In this file, there are responses to both Reviewer#1 and Reviewer#2.

Responses to Reviewer #1

We thank the Reviewers #1 and Reviewer #2 for submitting their reviews in due time and for constructive comments. We agree that explicitly stating the assumptions can be helpful to better follow the manuscript. However, we were unable to answer some of the comments from Reviewer #1 easily:

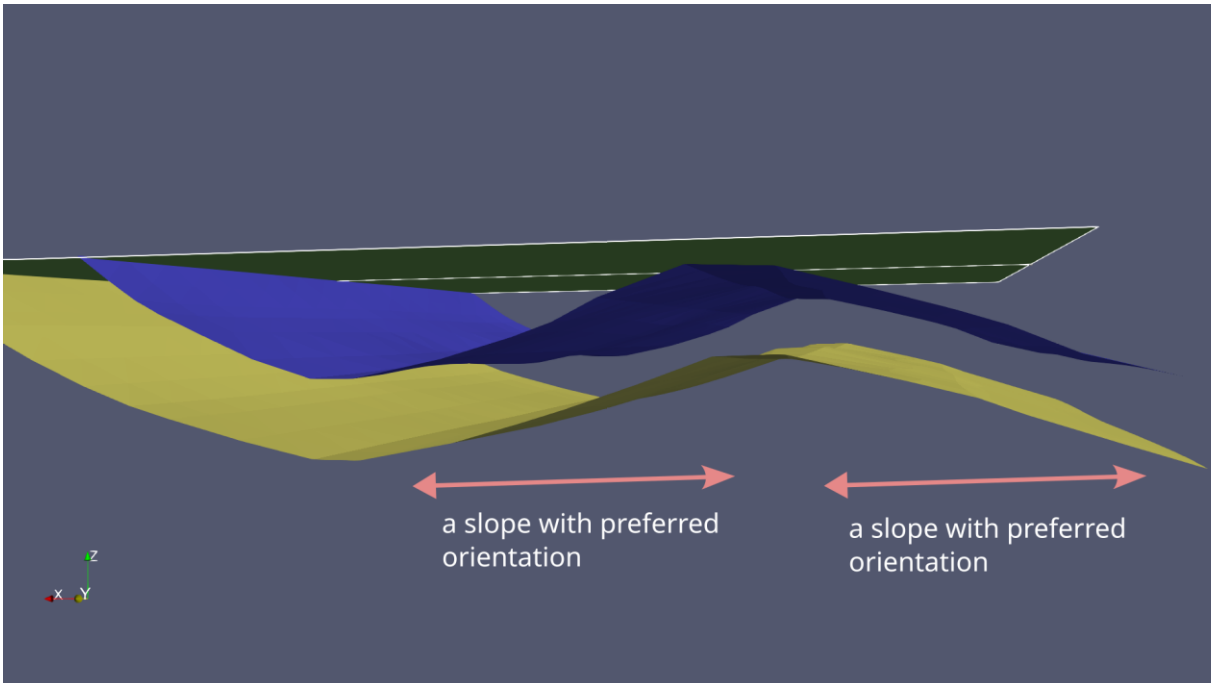
- comment #15 - we don't understand the symbols "XXXX"
- comments #2 and #25 say that Figures 2 and 3 are illustrating steps in the study but only Figure 3 does illustrate steps.
- comment #14 - The question is mathematically incomprehensible because a vector does not have its own distance ("distances of normal vectors").

To better observe communicating our response, we divided our responses into three categories: Agree/Clarification/Disagree.

1.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
The manuscript titled "Broken Terrains v. 1.0: A supervised detection of fault-related lineaments on geological terrains" describes an approach to predict fault 3D geometry from changes in Triangular Irregular Networks (TINs). While this manuscript is within the scope of GMD and presents a novel approach to the classification of faults, I feel that there are substantial changes required to clarify assumptions, methods and results. For example, the key assumption that faults at the surface of the Earth are reflected by particular landforms (e.g. scarps or breaks in slope) and their geometry is not entirely valid nor is it clearly stated.	**Clarification** This is a misunderstanding. We didn't analyze faults at the surface of the Earth. We used borehole (subsurface) data with preferred orientation of the surface. We had this information in the section *Real data*: "we used borehole data (Michalak, 2024a) corresponding to a horizon separating Middle-Jurassic rock units: Kościeliska sandstones from ore-bearing clay deposits" "From a geometric perspective, KSH dips at low angles to NE" However, we agree that the explicit formulation was missing and it is worth adding more information about the assumptions in other sections.	We added a figure to illustrate the applicability of the method. A paragraph with explicit statements about the assumptions and data was added in the Introduction.

A new figure illustrating the assumption of having subsurface data with preferred orientation:



2.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
The methods section should be structured to reflect the steps summarised in Fig 2 (which should be moved from the introduction to the methods section).	**Disagree/Clarification** We are a bit confused about this request because Fig. 2 presents a triangle and its neighbors. So there are no specific steps illustrated in this figure. Probably you meant Fig. 3 because a comment of similar nature is written below (Comment #25). If this is the case, we think that the specific sections in the Methods section properly reflect what is illustrated in Fig. 3.	None about this comment. However, we followed the suggestions from comment #25 which points to the correct figure (Figure 3). Please note that the order of figures has changed.

3.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
The results are ambiguous, given that there is confusion around what is being compared in the test data and how it is being compared.	**Clarification** Actually, we don't compare anything in the test data. Test data are only used to evaluate the performance of the algorithm. Maybe you meant comparing performance metrics before and after hyperparameter tuning? This information was provided in the captions to Table 1 and Table 2. But we decided to add one clarifying sentence in section 4.1. Please note that our data sets are divided into: - synthetic data: training data, test data - real data (borehole data) What we actually compared are the results from the unsupervised classification (presented in the paper Michalak et al. 2022) and the supervised classification (presented in the manuscript).	We added one clarifying sentence to the section 4.1 Synthetic data: "However, the arbitrarily selected hyperparameters are not guaranteed to give the best performance of the algorithm. "

References:

Michalak, M., Teper, L., Wellmann, F., Żaba, J., Gaidzik, K., Kostur, M., Maystrenko, Y., and Leonowicz, P., (2022). Clustering has a meaning: optimization of angular similarity to detect 3D geometric anomalies in geological terrains Solid Earth, 13(11), 1697-1720, https://doi.org/10.5194/se-13-1697-2022

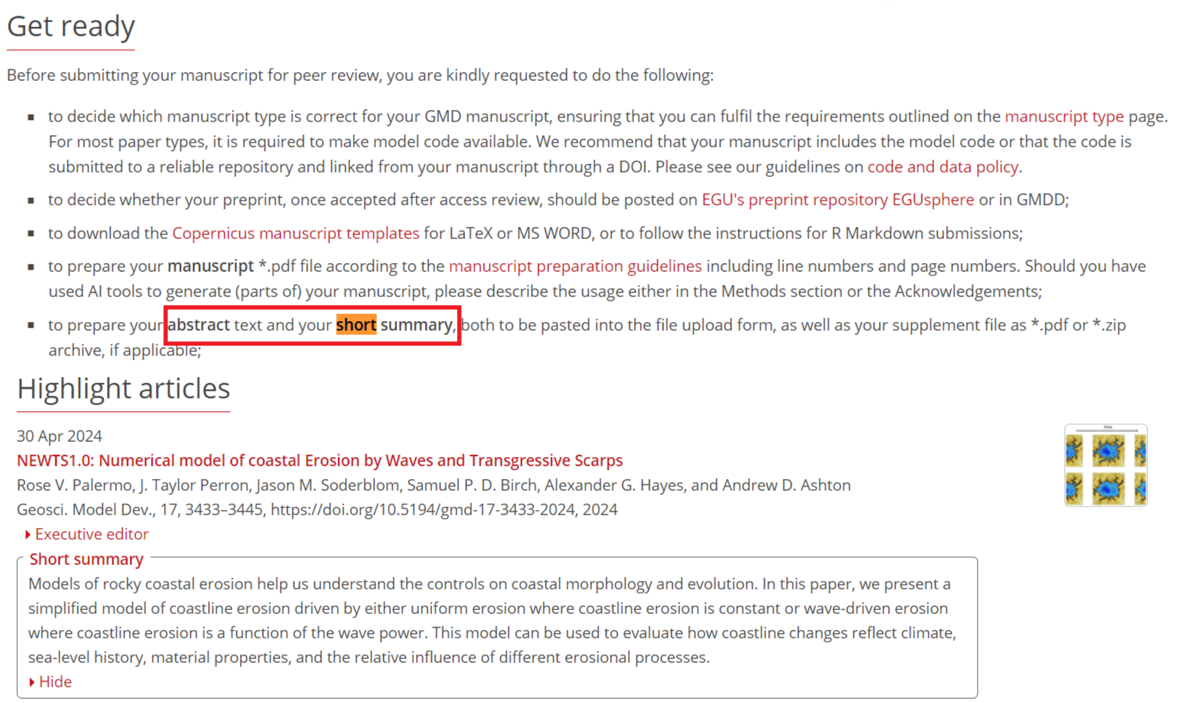
4.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
Finally, the manuscript is hard to follow in many sections (see specific comments below) and the figures need a substantial amount of editing to clearly communicate to the reader	**Clarification** We addressed specific comments below. See our next responses.	Figures have been corrected.

what they should glean from them (e.g. symbology, colours, quality). Unfortunately, for these reasons I am recommending that this manuscript be rejected.		

5.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
Specific comments **1 Introduction** Why is there a section called short summary? This information should be removed as everything is covered in the abstract	**Disagree** We have a short summary because short summaries are mandatory for Geoscientific Model Development. Please see the below screenshots.	None.



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Highlight articles

30 Apr 2024
NEWTS1.0: Numerical model of coastal Erosion by Waves and Transgressive Scarps
Rose V. Palermo, J. Taylor Perron, Jason M. Soderblom, Samuel P. D. Birch, Alexander G. Hayes, and Andrew D. Ashton
Geosci. Model Dev., 17, 3433–3445, https://doi.org/10.5194/gmd-17-3433-2024, 2024
Executive editor

Short summary
Models of rocky coastal erosion help us understand the controls on coastal morphology and evolution. In this paper, we present a simplified model of coastline erosion driven by either uniform erosion where coastline erosion is constant or wave-driven erosion where coastline erosion is a function of the wave power. This model can be used to evaluate how coastline changes reflect climate, sea-level history, material properties, and the relative influence of different erosional processes.
Hide

6.

Suggestion, Question,	Author's Response	Change in the Manuscript

or Comment from the Reviewer #1		
The use of the term geological terrains is a little misleading. The model uses changes in slope in triangular irregular network (TIN) models, presumably of the Earth's surface (this is not clear), as the basis for detecting faults.	**Agree/Clarification** We agree that the term "geological terrains" can be better replaced with "triangular irregular network (TIN) models". However, it is not true that we investigate changes in the slope of the Earth's surface. We used subsurface data sets. The surfaces are assumed to have preferred orientation (a sequence of conformal units).	We have changed the title to better reflect that we work with triangulated models of the terrain. A clarification about assumptions has been added in the Introduction.

7.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
What if for instance, the user has a digital elevation model? Would they still be able to use this approach given that the surface model is not irregular?	**Clarification** These are potentially interesting questions, however they again result from misunderstanding that we use data points from the Earth's surface. We note that we use subsurface borehole data (section 4.2 *Real data*). For the subsurface you could potentially obtain high resolution data (e.g. via seismic methods), however I believe that most researchers would disagree that one can use the term "digital elevation model" for the subsurface because traditionally the term "digital elevation models" is reserved for representing the Earth's surface (or other planets). In our study, we don't use regular data, so we cannot effectively communicate the answer to the question about applicability of data points in regular networks. However,	None.

	we cannot see any formal objection preventing the use of regular data sets. We believe that the assumptions about the terrain geometry are more important than the spatial arrangement of input points. As such, we would expect that the proposed fault detection method should work for regular data point sets provided that the data points represent a terrain with preferred orientation (e.g. a homocline being part of a syncline).	

8.

Suggestion, Question, or Comment from the Reviewer #1	**Author's Response**	**Change in the Manuscript**
One key assumption that I don't think has been stated clearly enough is that this approach assumes that all scarps, and/or breaks in slope are caused by faulting, i.e. they are fault-controlled landforms. This is probably not the case as some landforms will be controlled by other geological processes and features such as erosion and variability in rock type resistance to weathering. Furthermore, not all faults will be reflected as changes in the landscape.	**Clarification** We agree that for some datasets some of the identified anomalies can be attributed to erosion. In particular, this may relate to Earth's surface data. However, in our study, we used borehole data that documented a subsurface geological interface with preferred orientation (from a sequence of conformal units). So it is less likely that the lineaments are caused by erosion. We admit that there is a possibility that even in our case some of the identified lineaments can be attributed to erosion due to a hiatus related to the lack of an Ammonite zone but there is no research available about landforms developed in this time period. In the ideal example, one should have a continuous sequence of uniformly	In the Discussion, we added a subsection ''5.3 Complexities of real data''

	oriented layers. In such conditions, it is less likely that changes in the morphology of the interfaces are caused by erosion. However, we agree that the assumption should be more clearly presented.	We added a new figure in the Introduction and a paragraph with the statements about assumptions.

9.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
2 State of the art Supervised machine learning has been applied to a multitude of applications other than lithology classification, and I am not sure how relevant these applications are to your example, which is specifically the linking of TIN segments based on their location and normal and dip vectors.	**Clarification** While we agree that ”lithology classification” is not directly related to the study objective, we believe that it is within the more general scope of “geological mapping” which is also applicable for our study. Moreover, mentioning such studies can be useful for Editors to find referees with expertise in machine learning because the adoption of machine learning methods in structural geology is progressing but still it is not very much popular. Please note that “lithology classification” was only one example in our State of the Art (now Background) section. We had more relevant examples of using machine learning in fault detection problems. The references are given below.	None.

References

An, Y., Guo, J., Ye, Q., Childs, C., Walsh, J., and Dong, R.: Deep convolutional neural network for automatic fault recognition from 3D seismic datasets, Comput. Geosci., 153, 104776, https://doi.org/10.1016/j.cageo.2021.104776, 2021

Kaur, H., Zhang, Q., Witte, P., Liang, L., Wu, L., and Fomel, S.: Deep-learning-based 3D fault detection for carbon capture and storage, Geophysics, 88, IM101--IM112, https://doi.org/10.1190/geo2022-0755.1, 2023

Mattéo, L., Manighetti, I., Tarabalka, Y., Gaucel, J. M., van den Ende, M., Mercier, A., Tasar, O., Girard, N., Leclerc, F., Giampetro, T., Dominguez, S., and Malavieille, J.: Automatic Fault Mapping in Remote Optical Images and Topographic Data With Deep Learning, J. Geophys. Res. Solid Earth, 126, https://doi.org/10.1029/2020JB021269, 2021

10.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
3 Methodology The training data are synthetically generated based on user inputs (there is a list of these at lines 121-124). Please mention that the training data are synthetic in line 120 and consider providing the user defined variables as a table, for example, with an indication of the parameter name (as in the application) the range of possible values (surely there will be some parameters with restrictions on numeric values, e.g. non-negative) and the function of the parameter. This table may be useful to document other input parameters for the application if there are any.	**Agree/ Clarification** We agree that mentioning synthetic data and providing a table with the parameters with ranges can be useful. We are a bit confused, however, what you mean about "function of the parameter". Do you mean the name of the function in the code? There are no specific functions in the code for reading the parameters from the user. But since you say that the structure of the table is only an example, we decided that our last column will point to the names of the variables in the computer code.	• We added the word "synthetic". • a table with parameters was added to the manuscript (Methods)

11.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
The structure of the paragraphs for generating training data is hard to follow. It reads better	**Agree** We agree that it can read better using numbered dot points.	We introduced the numbered dot points.

with numbered dot points for each of the steps. For example, The faulted triangulated terrains are created in the following sequence (summarized in Fig. 5). 1. a container with 2D points is generated within a square of a given size. 2. a new container of 3D points is created with the Z coordinate corresponding to the random value of dip and dip direction. 3. noise is introduced to the surface defined as a random fraction of the elevation difference within the terrain. 4. …		

12.

Suggestion, Question, or Comment from the Reviewer #1	**Author's Response**	**Change in the Manuscript**
You must make sure that the table with user defined parameters has the same names as the parameters included in these steps to avoid ambiguity.	**Agree**	A table with user defined parameters was prepared. The names of the parameters in the table match the names of the parameters in the text.

13.

Suggestion, Question,	**Author's Response**	**Change in the Manuscript**

or Comment from the Reviewer #1		
Lines 150-153: it is unclear if dip direction is included in the final set of variables for supervised learning. The statement “northern directions indicate great numerical difference (e.g. 358-2=356) but very small geometric difference (4 degrees).” Needs to be clarified as I suspect that you trying to explain that the orientation difference between 358 deg and 002 deg (as measured relative to magnetic/grid north) is 4 degrees but numerically it is 356.	**Clarification** No, dip direction is not used as a feature for classification. This paragraph was actually a justification why dip direction should not be used for classification in our case.	We added a sentence saying that we don’t use dip direction for classification.

14.

Suggestion, Question, or Comment from the Reviewer #1	Author’s Response	Change in the Manuscript
Line 169: The authors state that “sort the distances to neighbouring triangles in decreasing order.” to avoid randomness issues. Which distance or distances are used to sort the neighbouring triangles? Is this the Euclidean distance or cosine distance of the normal and dip vectors or is this something else? Please clarify.	**Disagree/Clarification** We are not not computing distances of vectors (because distance for an individual vector does not exist) but distances between vectors. We only compare dip vectors with dip vectors and normal vectors with normal vectors. There is no mixing of normal vectors and dip vectors in these comparisons (distance measurements). Actually, distances between a triangle and its neighbors are sorted. This applies to all three types of distance: angular, Euclidean and cosine. The distances are calculated either between	None.

	normal vectors of a triangle and its neighbors or between dip vectors of a triangle and its neighbors. For example, for a triangle *t* and its three neighbors you can have three distances as follows: $d(t, n_1)=0.4$, $d(t, n_2)=0.1$, $d(t, n_3)=0.7$. And you just sort them: 0.7, 0.4, 0.1. And now we are able to rearrange the order of neighbors: so the first neighbor is the one with the highest value of distance equal to 0.7, the second neighbor is the one with the middle value of distance (0.4) and the third one is the neighbor with the smallest value of distance. This sorting is necessary because initially the order of neighbors corresponds only to a counterclockwise order (see References). So without sorting, for a sequence for triangles, their counterclockwise-ordered neighbors can have no consistent geographical position relative to the selected triangle. For example, for the first triangle its first neighbor can be to the North, and for the second triangle, its first neighbor can be to the South. So without sorting, we have the potential to confuse the algorithm.	

References (about counterclockwise order of neighbors):

Getting started with CGAL, https://graphics.stanford.edu/courses/cs368-04-spring/manuals/CGAL_Tutorial.pdf , p. 31

15.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
Line 176: Authors state that visualsaion uses spatial clustering. Not sure what you mean by spatial clustering as I cannot see any indication of a specific spatial clustering approach. XXXX Appears to be more like the spatial distribution of classes (fault or not fault) as plotted on a map	**Clarification** We believe that the method that we applied matches the definition of "spatial clustering" as defined by Fisher: "studying the directional aspect of the data separately from the spatial aspect, and then to put any resulting clusters of directions back into their spatial context" (p. 193) Indeed, the SVM performs the classification without taking into account spatial information (it uses only geometric information). And then, the resulting labels (-1 and 1) of classification are displayed on the map. We don't know what XXXX means.	We added more information about spatial clustering to the manuscript.

References: Fisher, N.I., 1993. Statistical Analysis of Circular Data. Cambridge University Press.

https://doi.org/10.1017/cbo9780511564345

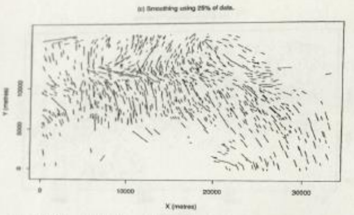


Fig. 7.15 (*cont.*) (c) Smoothing using 25% of data. See Example 7.9.

lineaments can be swung quite dramatically in a smoothed version of the data. Weighting is generally available in smoothing algorithms.

Example 7.9 For the lineament data displayed in Figure 7.3, it is appropriate to examine subsets in different arcs. Figure 7.13 shows the data in the 45° arc centred on the NE–SW axis. Some patches are evident in which this lineament set is under-represented. In Figure 7.14, two smoothed version are displayed, based on *loess* using spans of 10% and 25%. The more heavily smoothed version in Figure 7.14(b) seems to be revealing some tendency for the orientations to exhibit some systematic rotation from site to site across the region. This sort of exploratory analysis can be carried out for a set of arcs spanning the complete range, and the various bits of information combined. It is also helpful to explore the data set as a whole. Figure 7.15 shows three smoothed versions of the complete lineament set using length-weighting. The most lightly smoothed version (Figure 7.15(a)) clarifies the patterns locally, with the shortest lineaments altered slightly so that they conform more closely to their neighbours; the most heavily smoothed (Figure 7.15(c)) brings out gross predominant trends, although at the cost of rotating at least one major lineament substantially, so that the result may be misleading. Figure 7.15(b) preserves some local structure as well as revealing larger-scale patterns. The next step would be to relate possible rotations to the known geological history of the region.

References and footnotes. The spline method of Watson (1985) (see also Mendoza 1986) is an alternative form of smoothing. A general discussion of the spline method and methods based on local regression can be found in Hansen & Mount (1990), in the context of smoothing crustal

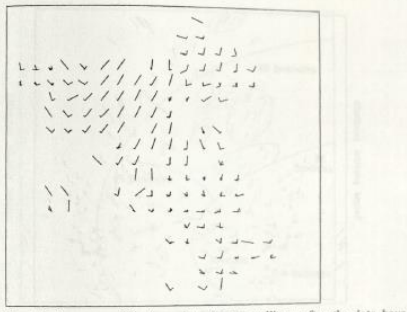


Fig. 7.16 Summary of fracture data from a colliery, after the data have been grouped into grid cells, then summarised in terms of the directions and strengths of the modal groups in each cell.

stress orientation measurements. Young (1987a, 1987b) has used a kriging approach to spatial smoothing of unit vectors and axes.

(ii) Spatial clustering. As a simple example of the sort of problem we have in mind, consider a region which has been affected by three significant fracturing events. The first and second of these may have created two ubiquitous sets of fractures trending N–S and E–W, say. Subsequently, a relatively narrow strip which passes through the centre of the region is affected by the third fracturing event trending NE–SW. The region is thus divided into three *structural domains*, within each of which the fracture pattern is homogeneous. Two major objectives of domain analysis are to identify the number of homogeneous structural domains and to determine which are similar.

One way of identifying spatially non-contiguous areas of similar fracture pattern is to study the directional aspect of the data separately from the spatial aspect, and then to put any resulting clusters of directions back into their spatial context. As an example of how this might be done, the

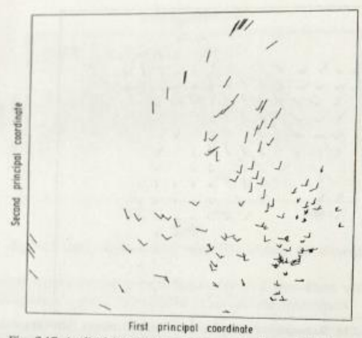


Fig. 7.17 A display resulting from performing a Principal Coordinates' Analysis (PCA) on the summary cell diagrams, or 'birds' feet', in Figure 7.17, using the similarity measure $S(P, Q)$. Each bird's foot has been plotted out in the x–y space defined by the first two principal coordinates.

analysis of Fisher *et al.* (1985) will be described briefly: for fuller details, the reference should be consulted. (The data set considered in that paper consisted of fractures in the tunnel roof throughout a coal mine, with the fractures tending to be of comparable length. By way of comparison, the fracture data in Example 7.3 have a wide range of fracture lengths; however, for the grid-based method below, this difference is less pronounced than it might be for other methods.)

There are three basic steps to the procedure:

(1) Summarisation. A grid is placed on the data map. For each grid cell, the trends of all fractures intersecting that grid cell are recorded. Denote the number of non-empty grid cells by N. The sample of measurements in each cell is then analysed to identify the number of modal groups, and the relative size and frequency of each. For a typical cell in which, say, m modal groups have been identified, denote the summary information by $\{(\bar{\theta}_i, p_i), i = 1, \ldots, m\}$, where p_i is the proportion of the cell data in the modal group with mean trend $\bar{\theta}_i$. A simple summary plot for this cell is then

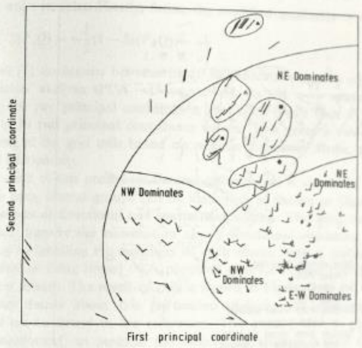


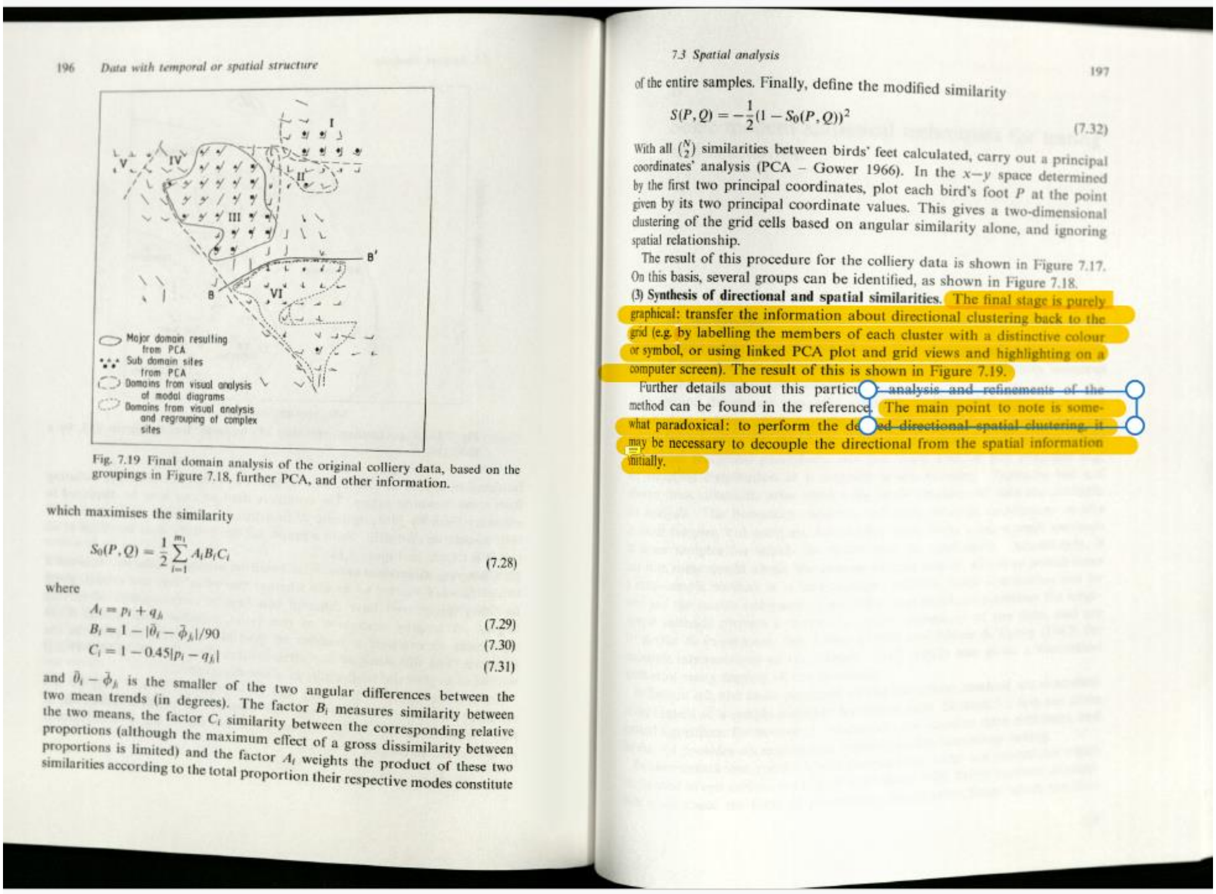
Fig. 7.18 A preliminary grouping of the birds' feet in Figure 7.17, by a geologist.

furnished by a plot of the m mean trends $\bar{\theta}_i$ as vectors of length p_i radiating from some common origin. The complete data set can now be displayed in summary form by plotting these N individual 'birds' feet' at the centres of their respective grid cells. Such a graph for the colliery data in Fisher *et al.* (1985) is shown in Figure 7.16.

(2) Clustering directional summaries based on angular similarity. It is not a straightforward matter to decide whether two birds' feet are similar, given that they might well have different numbers of trend vectors of varying lengths. A lengthy discussion of this point, together with details of an experiment to evaluate a number of possible measures, is given in the reference. The following *ad hoc* method (including formulae (7.28)–(7.31)) was found to give the best results in a test experiment.

Let $P = \{(\bar{\theta}_i, p_i), i = 1, \ldots, m_1\}$ and $Q = \{(\bar{\phi}_i, q_i), i = 1, \ldots, m_2\}$ be two summary sets, where $m_1 \leq m_2$, say, and consider all possible match-ups of the m_1 mean trends $\bar{\theta}_1, \ldots, \bar{\theta}_{m_1}$ with m_1-subsets of $\bar{\phi}_1, \ldots, \bar{\phi}_{m_2}$. We shall define as *optimal* the particular match-up

$$(\bar{\theta}_1, \bar{\phi}_{j_1}), \ldots, (\bar{\theta}_{m_1}, \bar{\phi}_{j_{m_1}})$$



196 *Data with temporal or spatial structure*

Fig. 7.19 Final domain analysis of the original colliery data, based on the groupings in Figure 7.18, further PCA, and other information.

which maximises the similarity

$$S_0(P,Q) = \frac{1}{2}\sum_{i=1}^{m_1} A_i B_i C_i \qquad (7.28)$$

where

$$A_i = p_i + q_{j_i} \qquad (7.29)$$
$$B_i = 1 - |\bar{\theta}_i - \bar{\phi}_{j_i}|/90 \qquad (7.30)$$
$$C_i = 1 - 0.45|p_i - q_{j_i}| \qquad (7.31)$$

and $\bar{\theta}_i - \bar{\phi}_{j_i}$ is the smaller of the two angular differences between the two mean trends (in degrees). The factor B_i measures similarity between the two means, the factor C_i similarity between the corresponding relative proportions (although the maximum effect of a gross dissimilarity between proportions is limited) and the factor A_i weights the product of these two similarities according to the total proportion their respective modes constitute

7.3 *Spatial analysis* 197

of the entire samples. Finally, define the modified similarity

$$S(P,Q) = -\frac{1}{2}(1 - S_0(P,Q))^2 \qquad (7.32)$$

With all $\binom{N}{2}$ similarities between birds' feet calculated, carry out a principal coordinates' analysis (PCA – Gower 1966). In the $x-y$ space determined by the first two principal coordinates, plot each bird's foot P at the point given by its two principal coordinate values. This gives a two-dimensional clustering of the grid cells based on angular similarity alone, and ignoring spatial relationship.

The result of this procedure for the colliery data is shown in Figure 7.17. On this basis, several groups can be identified, as shown in Figure 7.18.

(3) **Synthesis of directional and spatial similarities.** The final stage is purely graphical: transfer the information about directional clustering back to the grid (e.g. by labelling the members of each cluster with a distinctive colour or symbol, or using linked PCA plot and grid views and highlighting on a computer screen). The result of this is shown in Figure 7.19.

Further details about this partic[illegible] analysis and refinements of the method can be found in the reference[illegible] The main point to note is somewhat paradoxical: to perform the de[illegible]ed directional-spatial clustering, it may be necessary to decouple the directional from the spatial information initially.

16.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
Lines 210-215: please format the equations for precision and recall and F1 such that they are on separate lines from the text.	Agree	Done.

17.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript

4 Results How many samples in the synthetic training data and how many samples are in the synthetic test data? What were the parameters used to generate the synthetic data for this experiment?	**Clarification** There are 1000 files and every file contains 100 input points (3D points). As such every file will have a bit less than 200 triangles (according to the well-known theorem linking vertices with faces of the triangulation - see below). So there are a bit less than 200 000 triangles. We also performed cleaning: removing collinear configurations, and removing triangles with the infinite face as one of their neighbors. Therefore 145297 triangles are left. And only a small fraction of triangles are fault-related triangles (12411). Therefore, to reduce class-imbalance, we randomly select 12411 observations from the class with non-fault observations. Taking all considerations into account, we have 12411 observations for each class (-1 and 1). The parameters can be found in the uploaded data set (Zenodo). However, we provide the information here, as well: Number of files: 1000 Terrain size: 1 Dip angle: 0.5-2 Dip direction: 20-70 Number of points in the triangulation: 100 Noise of the surface: 0.02-0.04 Fault throw: 0.05-0.25 The meaning of each parameter is described in the section 3.1 Generating terrains.	Information about the number of samples was added to the Result section (4.1). A Table with the parameters used in this study was added to the manuscript (section 3.1).

References: De Berg, M., Cheong, O., Van Kreveld, M., and Overmars, M.: Computational Geometry: Algorithms and Applications, 3rd Ed., Springer, 364 pp., https://doi.org/10.2307/3620533, 2008.

This is made precise in the following theorem.

Theorem 9.1 *Let P be a set of n points in the plane, not all collinear, and let k denote the number of points in P that lie on the boundary of the convex hull of P. Then any triangulation of P has $2n-2-k$ triangles and $3n-3-k$ edges.*

Proof. Let $\mathcal{T}$ be a triangulation of P, and let m denote the number of triangles of $\mathcal{T}$. Note that the number of faces of the triangulation, which we denote by n_f, is $m+1$. Every triangle has three edges, and the unbounded face has k edges. Furthermore, every edge is incident to exactly two faces. Hence, the total number of edges of $\mathcal{T}$ is $n_e := (3m+k)/2$. Euler's formula tells us that

$$n - n_e + n_f = 2.$$

18.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
It would be great to present the evaluation and validation data as a confusion matrix. Precision and recall can be appended to these tables.	Agree.	We added confusion matrices before and after hyperparameter tuning (Tables 3 and 5). We modified the computer code to generate confusion matrices before and after hyperparameter tuning.

19.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
Please change Tab to Table where it occurs.	Agree.	Done.

20.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
I am a little confused about how borehole data and the fault models based on the analysis of topographic features can be compared? Please explain this more clearly. Also you need to include at least a confusion matrix of the comparison. If it is not a quantitative comparison then I suggest that you exclude this.	**Clarification** We are not sure but this comment can again be a result from misunderstanding that we use Earth's surface data. To better understand the workflow of the study we note that it is divided into following stages: • generation of synthetic faulted terrains based on random point generators (they can be considered synthetic borehole data) , • training the classification algorithm SVM on synthetic data, • evaluating the SVM on synthetic data • investigating generalizability of the classification by evaluating the SVM on real data, for example borehole data. In the Result section we also studied the added value of using the supervised version compared to the unsupervised version used in our previous papers (Michalak et al. 2022). The conclusion from this comparison is that we were able now to find more types of faults, specifically we were able to detect faults trending perpendicular to	We added confusion matrices before and after hyperparameter tuning.

	the preferred dip direction of strata.	

References:

Michalak, M., Teper, L., Wellmann, F., Żaba, J., Gaidzik, K., Kostur, M., Maystrenko, Y., and Leonowicz, P., (2022). Clustering has a meaning: optimization of angular similarity to detect 3D geometric anomalies in geological terrains Solid Earth, 13(11), 1697-1720, https://doi.org/10.5194/se-13-1697-2022

21.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
It seems that the only measure of success is fault or not fault and there is no measure of the successful classification of the orientation of the faults. Have you considered this as measure of fit for your classification model?	**Clarification** In the literature the fault detection problem was always posed as a binary classification problem. And for every binary classification problem you need variables used for training and target labels. The confusion matrix and the metrics resulting from the confusion matrix such as precision and recall are standard for evaluating performance of the algorithm. As such, we don't use the orientation of the faults as a measure of the successful classification. Maybe it could be used for regression problems where the goal is to predict the fault orientation but regression problems are different from classification problems.	None.

22.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
5 Discussion I have read this section several times and I am still a little confused. I suspect that there	**Agree/ Clarification** We agree that separating Discussion into separate sections can be useful.	

are several aspects that you are trying to discuss: • the use of TINs means that there are only a limited number (3) neighbours to every face and that this simplifies the modelling • The assumptions when generating synthetic training data, e.g. planes representing faults • Issues with multiple faults being predicted from a single synthetic fault training example that have different dips (although I am not entirely sure if I understand this correctly) I suggest a careful review of the discussion with the view to clearly distinguish the main points (as sub sections of the discussion with headings) and clarify to the reader the key message for each of the points.	We will now discuss the questions raised in the points: • The use of TINs means that there is a constant number of features for observations (except those that are at the edge of the convex hull but these are removed). This is not very much about simplifying the modelling (we note that modelling is simplification by definition) but making it actually valid. • One of the major assumptions that we discuss is that we don't allow points to lie on the fault surface. • Regarding "multiple faults": The problem is that for wide fault zones with points lying on the fault surface, we could get two sequences of fault-related points instead of one sequence.	We divided the Discussion into separate sections.

23.

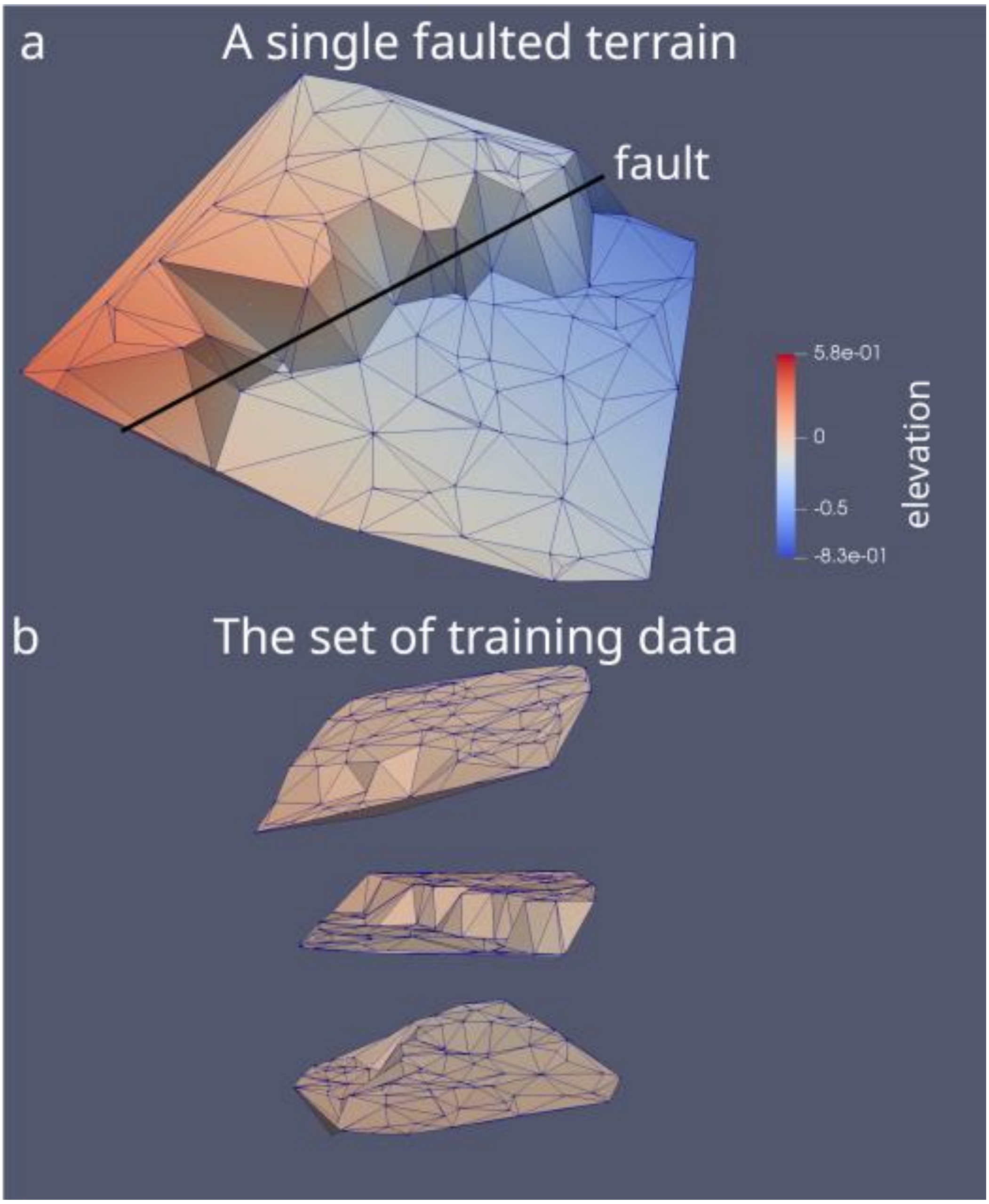
Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
6 Conclusions The conclusion should clearly state, what you did (developed a supervised fault classifier) and how it is novel and	Agree/ Clarification We added more fundamental information of this kind to Conclusion. In particular, we added that the	Conclusion section has been modified, accordingly.

different from other approaches (generate synthetic terrain data representing faults that control landscape geometry, use of TINs to simplify modelling) and the key assumptions of the method. You should also communicate the impact of your work (who should be using your fault classifier and why).	terrains should have preferred orientation. We believe that the classification approach can be used by geologists interested in geological complexity of subsurface environments with preferred orientation and limited availability of data.	

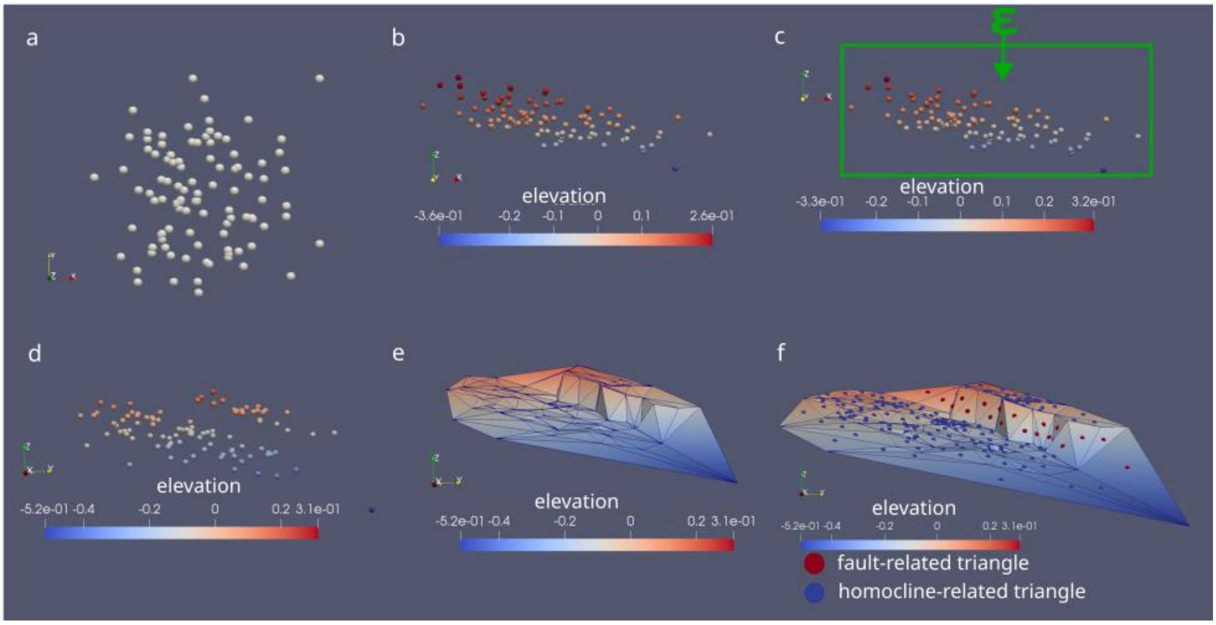
24.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
Figures Figure 1 - What do the colours in A represent? The legend states scalars but it is not clear what the scalars are, I suspect it is distance above some reference?	**Agree/ Clarification** Colours in A (scalars) represent elevations.	We improved the following figures: • Figure 1 (presenting a single faulted terrain and three example terrains) • Figure 5 (workflow of generating synthetic terrains)

The improved Figure 1 looks as follows: (elevation instead of scalars)



We also improved the old Figure 5 (now Fig. 6):



25.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
Figure 3 - This figure needs to be moved to the Methods section where the steps are summarised in detail. Likely introduced in an initial paragraph before section 3.1. At the moment this workflow lacks this clarifying information.	Agree	We moved Figure 3 to the Methods section. Please note that its number has changed now. We added an initial paragraph before section 3.1. We decided to move the sub-section about Visualization (now Spatial clustering) to the end of the Methods section.

26.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
Figure 4 - It is unclear what is being presented here. Is this a 2D view of an underground mine or mining region? What	Agree/ Clarification Figure 4 presents a subsurface geologic horizon restricted to the area studied	We added more information in the caption such as:

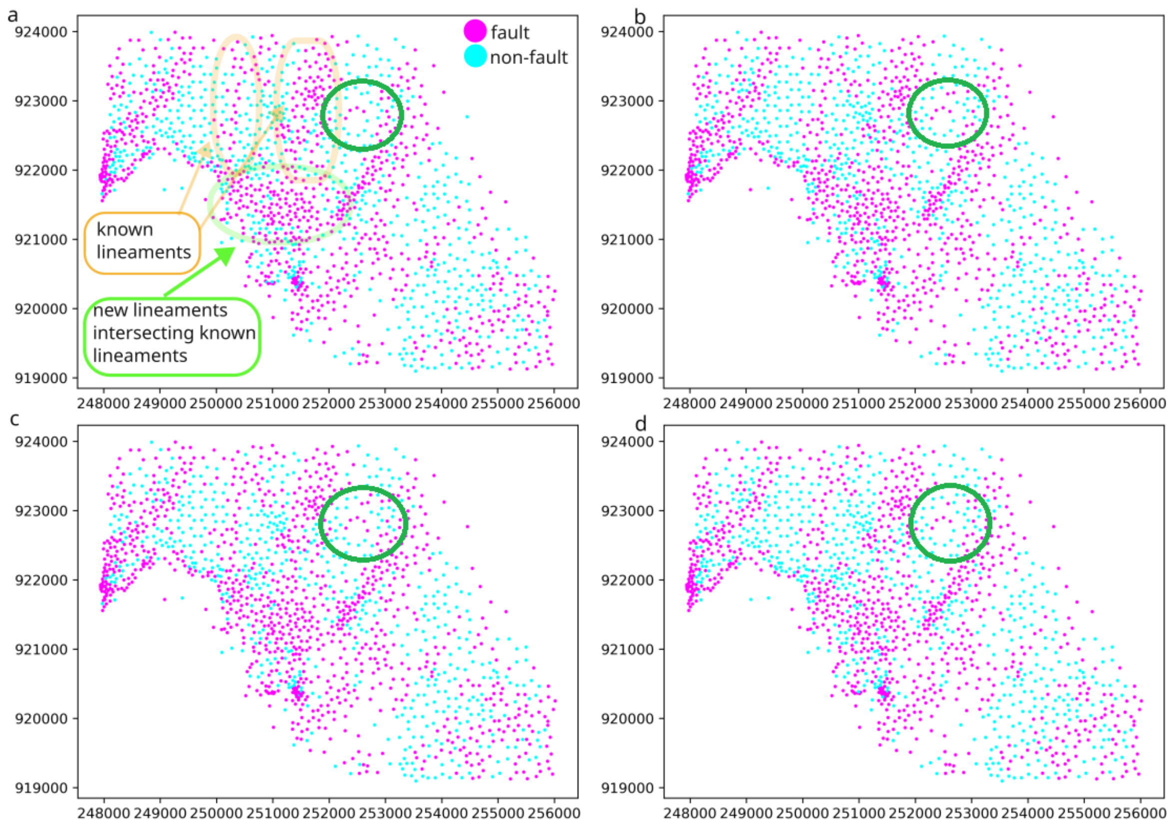
data are used to generate the points in 4B and 4C? What clustering algorithm used and what are the variables used in clustering? It appears that this information is provided in Michalak et al. (2022). I realise that a certain level of knowledge is assumed but for someone who has not read previous iterations of this research need to be provided with more background knowledge. It is probably worth indicating that this figure is modified from	in our manuscript. Figure 4 is composed of three panels: a) faults identified by miners within a displaced ore-bearing clays horizon, b) results from clustering dip vectors to Delaunay triangles using k-means with two clusters, c) results from clustering dip vectors to Delaunay triangles using k-means with three clusters. We will now answer the questions. • What data are used to generate the points in 4B and 4C? We used borehole data (3 D points) from a displaced geologic interface between two geologic units. Then, we used Delaunay triangulation and the points in the figure represent geometric centres of Delaunay triangles. • What clustering algorithm used and what are the variables used in clustering? The k-means algorithm was used and the variables were either normal vectors to triangles or dip vectors defined as the projections of the normal vectors onto the triangle's plane.	• algorithm used for unsupervised learning • we used the same borehole data in the unsupervised version • the figure is a modified version of the figure from a paper already published

27.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
Figure 6 -I am having trouble seeing the differences between	**Agree/Clarification**	

all of the plots in Fig 6. Is there some way that you can change the shape or the colour of the points in each of the models and indicate how these points compare with the borehole data or the unsupervised model, whichever is being compared in this figure?	It is true that it is difficult to see the differences. There may be two reasons:
	
	- results are not very much sensitive to changing hyperparameters of the algorithm.
	
	-there was a bug in the code and panel a) was repeated on panel c). It has been corrected.
	
	I marked with a green circle an example area where the classification results are different for every plot.
	
	We agree that it can be a good idea to enhance differences between the results for supervised classification and results from the unsupervised model.
		We corrected the Python notebook because there was a bug in the creation of panels for real data.
		
		Old (bad) version:
		`training_mono.insert(2, "svm_configuration2", predictions_mono)`
		
		Correct version:
		`training_mono.insert(2, "svm_configuration2_corrected_2", predictions_mono_configuration2)`
		
		On the panel (a), we marked lineaments known from the unsupervised learning revealed in previous studies (Michalak et al., 2022). The new lineaments revealed in this study using the supervised classification and the area where both groups intersect are marked, as well.

Improved figure illustrating the added value of supervised classification compared to the unsupervised classification.



28.

Suggestion, Question, or Comment from the Reviewer #1	Author's Response	Change in the Manuscript
Figures 7 and 8 - The symbols in these figures are hard to see as they are very small. Also these figures can probably be combined into a single figure as A and B.	Agree	Done.

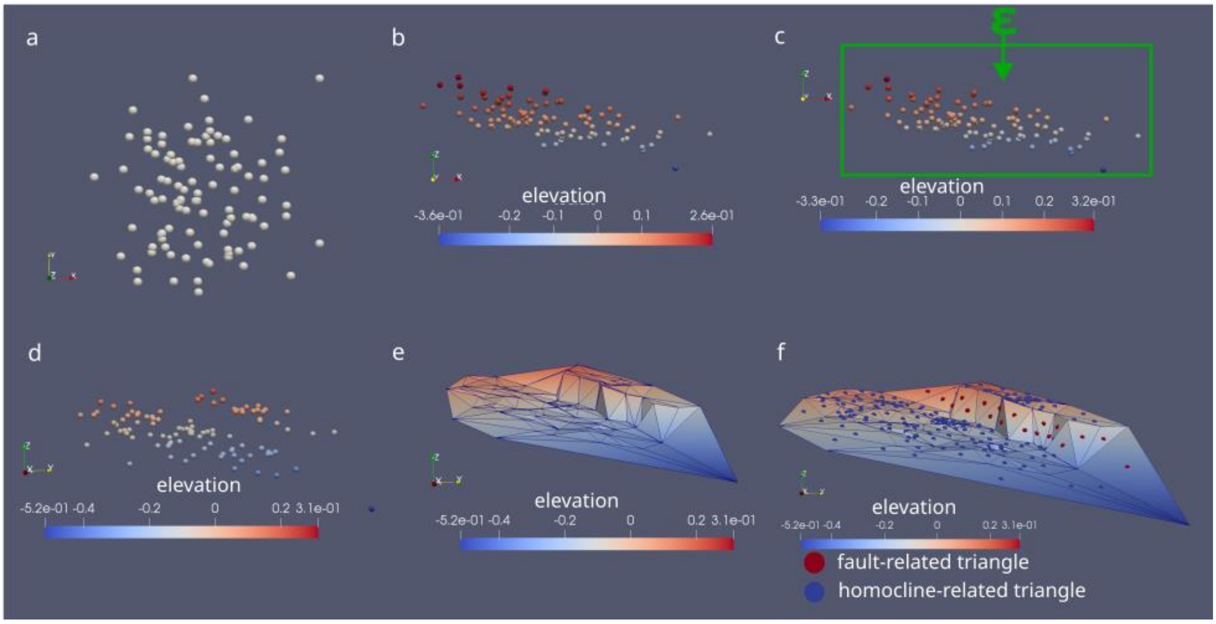
Responses to Reviewer #2

1.

Suggestion, Question, or Comment from the Reviewer #2	Author's Response	Change in the Manuscript
General comments The manuscript "Broken Terrains v. 1.0: A Supervised Detection of Fault-Related Lineaments on Geological Terrains" introduces a novel machine-learning approach but challenges readability, making it difficult to follow the progression of ideas. For example, the section on geological settings is well-contained within a single paragraph. Still, whether the subsequent text belongs to this section or would be more appropriately placed in the Results or Discussion sections. The manuscript would benefit significantly from a comprehensive restructuring to enhance coherence and flow. Additionally, the figures require careful editing to improve their visual impact; for instance, Figure 5 uses blue points on a deep grey background, a combination that lacks sufficient contrast and hinders clarity. Still, some technicalities need to be clarified, mainly how a detection model designed with synthetic 3D faults could be applied to borehole data.	Agree/Clarification We would like to have the Geological setting composed of two sub-sections: one about regional information and the second about previous results. This is because we have a large figure there showing results from using unsupervised learning. So if it was in the Results section, one could be confused whether this a new result or an old one. But this is an old result which is shown in the manuscript to better see the added value of using supervised classification. We agree that some of the figures required editing. Regarding the question about synthetic data and borehole data: you can imagine that synthetic data are also (synthetic) borehole data. Actually, we believe that it is of less importance whether the data points are from boreholes or other sources. It is more important whether the points are sampled from a surface with preferred orientation.	We divided Geological setting into two sections: • 2.2.1 Regional and geometric background • 2.2.2 Discussion of previous results Figure 5 (now Figure 6) has been corrected. Now, we have white points for better contrast. We added a paragraph to Introduction that states the assumptions in a more explicit way. A new figure illustrating the assumption was added as well.

Based on the comments from two Referees, we have improved the figure as follows:

- dark blue on panel A was replaced with white
- “elevation” instead of “scalars”
- additional legend to points on panel “f”



2.

Suggestion, Question, or Comment from the Reviewer #2	Author’s Response	Change in the Manuscript
Specific comments 0.- Short Summary This section does not look necessary to get the correct general idea of the manuscript, just like the words "to classify terrain shape or nearby features" when the main goal is fault detection.	**Clarification** We agree that the words "to classify terrain shape or nearby features" may be confusing. However, we must have the Short summary because it is mandatory in GMD.	We have rewritten the Short summary to better reflect the intention that we detect faults with triangulated models.

3.

Suggestion, Question, or Comment from the Reviewer #2	Author’s Response	Change in the Manuscript

1.- Introduction line 38 "lineament/fault" is not recommended to use the "/" in formal manuscripts. The training set of Figure 1 looks very similar and has short faults but is rotated in different 3D positions. It looks like quite a simple idealized model. Could you add more complexity, such as fault displacement variation?? In Figure 3 and general, it is better to be specific with quantities instead of using the term "many."	**Clarification** We agree that "/" can be avoided. Regarding the old Figure 1 (now Fig. 2): this is only an illustration that we use triangulated terrains in the training data. Of course, we don't have only three terrains in the training data but one thousand terrains. Adding complexity in terms of fault displacement variation can be a good idea in future developments but in this study, we investigate if the simplest scenario works. We agree about using quantities.	In most cases, we deleted "/" and replaced it with "or" . In this particular case (l. 38), we decided to make it shorter: "to predict possible fault presence" We replaced "many" with "one thousand" regarding the number of terrains.

4.

Suggestion, Question, or Comment from the Reviewer #2	Author's Response	Change in the Manuscript
2.- State of the art I prefer to call this section "Background" instead of "State of the Art."	**Agree**	Done

5.

Suggestion, Question, or Comment from the Reviewer #2	Author's Response	Change in the Manuscript

2.2 Geological Setting As I mentioned earlier, this section needs to be completed, and 105 paragraphs sound like a discussion instead of describing a geological terrain or setting.	**Clarification** We would like to have the Geological setting composed of two sub-sections: one about regional information and the second about previous results. This is because we have a large figure there showing results from using unsupervised learning. So if it was in the Results section, one could be confused whether this is a new result or an old one. But this is an old result which is shown in the manuscript to better see the added value of using supervised classification. We agree that more geological information can be good for discussing Results.	We divided Geological setting into two sections: • 2.2.1 Regional and geometric background • 2.2.2 Discussion of previous results We added more geological information in Discussion (5.3 Complexities of real data)

6.

Suggestion, Question, or Comment from the Reviewer #2	Author's Response	Change in the Manuscript
3.- Methodology 3.1 .- Genereting terrains It needs to be rewritten for clarity.	**Agree**	Section 3.1 has been rewritten.

7.

Suggestion, Question, or Comment from the Reviewer #2	Author's Response	Change in the Manuscript

3.2 Selecting meaningful and consistent variables I think that some terminology upgrades can be made here, like "variable features" or "feature" instead of just "variables," which could be general and prone to confusing terms.	**Agree/Clarification** We would prefer to use the term "features".	We replaced "variables" with "features". We first introduce the term "input variables" in the abstract and later on the term "features" is used, for brevity. To avoid ambiguity with other applications and meaning of "features", we replaced the term "features" with "patterns" in the Discussion (5.4 Modelling assumptions").

8.

Suggestion, Question, or Comment from the Reviewer #2	**Author's Response**	**Change in the Manuscript**
3.3 Visualization This section is too short; eliminate or combine it with other sections.	**Disagree** We decided to expand this section and rename it because the concept of "spatial clustering" (Fisher, 1993) is not only about visualization. It is also about investigating directional information separately from spatial information. The spatial information is added at the end when the clusters of directional information are identified. Our study can be considered a very specific version of the concept where clusters are identified using geometric information and supervised classification.	We added more information regarding the concept of "spatial clustering". We replaced the section name "Visualization" with "Spatial clustering".

References

Fisher, N. I.: Statistical analysis of circular data, Cambridge University Press, 277 pp., https://doi.org/10.1017/cbo9780511564345, 1993.

9.

Suggestion, Question, or Comment from the Reviewer #2	Author's Response	Change in the Manuscript
4 Results. In line 217, the parentheses are incorrectly placed. Additionally, there needs to be more essential details typically included in a machine learning approach, such as the number of samples used for training and testing and the number of correctly classified samples. The sections overall appear too brief; therefore, it would be beneficial to provide a more thorough description of the experiment to ensure that others can fully understand the methodology and results.	**Agree** In our study, we used 1000 triangulated terrains with 100 points in every terrain. This configuration resulted in the initial number of 185980 triangles. We removed collinear configurations (collinearity>0.90) and triangles which did not have three finite neighbors. As a result, 145297 triangles remained. And only a small fraction of triangles are fault-related triangles (12411 vs 132886). Therefore, to reduce class-imbalance, we randomly select 12411 observations from the class with non-fault observations. Taking all considerations into account, we have 24822 samples with 12411 observations for each class (-1 and 1). Then, the set was divided into training (18616) and test (6206) set. The below results were obtained before hyperparameter tuning (the sum relates to the number of samples in the test data): 2993 (true negatives) 243 (false positives) 123 (false negatives) 2847 (true positives)	Information have been added.

10.

Suggestion, Question, or Comment from the	Author's Response	Change in the Manuscript

Reviewer #2		
5.- Discussion This section is challenging to follow; I suggest it be rewritten for clarity.	**Agree** We agree with Reviewer #1 and Reviewer #2 that this section can be divided into sub-sections.	Discussion section has been divided into sub-sections according to comments from Reviewer #1. We also transferred the more “analytical” part of the Conclusion section to Discussion according to suggestions from Reviewer #2.

11.

Suggestion, Question, or Comment from the Reviewer #2	Author’s Response	Change in the Manuscript
6.- Conclussions. This section reads more like a discussion than a conclusion. Only lines 294 and 295 align with the intent of a conclusion. While the section is well-explained, I recommend relocating it to the discussion section.	**Agree**	We transferred the more “analytical” part of the Conclusion section to Discussion .