on the estimated fault plane orientation. This procedure also hardens the outlier removal. If the family location is unstable, a bootstrap approach, while reconstructing the PCA, will yield large uncertainties and results will not be interpreted. Since the original catalog lacked event uncertainties [Del Fresno et al. 2023], these were not used in the experiment. Therefore, the outlier removal and bootstrapping are very important steps in order to achieve interpretable results.

2.2.3 Fault analysis

The spatial distribution of the hypocenters and the orientation of fitted planes are used to resolve the ambiguity between fault and auxiliary plane of reported moment tensor solutions for the largest earthquakes [Del Fresno et al. 2023]. For this purpose, whenever we have more than one moment tensor solution per family, we extract a representative moment tensor, which is the one minimizing the cumulative moment tensor distance, obtained as the sum of pairwise cosine distances in normalized moment-tensor space to the set of available moment tensors [Cesca 2020]. Ideally one of the two possible fault planes of the moment tensor should have a similar orientation (strike and dip) as the plane derived by the PCA analysis: this would then be the moment tensor fault plane, and the other the auxiliary plane. As a result of our analysis we report the dihedral angle between moment tensor fault plane and PCA plane. The coherent orientation of these two planes can be assessed in the frame of orientation uncertainties.

3 RESULTS

3.1 Seismicity clustering

Performing the waveform similarity clustering revealed a systematic dependence of the number of detected event families on the frequency band of the applied band-pass filter (Figure 5). In both the shallow and deep event datasets, higher-frequency filters resulted in a larger number of families, whereas broader or lower-frequency filters produced fewer families. Results are illustrated for three frequency ranges (0.5-5 Hz, 2-10 Hz, 6-16 Hz), both for the deep and the shallow cluster (Figure 5, Suppl. Fig. 4). These frequencies span a relatively broad range. At lower frequencies, the analysis is limited by seismic noise

contamination, both related to eruption induced and oceanic microseismic noise. At higher frequencies, it is limited by the corner frequencies of the largest events, and waveform differences may arise from differences e.g. in the source time function, which are beyond our target. The flow diagram (Figure 5, Suppl. Fig. 4) shows a systematic increase of the number of families with increasing frequency. We finally selected the 6-16 Hz frequency band, as it resolves a large number of families and a representative number of earthquakes. Lower frequency bands tend to merge families together, potentially hindering the resolution of single structures. On the other side, higher frequencies result in smaller families. Furthermore, these frequency ranges may exceed the corner frequency of the largest events, for which a moment tensor solution is available: this poses the risk that these earthquakes are considered unclustered and their moment tensors cannot be used to constrain the plane geometry. Suppl. Fig. 5 illustrates how clustering results change, for the same frequency bands, when perturbing the DBSCAN parameters.

After selecting the frequency band 6-16 Hz based on the aim to study a larger number of well-populated event families, we choose $N_{min}=10$ and two ϵ values (0.175 and 0.100) for the deep and shallow clusters, respectively, as an optimal selection for the connectivity threshold (ϵ) and minimal number of neighbors (N_{min}), based on the number of clusters and the silhouette scores plot (Suppl. Fig. 6; Rousseeuw 1987). The selection of clustering parameters depends on the purpose of the clustering. Low ϵ values, corresponding to small distances in the waveform similarity metric, ensure clustering only earthquakes with highly similar waveforms, thus with highly similar locations and mechanisms. However, under noisy conditions as during volcanic activity, a too low ϵ value results in small numbers of populated families with only few events, which cannot be analyzed further with respect to hypocenter distributions mapping activated fault segments. Therefore, a set of clustering parameters need to be found that results in a number of families that are sufficiently populated. Conversely, too high ϵ values cannot ensure proper similarity of mechanisms and locations. The parameters chosen here ensure a sufficient number of events in each family and a good agreement of waveforms. The variety of parameters is shown in the Suppl. Fig. 5. ϵ of 0.1 and 0.17 reflect averaged cross-correlations above 0.9 and 0.83, respectively. Given the broad frequency band, this represents a high similarity.

In total, we identify 31 event families within the shallow cluster and 16 event families in the deep cluster (Figure 6, see Suppl. Fig. 7 with full MT solutions instead of DCs). Both shallow and deep clusters contain 6 families with at least one event with a moment tensor solution. In the next step, we refine these results with the outlier removal procedure. We focus on larger event families with moment tensors available in order to compare them both within different families and with results of the geometrical reconstruction.

3.2 Active structure modeling

The PCA analysis produced quantitative estimates of linearity and planarity for each family (Table 1, Table 2), and the bootstrap approach provides uncertainties for the corresponding line and plane orientations. Planar structures are only discussed for those families where the orientation of the plane-normal vector has an uncertainty below 10° . For those resolved families the planarity coefficient ranged from 0.08 to 0.81 at the shallow cluster and 0.27 to 0.64 at the deep one; planarity/linearity ratios span from 0.09 to 2.36 at the shallow cluster and 0.19 to 1.96 at the deep one. For families with a planar geometry,

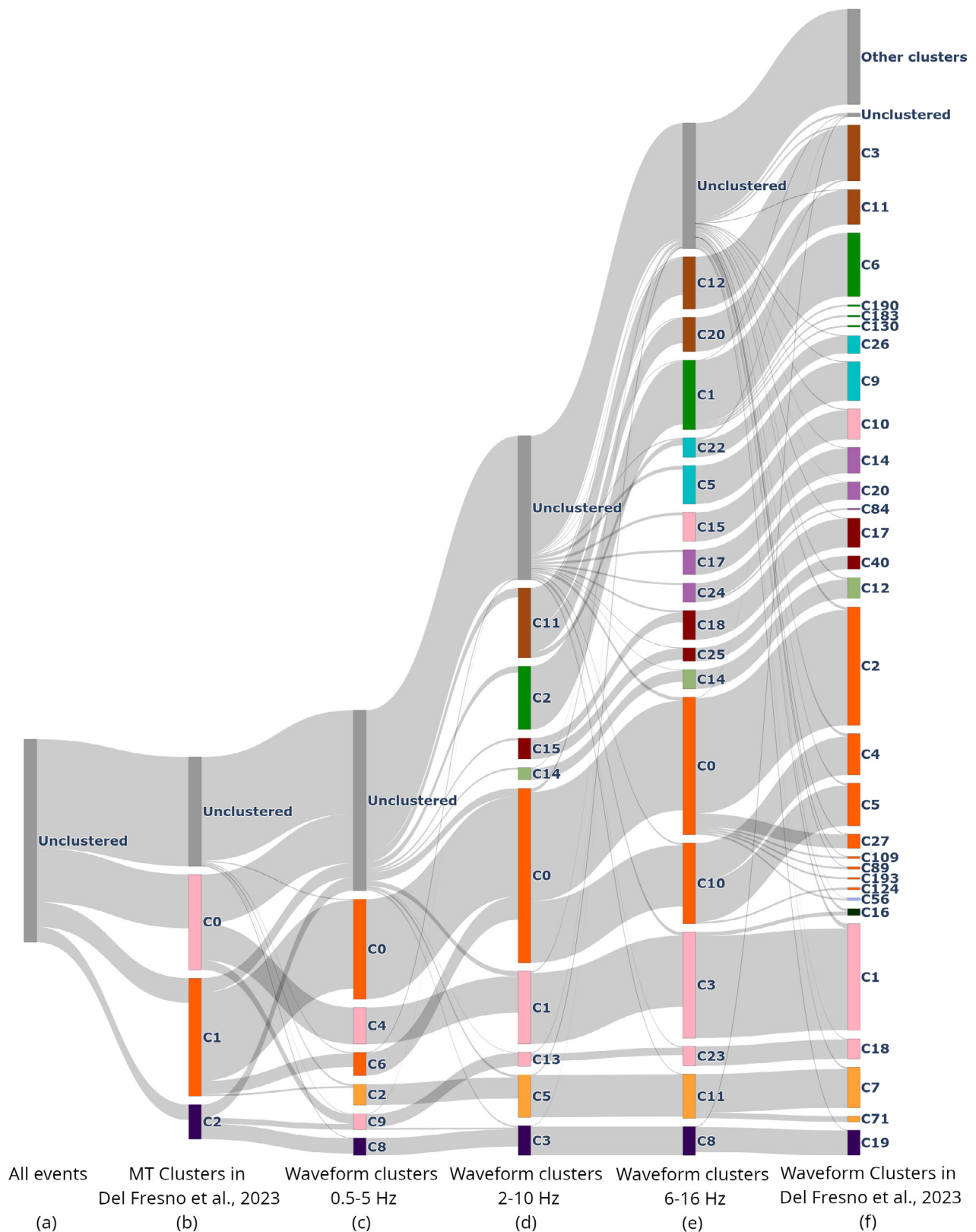


Figure 5: Flow diagram comparing the results of different clustering approaches for the deep seismicity cluster. Steps: (a) Unclustered full catalog; (b) Double couple-based clustering results [Del Fresno et al. 2023]; (c) Waveform-based clustering, Bandpass 0.5-5 Hz; (d) Bandpass 2-10 Hz; (e) Bandpass 6-16 Hz; (f) Waveform-based clustering results obtained in Del Fresno et al. 2023 using the bandpass filter from 6 to 16 Hz. Colors are retained in between the different clustering results if more than 50% of events are inherited. To enhance visual interpretability, the unclustered segment is scaled down by a factor of 10 relative to the clustered segments.

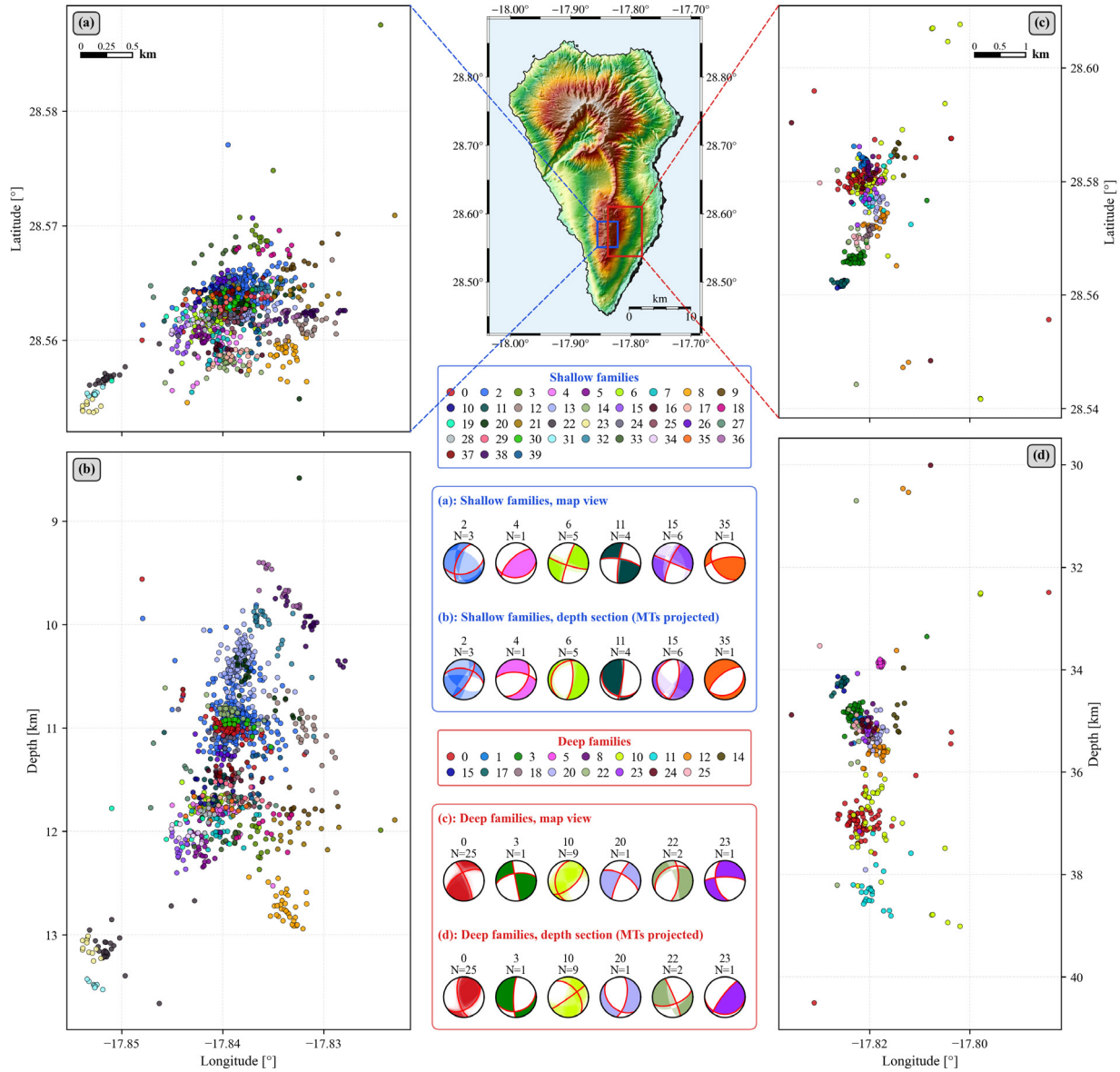


Figure 6: Spatial distribution of waveform similarity based event families before the outlier removal in map views and depth sections for the shallow (a, b) and deep (c, d) clusters. Colors represent the event families and match the color of the *fuzzy* moment tensor (= overlay of all moment tensors in the family, red lines mark representative MT) shown in the central panel; N is the number of moment tensors per family, double-couple components are shown. The upper central inset marks the locations of map views (a) and (c) on La Palma. Topography color same as in Figure 1.

PCA strike and dip values are reported together with bootstrap-derived uncertainties (Table 1, Table 2); in most cases, the first two eigenvalues accounted for the majority of the spatial variance, yielding well-constrained plane orientations. In families organized along linear structures, we report the azimuth (horizontal angle from north) and plunge (inclination angle from the vertical). We also assess the coherence among planar (and linear) structures and the nodal planes of the representative moment tensors, reporting the minimum dihedral angle between the PCA plane (or the PCA vector, for linear family) and the two focal planes from the moment tensor. With one exception, small dihedral angles are found ranging from 8° to 29° , pointing at generally coherent results of moment tensor and PCA analyses, which can then be jointly interpreted to map the geometry of active structures. In one exception, the dihedral angle of family 10 reaches 41° . In the case of this family increased uncertainties of both, PCA and MT strike angles already point at less resolution. Furthermore, the family geometry is linear, not planar, additionally indicating that a (fault) plane is not a good representation.

Because the original MT dataset by Del Fresno et al. 2023 lacked solutions for family 12 of the deep cluster, we complemented previous results with a new moment tensor inversion for the largest event in this family. The moment tensor inversion was performed using Grond [Heimann et al. 2018] and the same inversion setup as discussed in [Del Fresno et al. 2023]. The resulting fuzzy moment tensor is shown in the Suppl. Fig. 8.

Figure 7 illustrates the results of PCA along with MTs for the deep cluster. The figure panels (Figure 7a,b) show two perpendicular vertical cross-sections, one oriented in NE-SW and one in SE-NW direction: these orientations were chosen on the base of results in Table 2, as they allow us to observe the resolved planar features roughly from side (Figure 7a) or coplanar (Figure 7b) views. A similar figure for the shallow cluster figure is shown in Suppl. Fig. 9. A 3-dimensional visualization with all event families and resulting planes including the linear vectors is provided as an HTML-figure in the supplementary Zenodo repository [Sidorov-Biryukov et al. 2026].

4 DISCUSSION

4.1 Parameter sensitivity and stability of the results

4.1.1 General comments

The workflow illustrated in Figure 4 involved several trials to select the appropriate clustering parameters and frequency bands. In any clustering approach, the settings to define which data belong to a cluster and which data is considered noise needs to be carefully addressed according to the goal of the study and reflecting uncertainty in subsequent interpretations. In this section, we discuss our reasoning for tuning the clustering parameters, providing some indications for future applications of this approach.

Considering that the final objective in our study is to resolve individual seismogenic structures such as fault segments through PCA analysis of the spatial distribution of earthquake hypocenters, we propose the following criteria:

- It is desired that the clustering assigns a significant number of earthquakes in each family, also considering that the outlier filtering procedure can reduce the family size. A sufficient number of event hypocenters is required for a reliable reconstruction of the fault geometry.

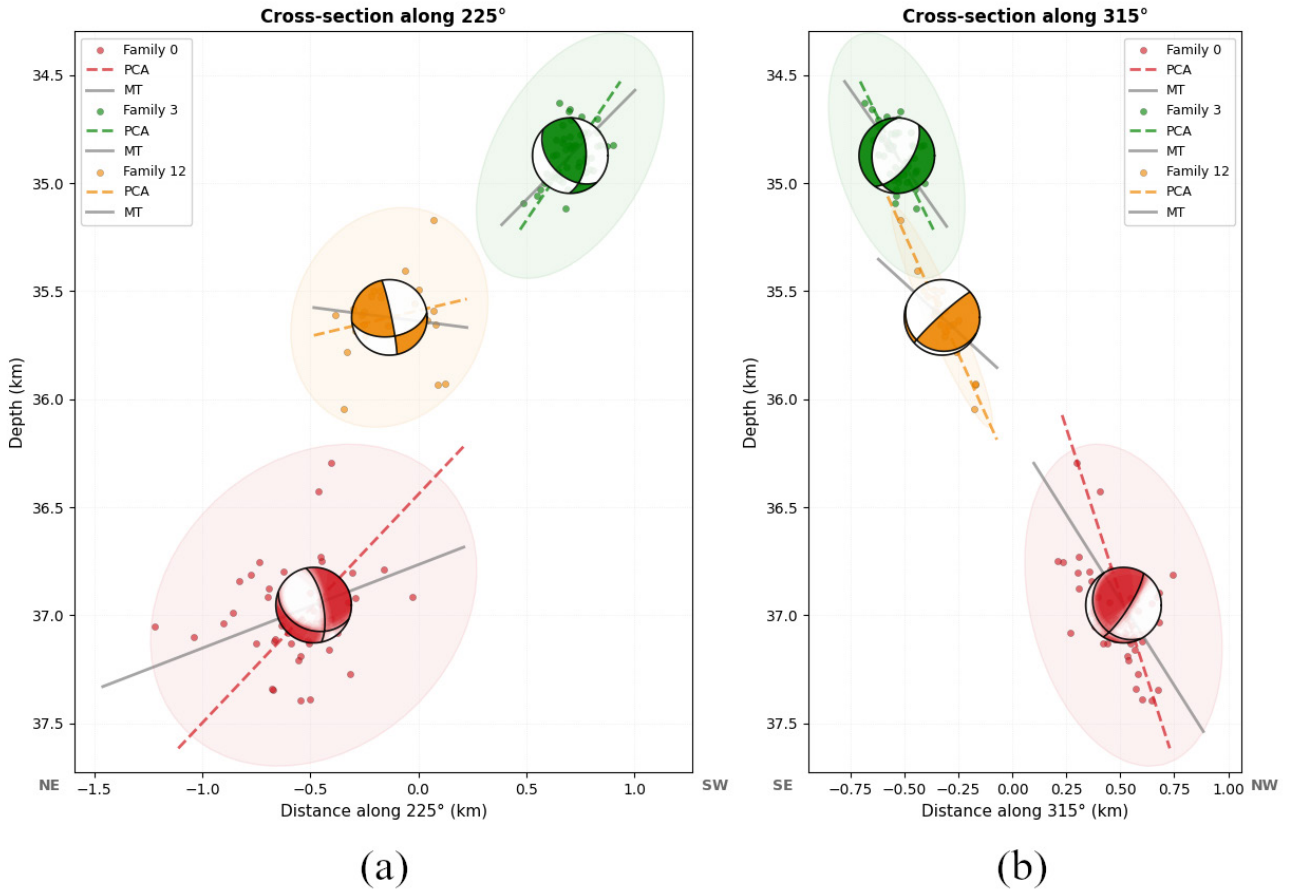


Figure 7: Cross-section plot for the deep cluster featuring event families 0, 3, and 12; (a) along a strike of 225° (NE-SW) and (b) perpendicular to it, 315° (SE-NW). Ellipses show the family extent in the cross-section if the whole family (after outlier removal) is considered as seismicity cloud. Only the double couple component is plotted for the moment tensor.

- Resolving individual structures requires distinguishing families associated with neighboring structures, which implies that the similarity among earthquakes pertaining to a family should be substantially larger than the average similarity among different families.

These two criteria balance the need to resolve families that are neither too large, to avoid heterogeneous families involving multiple structures, nor too small, to avoid unreliable fault geometry reconstructions.

4.1.2 Frequency band selection

The first main step of the experiment concerns selecting the frequency band. A proper selection should take into account several aspects, such as the network layout, the azimuthal coverage of the seismogenic region, and the range of source depths and magnitudes. A general rule is to choose a frequency band where the signal-to-noise ratio is large, which is linked to the range of magnitudes of the target seismicity, the range of source-received distances, and the characteristics of the seismic noise. In the case of our dataset, at too low frequencies the SNR suffers from high oceanic microseisms as well as noise related to the volcanic eruption processes. At too high frequencies, scattering of waves and high attenuation lead to low SNR and low cross-correlation values. These aspects need to be balanced.

We test a number of different frequency bands that produce a sufficient SNR (Figure 5 and Suppl. Fig. 5). Higher frequencies tend to produce a larger number of families, with lower numbers of events in these families, and to reduce the number of unclustered events. Thus, higher frequencies can reconstruct small, homogeneous families of very similar events. Conversely, lower frequencies can resolve few, larger families, which share general features, e.g. a similar radiation pattern, but not necessarily small-scale similarities, with e.g. the risk that seismicity on neighboring structures is merged within a single family. Indeed, our tests over a range of frequencies bridge the previous clustering results by Del Fresno et al. 2023. At the lowest tested frequency band, we find results that are comparable to those previously obtained, resolving broad spatial clusters with homogeneous focal mechanisms. At the higher frequency end, our results resemble those by Del Fresno et al. 2023 based on waveform correlation. In between, Figure 5 shows a progressive evolution in the number and configuration of the resolved families, where we finally chose the frequency band 6-16 Hz to best resolve and populate the family inside a cluster. This frequency band also corresponds to the highest spectral density on multiple components (Suppl. Fig. 10). Waveform similarity for this band is shown in Suppl. Fig. 11.

4.1.3 ϵ and N_{min} selection

ϵ and N_{min} are the clustering parameters that define which events are connected to a cluster and which events should be considered noise. While some reasoning can be done independently for each of the two parameters, the clustering performance depends on their combination, as illustrated in Suppl. Fig. 5. The selection of N_{min} is the least concerning, as this parameter defines the minimal amount of densely connected events of a family. Using too large N_{min} values will decrease the number of identified families, eventually eliminating them all, while using very small values may result in a large number of small families (Suppl. Fig. 5). Therefore, our suggestion is to select the value of N_{min} first, depending on the specific task and considering the general criteria defined above.

Regarding the selection of ϵ , Suppl. Fig. 5. shows that increasing ϵ generally results in larger (less homogeneous) families. While it might be tempting to obtain larger families and eventually improve the fault geometry reconstruction, such a choice risks to include heterogeneous events in the same families which are associated with multiple structures. The concept is illustrated in Suppl. Fig. 6. Increasing the ϵ results in a drop in the Silhouette score [Rousseeuw 1987], which means that earthquakes within one cluster are no longer significantly more similar compared to those in other clusters. Previous research suggested looking for abrupt changes on the plot illustrated in Suppl. Fig. 6 that could indicate an optimal choice [Petersen et al. 2021]. In our selection, we followed this advice and adopted different ϵ values for the shallow and deep clusters.

4.1.4 Outlier removal and stability

The stability of the results can be affected by the selection of parameters at each step of our procedure. For example, the frequency band experiment illustrated in Figure 5 and Suppl. Fig. 5 shows the effect of different bandpass filters. A crucial, final step before the interpretation is thus the removal of outlier events. Hypocentral outliers can be present, reflecting location errors of single events. A high waveform similarity proves a close location, as the recorded waveforms reflect path effects. Therefore, outliers significantly far from the event family are likely to result from location errors. As event families are based on waveform similarity alone, no geometrical constraints are used in any earlier step. The removal of a few (in some cases even

one) events can substantially improve the fault reconstruction/mapping step and lead to a different, more stable interpretation. For an example, see Suppl. Fig. 2 and Suppl. Fig. 3 for both the shallow and deep clusters, respectively. There, a few removed outliers could have resulted in a substantially different structure geometry. In our case, we aimed at preserving as many events as possible and avoiding distorting the geometry. We finally ended up with the proposed DBSCAN hypocenter-clustering approach, with ϵ equal to one standard deviation in the standardized space. Only a few outlier events are removed (Suppl. Fig. 2,3), while the standardizing space allows us to avoid using a custom ϵ . A potential alternative approach could be to calculate the mean inter-event distance and ϵ for each family depending on its size. However, such an approach could fail for outliers located far away from a small cluster, which might not be identified and would hinder the proper structure reconstruction. Aware of these challenges, we limited our interpretation to the most robustly resolved structures, after applying a bootstrap test and testing for result stability. This additional requirement resulted in a small number of families (3, both in the shallow and deep clusters) being discussed from the geometrical point of view. Other families are also reported, but their geometries are not equally well resolved. Besides the proposed DBSCAN approach, we also tested alternative outlier removals, including, e.g., Mahalanobis distance [Reprint of: Mahalanobis, P.C. (1936) 2018], Local Outlier Factor [Breunig et al. 2000], and their different combinations. However, these trials either removed too many or too few events.

4.2 From clustering to structure mapping

Previous clustering attempts in La Palma have identified two main separated clusters, although with differences in their inferred depth ranges due to the velocity model used to locate the seismicity [D'Auria et al. 2022; Del Fresno et al. 2023]. Del Fresno et al. 2023 first attempted to resolve sub-cluster structures through spatial clustering, resolving few large families with similar moment tensors, which do not illuminate single seismogenic structures. Using waveform similarity based clustering, they resolved a large number of small size families. Here, by progressively increasing the frequency content from low (0.5–5 Hz) to high (6–16 Hz) frequency bands, we capture different levels of waveform detail and thereby progressively group earthquakes according to an increasing waveform similarity. Our approach successfully bridged the previous clustering results by Del Fresno et al. 2023: indeed, our result for the lowest tested frequency band matches well the original spatial clustering, while the one with the highest frequency band resembles the previous result based on waveform similarity (Figure 3). Optimizing the experiment parameters allowed us to balance the number of resolved families with their average size, providing an optimal setup to investigate the geometry of the responsible seismogenic structures and pushing the interpretation of seismicity for structure imaging well beyond the previous works.

This study illustrates some of the technical challenges in recovering the geometry of active structures from the spatial distribution of (clustered) seismicity. The procedure is very sensitive to outliers: in our case, these mostly concerned unreliable hypocentral locations, including some with large spatial offsets from the majority of events in the cluster, despite a high waveform similarity. Even after removing outliers, resolving the geometry and extent of the seismogenic structure may be difficult. We proposed here a bootstrap-based approach, which is both robust and helpful in quantifying the structure orientation uncertainties.

It is important to point out that the presented application, focusing on an eruptive volcanic environment, involving a complex, pressurized, multi-reservoir plumbing system experiencing magma upflow, constitutes a highly complex and particularly challenging case study. Specifically, the fluid-rock interaction, the interplay among pre-existing and newly developing faults and the spatial and temporal evolution of stress conditions affect the spatiotemporal evolution of seismicity and the activation of different seismogenic structures. In tectonic environments the combined usage of waveform similarity across different frequency bands, fault planes from MT inversions, and precise relocations, may be simpler, offering the opportunity to study fault orientation and segmentation in greater detail. However, even in the case of the Tajogaite volcanic sequence, in presence of weak to moderate volcano-tectonic events and high noise levels, the proposed workflow is able to provide valuable insights into the geometry of active structure of La Palma volcano.

4.3 Spatial and temporal patterns

In the following, we discuss the resolved spatial features and their temporal evolution. We first focus on the deep cluster, and later on the shallower one, as they display two distinct features.

At the deep cluster, most families illuminate quasi-parallel planar structures (Figure 7). They show small, but significant differences in depth. The most active family 0, which remains steadily active over longer time periods, is located at larger depths (~37 km). Shallower families of the deep cluster (~35 km), in contrast, are only active over limited time periods, i.e. family 12 in October 10-23 and family 3 in November 21-23. Taken together, shallower and deeper families illuminate a narrow, steeply oriented volume, deepening to the NW, which extends from ~37 to ~35 km depth. We interpret that such seismicity distribution maps an extended volume influenced by a stress perturbation, which we attribute to a planar magmatic intrusion above a deep reservoir, which would then be located below 37 km. The resolved geometry matches well with the steep, narrow, high V_p/V_s anomaly deepening towards NW that has been imaged by repeated seismic tomography above the deep reservoir, although at shallower depths [Koulakov et al. 2026]. Furthermore, the proposed intrusion scenario, accompanied by a progressive activation of shallower families (see Figure 8), is consistent with fluid inclusions, which have been hypothesized to occur at and above the deep reservoir [Dayton et al. 2023].

At the shallow cluster, the situation is more complex. The distribution of the seismicity at the lowest level during the eruption suggests the shallow reservoir has an elliptical shape of ~3 km x 2 km, elongated in the NE-SW direction (Figure 9). Seismicity starts slightly deeper, likely marking the original location of the reservoir, i.e. at ~13 km depth, and progressively affects shallower sources (Figure 8a). The geometry and progressive upward extent of the seismicity are coherent with progressive faulting, accompanying destabilization processes above a depleting reservoir. Such type of seismicity is expected to occur on newly formed fractures in the early stage of roof failure in response to reservoir depletion [Acocella et al. 2000; Acocella 2007; Holohan et al. 2015; Levy et al. 2018]. Single families are scattered at different depths, but also in different directions, with respect to the reservoir location. They often form linear structures, rather than planar ones. Linear, post-eruptive seismogenic features identified at the shallow cluster (Figure 9) may reflect magma propagation through narrow pathways.

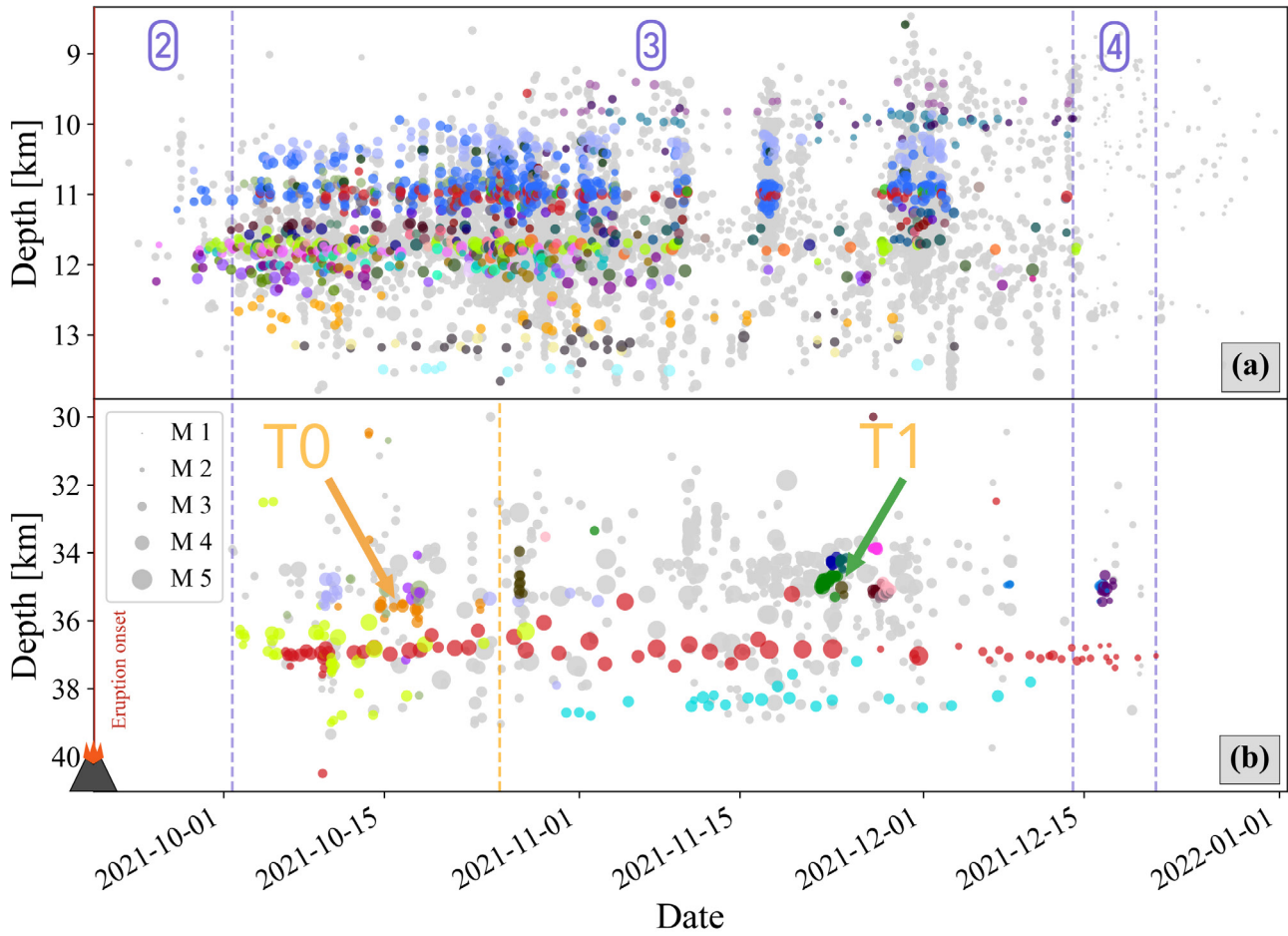


Figure 8: Temporal evolution of seismicity at the shallow (a) and deep (b) cluster showing depth as a function of time. The eruption onset was on September 19, at 14:15 UTC, corresponding to the minimum of the time axis. Circle colors correspond to the earthquake families (as in Figure 6); sizes are proportional to magnitudes. Purple vertical lines and numbers mark the main eruption stages according to [Del Fresno et al. 2023] and discussed in this study; orange ones mark periods of activation of specific families in the deep cluster. (a) [2] marks the beginning of the shallow reservoir drainage, followed by [3], the magma drainage and incomplete refill, and [4] marking the end of the eruption. (b) The line between T0 and T1 divides the time periods with activity in family 3 (dark green) and 12 (orange). Families 3 and 12 are additionally highlighted with an arrow colored using the family color, starting from the times T0 and T1 pointing to the majority of family events.

The temporal evolution of earthquake families in the shallow and deep clusters (Figure 8) highlights different variations in the seismic activity throughout the observational period. At both clusters, the seismicity starts upon the eruption onset within confined depths, but affects progressively larger depth intervals, involving both slightly shallower and deeper volumes. Both shallow and deep clusters were almost inactive before the eruption onset: in the years before the eruption, weak earthquake swarms occurred along the path connecting the two clusters, while shortly before the eruption the seismicity was confined along the path of a shallow dike intrusion from the shallow cluster to the surface [Del Fresno et al. 2023]. At the shallow cluster, the very first earthquakes occur at a depth of ~12 km, while during the late eruption stages they span over a 4 km wide depth interval from ~9.5 to ~13.5 km depth (Figure 8). Beyond general fluctuation of the whole seismicity rate, all families at the shallow cluster remain continuously active. At the deep cluster seismicity starts at ~36–37 km, and later grows up to ~34–39

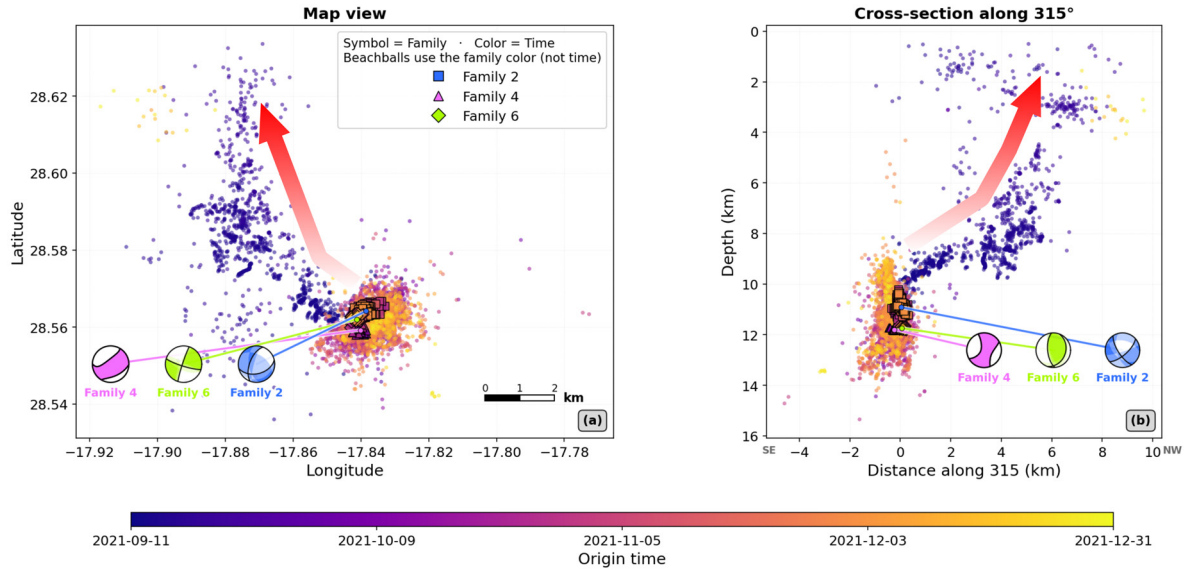


Figure 9: Time evolution plot for the seismicity at the shallow cluster in map view (a) and in depth section (b). Color represents the time evolution from blue to yellow. Blue colors mark the pre-eruption seismicity illuminating the dike propagation, the red arrow sketches the approximate magma path before eruption. After the eruption onset, seismicity is localized in the shallow cluster at 9-14 km depth. Within this cluster, earliest events occur at greater depth and an upward propagation is observed (purple to yellow colors).

km. Some families are only episodically active, with bursts of seismicity lasting hours to a few days. This is mostly seen for the shallower families of the deep cluster (e.g. at ~34-36 km depth), in contrast to the deeper ones, which show relatively steady rates of occurrence along weeks to months. Such cases of increased seismicity rate over short duration periods at ~34-36 km (Figure 8) suggest a combination of stress transients, e.g. in response to discontinuous reservoir pressurization and intermittent upward magma flow, and/or full strain release along seismogenic structures at those depths.

4.4 Magma intrusions interpreted from seismicity

Spatially and temporally localized bursts of seismicity have been modeled and observed at the tip of propagating magma batches or dikes [Belachew et al. 2011; 2013; Passarelli et al. 2015]. There, tensile stresses induced by planar magmatic intrusions can induce the formation of new fractures or trigger seismicity along pre-existing weak structures; because the fluid is exploiting a 2D fracture plane, the resulting hypocenters would occur within a narrow, quasi-planar volume affected by the dike induced stress-perturbation, either organizing within a single fault or multiple cracks. Conversely, magmatic intrusions can introduce compressional stresses on the lateral side of a magmatic intrusion [Roman et al. 2006; Cesca et al. 2023; Olive et al. 2024]. Our observations at the deep cluster are coherent with such a scenario and the process is illustrated for two subsequent time snapshots in Figure 10: T0 and T1 cover the periods of activity of family 12 (orange) and 3 (dark green), respectively, both of them accompanied by sustained activity at the deeper family 0. Seismicity during stage T0 can be attributed to a first stage of magma intrusion, reaching up to ~36 km depth: family 12 would occur above the intrusion tip. Note that moment tensors are here inconsistent with the background tectonics (Figure 10), requiring a local stress perturbation. After these fracturing processes take place, the intrusion can propagate or extend further upward to 35 km, triggering family 3, which is shallower and located at the new tip, while family 12 disappears. Again, moment tensors of family 3 are inconsistent with the regional

stresses and require a stress perturbation. During both phases earthquakes continuously occur in the steadily active family 0. Here, however, moment tensors are reversed to those in families 3 and 12 and in agreement with the tectonic stresses. Overall, the reversed moment tensor of families 3-12 on one side, and the deeper family 0, on the other side, suggest spatiotemporal stress transients introduced by the magma ascent.

Overall, the activation of earthquakes with different focal mechanisms during the eruption likely reflects the interplay between structural and stress heterogeneities at the volcanic plumbing system and their evolution during reservoir destabilization, pressurization and drainage [Del Fresno et al. 2023]. A focal mechanism rotation or reversal, similar to those resolved within the shallow and deep cluster, respectively, has been observed at other volcanic systems [Roman 2004; Roman et al. 2006; Roman and Gardine 2013; Cesca 2020; Roman et al. 2021; Zhan et al. 2022; Cesca et al. 2024], where they were generally attributed to local spatial or spatio-temporal stress heterogeneities, often in relation to magma transfer processes. Opposite faulting involving larger earthquakes, was recently found also at a mid-ocean ridge, where they were explained as the result of stress perturbations due to the intrusion and thickening of a magma dike [Cesca et al. 2023; Olive et al. 2024]. Magma intrusion is a plausible mechanism also for the occurrence of neighboring, opposite faulting at La Palma.

Magma intrusion in the form of a dike has been proposed for the deep cluster [Dayton et al. 2023; Ubide et al. 2023]. Such a scenario is supported by our seismological results. The deep cluster seismicity occurred on steep, sub-parallel structures within a relatively narrow volume, which we assume surrounds the upward magma path. The upward propagation of a magma dike, in our case with an oblique path dipping $\sim 70^\circ$ and a strike of $\sim 245^\circ$ (ENE-WSW) Figure 10, introduces spatiotemporal stress anomalies, which can explain the mechanism reversal. Indeed, stress inversion already showed a stress rotation at the deep cluster as a function of depth [Del Fresno et al. 2023]. The intrusion of a magma dike produces tensile stresses ahead of the dike tip and compressional stresses on its side [Rubin and Pollard 1988]. This model is consistent with the average CLVDs at the deep cluster, which are positive for the families located above in the cluster (families 3, 20, 22), at 35 km depth, and negative below (families 0 and 10, at 37 km depth) [Del Fresno et al. 2023]. The superposition of homogeneous compressional tectonic stresses [Mezcua et al. 1992; Geyer et al. 2016] with compressional vs tensional stresses due to diking [Rubin and Pollard 1988] can also explain the reversal of the shear faulting components, which are characterized by oblique to strike-slip mechanisms of different polarity. In the lower part of the deep cluster, where the compressional orientation of the dike induced stress is consistent with the background tectonics, the mechanism polarity is consistent with the background tectonic stresses. Above it, if the extensional stress of the dike counteracts and overprints the tectonic compression, a slip reversal would occur. At the deep cluster, the upward migration of seismicity is progressive, but discontinuous, occurring in the form of short-duration seismicity bursts, which become progressively shallower. Their reversed mechanisms last for a short time period, in response to short duration stress anomalies. This is illustrated in Figure 10 and Suppl. Fig. 12.

At the shallow cluster, seismicity patterns are only partially similar and probably controlled by different stress conditions at different depths and at different sides of a shallow reservoir. The background stress conditions at the shallow cluster have been modeled as a roughly N-S oriented compression [Del Fresno et al. 2023], but spatially heterogeneous stress perturbations have been hypothesized in the vicinity of the shallow reservoir, in response to pressurization or depletion stages [Del Fresno et al. 2023]. Such a simplified stress model could also explain the upward, curved path of the final dike ascent, leading to

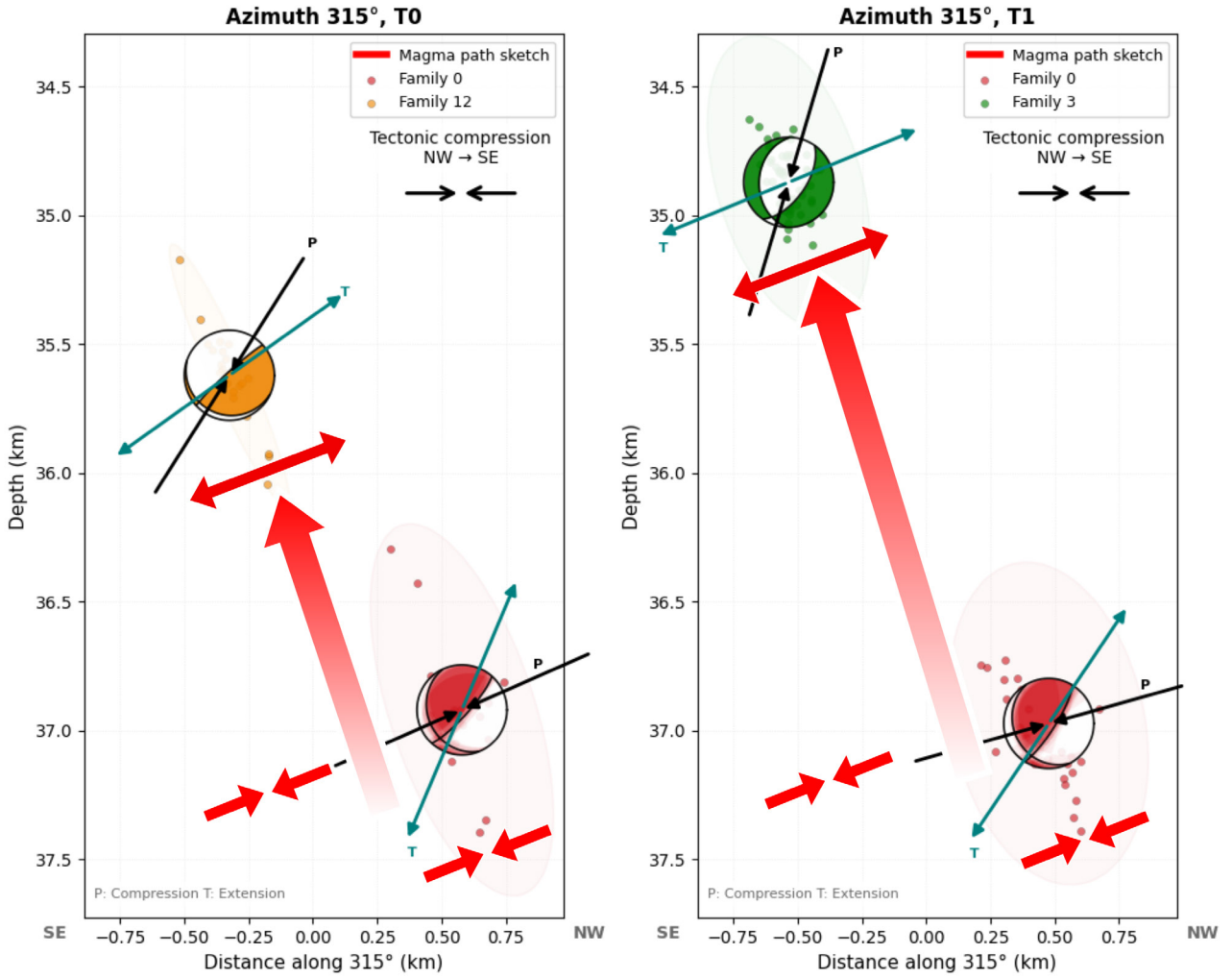


Figure 10: Sketches of the magma path evolution in the deep cluster for the time period T0 (left) and T1 (right), viewed along vertical, SE-NW cross-sections. T0 and T1 are marked in Fig. 9. Red arrows show the orientation of compressional stresses introduced on the side of a planar magma intrusion, and double-headed red arrows show corresponding extensional stress above a propagating intrusion tip [Rubin and Pollard 1988]. The orientation of background tectonic stresses is marked by thin, black arrows [Mezcua et al. 1992]. Gradient red arrow sketches the magma path. Double couple moment tensor component plotted, see Suppl. Fig. 13 for full MTs.

the eruption during the reservoir pressurization. Our moment tensors, however, sample the period after the eruption onset, which has been modeled by Del Fresno et al. 2023 as associated with a depleting shallow reservoir, following upward magma transfer. According to that model the observed mechanism rotation could be explained if the different families were located at different sides of the reservoir, which is qualitatively confirmed by their different locations. Compared to the deep cluster, in the shallow one the expected moment tensors should be rotated, but not fully reversed [Del Fresno et al. 2023], in agreement with our representative moment tensors. On the other hand, within the shallow cluster focal mechanisms at different depth levels show different rotations; similar differences in focal mechanisms and depth patterns are also found at the deep cluster. Also at the shallow cluster moment tensors of deeper families are consistent with tectonic stresses, whereas those of the shallower ones are rotated, suggesting a stress anomaly induced by magma upflow (Suppl. Figs. 3, 4). A last, relevant difference against

the deep cluster is that both families at the shallow cluster occur over the whole eruption period; their sustained occurrence suggests they occur in response to a spatial stress heterogeneity, rather than to short term temporal transients.

5 CONCLUSIONS

This work extends the seismological analysis of volcano-tectonic earthquakes accompanying the 2021 Tajogaite eruption at La Palma, Canary Islands, Spain. We implemented a novel approach for modeling the geometry of activated seismogenic structures based on waveform and spatial clustering, including an outlier detection that enables the use of PCA for fault geometry reconstruction. This new approach allowed us to investigate the spatial and temporal evolution of seismogenic processes in unprecedented detail. We resolved a number of earthquake families, their geometry and type (linear or planar), where earthquakes are characterized by similar waveforms, and consequently, similar locations and similar mechanisms. Comparing these mechanisms with the planes obtained using the PCA, points to the possibility of using that method even in the case of insufficient moment tensor data. This way, we successfully bridged the clustering information previously proposed on the basis of waveform and moment tensor similarity [Del Fresno et al. 2023], independently. Our analysis identifies 47 earthquake families in the two main seismicity clusters at 11 and 35 km depth. Planar or linear seismicity features are resolved for 12 of those families, providing information on the geometry of the responsible seismogenic structures. In the deep cluster, co-planar structures, stretching along a narrow volume, illuminate the assumed upward magma path. There, slightly deeper seismogenic structures are steadily active, with the earthquakes' moment tensors in agreement with compressional tectonic and magmatic-induced stresses. Conversely, opposite faulting occurs along slightly shallower structures. We interpret this process to be related to the discontinuous magma ascent and pressurization in response to intermittent magma flow: tensile stresses localized at the upper tip of a magma dike or ascending magma batches can overlay the background tectonic stresses over short time periods resulting in transient occurrences of opposite faulting. In the shallow seismic cluster, earthquake families are organized in linear or planar structures that remain active throughout the eruption period. A high variability of moment tensors is also observed here, as well as a modulation of earthquake families and moment tensors with depth. We attribute the different focal mechanisms at the shallow cluster to spatial heterogeneities of the stress field, likely resulting from a progressive depletion of a magma reservoir at ~11-13 km depth. From a technical perspective, our approach, combining seismicity clustering and fault reconstruction, provides a valuable tool for mapping seismogenic structures, with potential application to tectonic, induced and volcanic seismicity.

6 TABLES

Family Number	Number of Events	Number of MT solutions	$\varphi/\mathcal{L}$ ratio	Strike/Dip (for planar) or Azimuth/Plunge (for linear) PCA (°)	Strike/Dip MT (°)	Dihedral angle (°)
2	314	3	0.79 (linear)	8±18 / 71±3	77±18 / 46±9 201±12 / 59±8	25
4	42	1	13.5 (planar)	163±47 / 5±3	226±n.a / 66±n.a 83±n.a / 29±n.a	29
6	58	5	0.54 (linear)	217±8 / 6±3	107±4 / 81±7 198±5 / 85±5	18
13	120	n.a.	0.26 (linear)	326±19 / 79±3	n.a.	n.a.
22	22	n.a.	2.36 (planar)	66±7 / 87±4	n.a.	n.a.
24	10	n.a.	0.26 (linear)	102±8 / 38±11	n.a.	n.a.
32	25	n.a.	0.09 (linear)	75±2 / 54±4	n.a.	n.a.

Table 1: Shallow cluster. The table reports the cluster number, planarity/linearity ratio, strike and dip from the PCA and dihedral angle to the representative moment tensor fault plane. For each family a representative moment tensor is used. The precision is estimated by mean absolute deviation of all moment tensors available in the family to the representative one.

Family Number	Number of Events	Number of MT solutions	$\varphi/\mathcal{L}$ ratio	Strike/Dip (for planar) or Azimuth/Plunge (for linear) PCA (°)	Strike/Dip MT (°)	Dihedral angle (°)
0	69	22	1.96 (planar)	244±5 / 73±4	238±7 / 58±8	15
3	52	1	1.15 (planar)	261±2 / 68±2	260±n.a / 60±n.a	8
10	34	9	0.40 (linear)	352±26 / 73±6	48±18 / 62±11; 186±34 / 36±16	41
12	24	n.a.	1.833 (planar)	231±2 / 66±1	217±n.a. / 43±n.a	26
24	8	n.a.	0.19 (linear)	40±5 / 16±9	n.a.	n.a.

Table 2: Deep cluster. The table reports the cluster number, planarity/linearity ratio, strike and dip from the PCA and MT and the smallest dihedral angle to the moment tensor fault plane. For each family a representative moment tensor is used. The precision is estimated by mean absolute deviation of all moment tensors available in the family to the representative one.

AUTHOR CONTRIBUTIONS

Contribution	Authors
Conceptualization	1, 2, 3
Data curation	1, 2, 3, 4, 5, 6
Formal analysis	1, 2
Funding acquisition	
Investigation	1, 2, 3
Methodology	1, 2, 3
Project administration	1, 2
Resources	2, 3, 4, 5, 6, 7
Software	1, 2, 3
Supervision	2, 3, 7
Validation	1, 2, 3
Visualization	1
Writing – original draft	1, 2, 3
Writing – review & editing	2, 3, 4, 5, 6, 7

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DATA AVAILABILITY

- Seismic catalogs used in this study are available from the supplementary material of the [Del Fresno et al. 2023]
- Waveform data availability
 - Seismic data was obtained from the GEOFON data centre of the GFZ Helmholtz Centre for Geosciences.
 - Seismic data was obtained from the IGN [Instituto Geografico Nacional, Spain 1999]
 - Dataset contains 2 networks from [Instituto Geografico Nacional, Spain 1999; Walter et al. 2021]
- GMT tools [Wessel et al. 2019] and PyGMT [Tian et al. 2026] was used for plotting and topology data
- (Bellock et al., 2021; Glasbey et al., 2007; Harris et al., 2020; Heimann et al., 2017; Hunter, 2007; Inc, 2015; Joris Van den Bossche et al., 2025; Pedregosa et al., 2011; The pandas development team, 2026; Virtanen et al., 2020) were used for plotting and analysis

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