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28 April 2020

Dear Professor Frederico Rossetti,

My co-authors and I are now resubmitting our manuscript entitled “A review and evaluation of the methodology for digitising 2D fracture networks and topographic lineaments in GIS”. The three reviewers provided helpful comments that have greatly improved the quality and clarity of our manuscript.

We have included a response to all the comments made by the reviewers, both the general and the line by line comments. In addition, we have included a tracked changes version of the manuscript, which contains all the changes that were made.

Thank you for taking the time to consider our manuscript for publication with Solid Earth.

Yours sincerely,

Dr Romesh Palamakumbura

Response to reviewers:

Reviewer 1

Reviewer 1 has accurately pointed out the paper is aimed at a broad range practitioners, beyond the realms of structural geology, particularly as open access GIS software because more accessible. Below we address your various comments regarding clarifying the manuscript.

1) The paper is slanted towards the applied geoscience communities particularly engineering geology community, and focuses on the data collection methodology rather than the sample selection challengers. This is because such challengers relating to sample selection would be very dependent on the nature of the study untaken, however we agree that useful reference would be beneficial therefore we have now included a new section called 'outcrop selection' to introduce the reader to importance of outcrop selection.
2) The balance between the benefits of the speed of the method and the potentially accuracy issues is important. This issue is discussed in the Andrews et al., 2019 paper, which is referenced lien 188. We did not feel it was necessary to discuss this further as the approach for limiting this error will be dependent of the type of study undertaken which is beyond the breadth of this paper.
3) This opening sentence is important because it states early outright the broad potential users of this method.
4) Line 11: will correct the font of this line.
5) Line 20-21: The drawbacks of the technique are discussed in detail later on in the text and hence we do not feel it is necessary to do so in the abstract.
6) Line 23-30: This is an important point and needs to be addressed by moving current reference and several additional references to the appropriate parts of the text to show wide variety of applied geoscience studies that could use this methodology.
7) Line 33: We agree with this correction.
8) Line 53-54: This is an important point however, it is beyond the scope of the paper as it related to the understanding of fracture topology, while the point of the paragraph is demonstrate the method aids topology analysis.
9) Line 54: This is an important point and we have now included a short sentence to reference this point and a reference to the Laubach et al. (2009) paper.
10) Line 57: Removing the word 'very' would help sharpen this sentence.
11) Line 59: This is helpful correction and we will move lines 57–58 to the previous paragraph.
12) Line 37-56: This is an important point and we believe would better suited in the pros and cons sections of the paper. We have no included a short discussion of this point in the pros and cons sections of the paper.
13) Line 62: We agree with this comment and would change 'decent' to 'high-quality'

14) Line 75: This is very important point and we have now included a section on outcrop selection and the Ukar et al 2019 reference. Although this is beyond the scope this study and will be highly variable depending on the type study hence we have only briefly introduced this idea.
15) Line 184: Earlier on we state that this method is ideally used in conjunction with such packages. Specifically, DigiFract is not included in this list but this would be a beneficial correction.
16) Line 185: We agree with deleting the term 'detailed' to make the sentence concise.
17) Line 199: We changed the emphasis of this sentence so that it is not suggesting an exhaustive list of fracture parameters but introducing the idea of more evolved digital analysis of fracture network data.
18) The common use of 'fracture height' is dependent on the type of study, as with the previous point we are not providing a comprehensive list but a selection of potential derived parameters.
19) Line 202: This is an important clarification and we have now changed the emphasis of this paragraph to making the reader aware of the multiple geological and anthropogenic causes of fractures that will vary depending on the type of outcrop. The type of fractures digitised and interpreted will depend on the type of study undertaken.
20) Line 217–202: A reference to the Laubach et al., 2019 paper here would provide the reader of sufficient background into these concepts.
21) Line 266–270: The scope of this paper is does not include a review of fracture network understanding and we feel this would be beyond the scope of the paper. We have use the coefficient of variation (Cv) in this case to simply quantitatively demonstrate the difference in clustering between fracture zones and background Peninsular gneiss.
22) Line 268: Correct spelling of 'Odling'.
23) Line 292: We agree with this correction of the positioning of the acronym.
24) Line 301–310: This is a valid point however, the point of the paragraph is to improve the accuracy and consistency of the method commonly used in engineering geology rather than assess the method itself.
25) Line 311–319: This is again a valid point, however these are parameters that are commonly used in engineering geology and it is beyond the scope of the paper to review this.
26) Line 320–322: This is the comparison between the qualitative method after Hoek (1983) and the modified version of this after Sonmez et al. Thus, the idea is that instead of using only subjective decisions about surface quality and fracture system as described by Hoek, the described methodology for digitising 2D fracture networks and topographic lineaments in GIS is useful when using the more quantitave GSI table suggested by Sönmez and Ulusay.

27) Line 361: We agree with this statement, as we haven't discussed the use of this method at the microscale, we would clarify this statement that the method can be used at the local outcrop and regional DEM scales.
28) Line 366–368: We are not stating that the digital method is 'more' accurate than the paper method but that it is a fast and accurate alternative. For rock mass strength characterisation, the method we suggest is more accurate as we introduce a quantitative way of calculating the geological strength index.
29) Finally, a thorough check to make sure the references in the text are mention in the comments will be made.

Reviewer 2

Review 2 has identified two main issues firstly, in regard to the novelty of the method and secondly, the usefulness of the method for the geological community. The novelty and usefulness of the method must be considered in terms of the intended audience of the paper. The manuscript describes a method that is not commonly used in applied geology communities and developing countries due to limited specialist knowledge and software. This manuscript presents a detailed breakdown of the technique, with particular emphasis on using open access software. The paper, is not proposing a new method but providing a breakdown of the pros and cons of digital fracture trace analysis, particularly for users outside of structural geological and particularly for users in developing countries.

In introduction of the paper we provide a brief overview of outcrop-based 1D to 3D fracture network analysis, which is aimed as an introduction to the basic concepts around fracture network analysis for non-structural geologist and users working in a broad range of fields. However, we acknowledge that a basic summary of the various studies that have used this type of method as the basis for detailed fracture network analysis would be beneficial for the reader. We believe a short paragraph in the introduction that introduces these studies would be helpful. Further detailed discussion of these type of work is beyond the scope of this study.

Regarding the usefulness of the technique, this is proven by the various studies that use it as the basis of more evolved fracture network analysis in the references provided for the suggested method background section. Hence, the examples provided demonstrate in detail how the method can improve the data collection process for a wide range of users, including engineering geologist, geomorphology and for groundwater modelling.

Francesco Mazzarini

Finally Francesco Mazzarini indentified three main issues including a better overview of the users of this method in fracture network analysis; secondly, a more evolved description of the pros and cons of the various methods of fracture data acquisition; and finally, a more detailed comparison of the results from different methods.

As part of the introduction a basic summary of 1D-3D fracture analysis is provided, however we acknowledge that this does not describe in detail the other various digital methodologies used to interpret fracture network traces, hence we would include a short summary that provides the reader with an insight into the broad range of studies that have used this method.

In the introduction of the paper, we briefly summarise the original method for measuring fracture networks in the field. Understanding the detailed pro's and con's of this field based method is important for understanding the benefit of carrying out the method digitally. An additional detailed description of the original field method could be provided, although we feel that this would be better served as a short paragraph as part of the introduction.

Finally, the qualitative and quantitative benefits of the method are demonstrated with various case studies. For each case study, we outline in detail how the digital method can be used to improve both the data collection process and the final dataset in certain circumstances. There is a broad range of benefits for using a digital method for collecting fracture data that affect various stages of the data gathering and analysis process. For example, the reliability and speed of initial data gathering, improving accuracy of the dataset and finally allowing for more evolved data analysis. Rather than only focussing on the benefits of the results, we have used a more multi-dimensional approach where we discuss the wide the ranging benefits of using a digital method. This point has not been fully brought out from the case studies, hence we would include a short summary at the end of the case study section to synthesis (section 4.4) the broad benefits of using a digital method on various aspects of fracture network analysis.

Line 43: The suggestion to include a reference to SfM methods here is very helpful and we have now included this.

Line 78: 'List of QGIS tools': This sentence is an introduction to this section and the QGIS tools used are described in the relevant parts of the following section.

Line 112: Illumination bias in DEMs: This is an important point regard bias with fracture lineaments in DEMs, which hinted at with work of Pless (2012), and using satellite images and geological maps

alongside any DEM work. To develop this, we have now included a sentence about bias resulting from the satellite position relative to the feature in the paragraph.

Line 205: Distinguishing blast damage from natural joints: We have now included a description if blast damage joints and how to identify them.

Line 267: Coefficient of variation reference: We have now included the Gillespie et al., 1999 reference as well in this line.

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A review and evaluation of the methodology for digitising 2D fracture networks and topographic lineaments in GIS

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Abstract. Understanding the impact of fracture networks on rock mass properties is an essential part of a wide range of ~~fields~~ applications in geosciences, from understanding permeability of groundwater aquifers and hydrocarbon reservoirs to erodibility properties and slope stability of rock masses for geotechnical engineering. However, gathering high quality, oriented-fracture datasets in the field can be difficult and time consuming, for example due to constraints on time or access (e.g. cliffs). Therefore, a method for obtaining accurate, quantitative fracture data from photographs is a significant benefit. In this paper we describe and evaluate the method for generating a series of digital fracture traces in GIS-environment, in which spatial analysis of a fracture network can be carried out. The method is not meant to replace the gathering of data in the field, but to be used in conjunction, and is well suited where fieldwork time is limited, or where the section cannot be accessed directly. The basis of the method is the generation of the vector dataset (shapefile) of a fracture network from a georeferenced photograph of an outcrop in a GIS environment. From that shapefile, key parameters such as fracture density and orientation can be calculated. Furthermore, in the GIS-environment more complex spatial calculations and graphical plots can be carried out such as heat maps of fracture density. There are a number of advantages to using a digital method for gathering fracture data including: time efficiency, generating large fracture network datasets, flexibility during data gathering and consistency of data.

1 Introduction

Fractures are the main pathways of fluid flow in rocks, and exert a strong influence on rock mass properties. The characterisation of fracture networks is an essential aspect of various ~~parts of~~applications in earth science, for example to understand and predict the behaviour of fluid flow in groundwater aquifers (Singhal and Gupta, 2010; Follin et al. 2014) and hydrocarbon reservoirs, and the erodibility and slope stability of rock masses. Fracture network data are essential for assessing future sites of nuclear waste repositories, predicting rock slope stability (Selby, 1982; Park et al., 2005) and understanding intact rock strength for engineering of infrastructure (~~e.g. Selby, 1982;~~ Hoek and Brown, 1997~~; Singhal and Gupta, 2010; Park et al.,~~

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~~2005; Follin et al. 2014~~; Zhan et al., 2017; Ren et al., 2017). For 2D fracture network analysis, there are a number fracture parameters that are widely used, including orientation, spacing, length, density/intensity and various connectivity proxies (summarised in Singhal and Gupta, 2010; Sanderson and Nixon, 2015; Peacock et al., 2016; Laubach et al., 2019). In this paper, we present and evaluate a 2D digital fracture network analysis method that is commonly in use in structural geology, and through numerous case studies we demonstrate the ~~potential~~ wider ~~uses~~ potential of this method for other users, for example geotechnical engineers, groundwater modellers and geomorphologists (Figure 1).

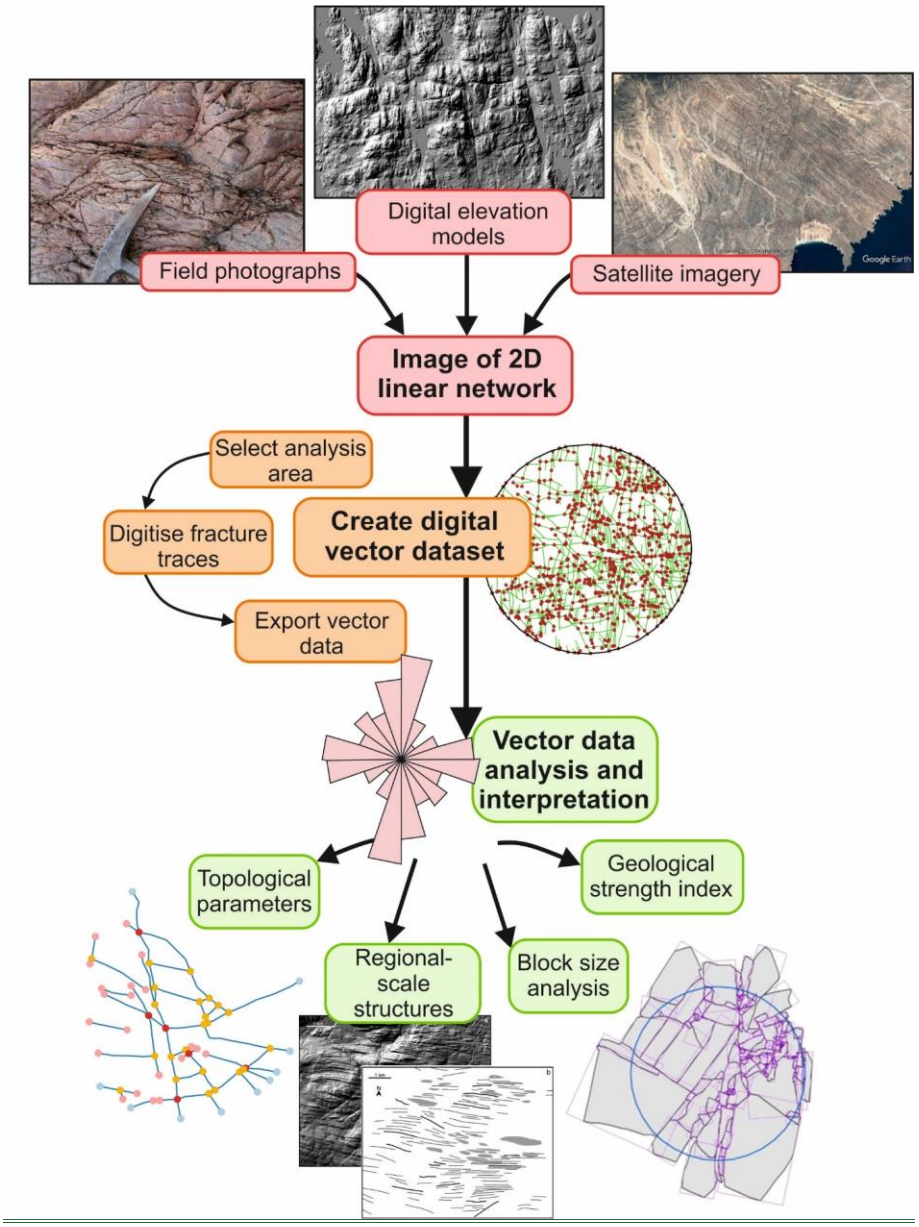

Figure 1: Flowchart providing an overview of the methodology used for digitising linear features, from preparing an image, digitising the features to output of data. Digital elevation model examples are taken from Next map © in Scotland, and the satellite image of Oman example is taken from Google Earth ©.

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Fracture networks can be characterised in different dimensions using a number of approaches. 1D approaches include borehole fracture analysis and outcrop-based scanline surveys, typically represented by the number of fractures per unit length, i.e. frequency. 1D approaches are relatively rapid, but cannot directly constrain certain parameters such as fracture length and connectivity: if the fracture network is anisotropic (which is ~~usually~~ commonly the case), the characterisation is biased by the orientation of the scanline or the borehole ('orientation bias'; Singhal and Gupta, 2010; Zeeb et al.~~,~~ 2013b; Watkins et al. 2015b). 3D (really 2.5D) outcrop analysis using laser scanning provides a fuller analysis (e.g. Pless et al., 2015) but requires expensive equipment and is time-consuming in its processing. Unmanned Aerial Vehicles (UAVs) are used to generate high resolution images of an outcrop, with 3D information generated with techniques such as structure from motion (SfM) photogrammetry (Vasuki et al., 2014). True 3D characterisation is possible using CT scanning, but is restricted to very small samples (Voorn et al. 2015). As a compromise, many studies employ a 2D approach. ~~-~~Normally, this uses some form of characterisation within a circular window ~~of~~ on a rock outcrop (Davies ~~&~~ et al~~Reynolds~~, 1996; Rohrbaugh et al. 2002; Watkins et al. 2015a). Generally, for 2D analysis a circular scanline or window approach is taken.~~,~~ ~~I~~In the former fractures intersecting the circular line are recorded, whereas in the latter fractures within the ~~line~~ window area are recorded. Circular scanline methods are more rapid than full 2D circular window methods and~~,~~ have less length and orientation bias compared to 1D methods. ~~,~~ A circular scanline can be used to calculate proxies for fracture density and length based on the ratio of the types of trace intersection (Mauldon et al. 2001). ~~but~~ However, circular scanline ~~analysis~~methods lack the full analysis of a complete 2D circular window approach. ~~A circular scanline can be used to calculate proxies for fracture density and length based on the ratio of the types of trace intersection (Mauldon et al., 2001).~~ Connectivity within two-dimensional fracture networks was parameterized by Manzocchi (2002), who characterised the different types of fracture intersections that can be used to characterise fluid ~~flow properties~~percolation potential. A complete understanding of the fluid flow properties of a fracture network requires a broader understanding of 3D fracture network connectivity factors, such as fracture fill and aperture (Laubach et al., 2019).

Field-based 2D fracture network analysis is commonly carried out by~~A full 2D circular window characterisation in the field,~~ using a circular 'chalk line' on and outcrop and measuring the fractures within the circular window. The benefit of the field-based method is an accurate data set that includes a range of parameters from fracture geometry (Singhal and Gupta, 2010) such

Commented [KM1]: This is needed to separate from the 1D scanline..

as length and orientations, fracture network parameters (Singhal and Gupta, 2010) such as density and spacing, network topology (Sanderson and Nixon, 2019) such as percolation potential, and clustering and fracture character (Laubach et al., 2019) such as aperture and paragenesis history. However, there are a number of limitations when gathering fracture network data in the field. Ffirstly this can be very time consuming particularly when collecting large datasets across a large field area. Secondly, some ~~of the~~ outcrops such as quarries or unstable cliffs ~~might~~may not be impractical or unsafe to access for making fracture measurements. Thirdly, collecting fracture network data from larger fracture networks of greater than 10 m can be challenging in the field, particularly when collecting fracture data from an entire outcrop. Finally, more evolved modern fracture network analysis and modelling often require a digital set of the fracture network traces.

The ~~is a very time consuming method, and requires the outcrop to be fully accessible which may not be practical or safe.~~ digital fracture trace method has been used for data collection in a range of structural geology studies, including multiscale fracture network models (Strijker et al., 2012), the development of 3D fracture models (Tavani et al., 2016; Menegoni et al., 2019) and developing discrete fracture networks (DFNs) to model fluid flow (Bisdom et al., 2017). This methodology is used as the basis of data generation in a broad range of structural studies, and this paper provides an evaluation of the method that will be helpful to improve the quality of data collection.

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Building on previous work (Krabbendam and Bradwell, 2014; Pless et al., 2015; Watkins et al., 2015a; Krabbendam et al. 2016; Healy et al., 2017) we present and develop a method for capturing a 2D fracture network as a digital (GIS) dataset from outcrop photographs ~~as a digital (GIS) dataset~~. From this dataset, numerous key spatial relationships and parameters can be calculated. The only equipment needed are a ~~decent~~ high-quality digital camera, a measuring stick and GIS software (e.g. open source QGIS) for digitisation and analysis. This method can also be applied to georeferenced (orthorectified) aerial photos, hillshaded DTMs and satellite imagery for the characterisation of topographic lineaments. In addition, historic photos from now-infilled excavations or quarries can be used, as long as the photos have a useable scale. The method provides a relatively rapid and accessible way to generate accurate 2D fracture datasets and will be beneficial for a wide range of users including engineering geologists and hydrogeologists.

2 Digital 2D fracture analysis method

The method in essence captures a set of digital traces (vectors) of a 2D linear feature network in a GIS project from a georeferenced image. Here, we use open source GIS software (QGIS),

making the method accessible to all potential users. A number of open tools within QGIS can be used for more advanced analysis of the digitised fracture network.

2.1 Outcrop selection

A suitable outcrop for digital fracture analysis must be first selected. Where spatial understanding of the distribution or diversity of fracture characteristics in a region is an important element of study, the implications of site selection choice on subsequent spatial analysis must also be considered.– The outcrop selected will depend on the nature of the study being undertaken and the type of fracture network parameters required. It is important to consider whether the outcrop is representative of the rock mass as a whole or whether multiple sites would better represent the diversity or distributions of fracture characteristics. Outcrop selection has significant implications on the final results, i.e. whether the outcrop is a proxy for wider-scale fracture network characteristics at depth or if it is the outcrop itself that is being studied in isolation at the surface (Laubach et al 2019; Ukar et al 2019). ~~Where spatial understanding of the distribution or diversity of fracture characteristics in a region is an important element of study, the implications of site selection choice on subsequent spatial analysis must also be considered.~~

Commented [WK2]: I think the key point is that in addition to the technical considerations of the method, site choice must be based on consideration of 1) how representative a particular site is of the rock mass as a whole, or 2) whether a collection of multiple sites are representative of the true diversity or distribution of fracture characteristics across a region. I suggested adding a sentence to reflect the latter point, but the paragraph could perhaps be reframed to bring this out a bit more clearly?

Commented [WK3]: I think the key point is that in addition to the technical considerations of the method, site choice must be based on consideration of 1) how representative a particular site is of the rock mass as a whole, or 2) whether a collection of multiple sites are representative of the true diversity or distribution of fracture characteristics across a region. I suggested adding a sentence to reflect the latter point, but the paragraph could perhaps be reframed to bring this out a bit more clearly?

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2.~~2~~1 Outcrop image preparation

The first step is to prepare a suitable photograph or image of the outcrop to be analysed. The image can be a photograph of a fracture network at outcrop of various scales from centimetres to 10s of metres. It is important that the fractures can be clearly identified in the photograph, and that not too much of the image is occupied by vegetation or broken ground (Figure 2a). It is important to include an accurate and clearly identifiable scale; a strip of plywood with duct tape works very well. However, in some dangerous outcrops (e.g. working quarries) this may be impractical and quarry machinery or other features of known dimensions may be used as a scale in the photograph. The photograph should be taken at right angles (or as much as possible) to the outcrop to minimise the issues created by a distortion of the image. The camera should have a focal length of 35mm (analogue 35 mm equivalent) or longer, to prevent further distortion. Horizontal outcrops should be photographed vertically to again minimise the distortion of the fractures. Mounting the camera on a stick is useful to increase the distance and capture a larger field of view (Figure 2b, c); or drones could also be used. For horizontal outcrops it is convenient to orient the measuring stick accurately to the north, using a compass (Figure 2c), this will help in capturing the correct orientations of the fractures.

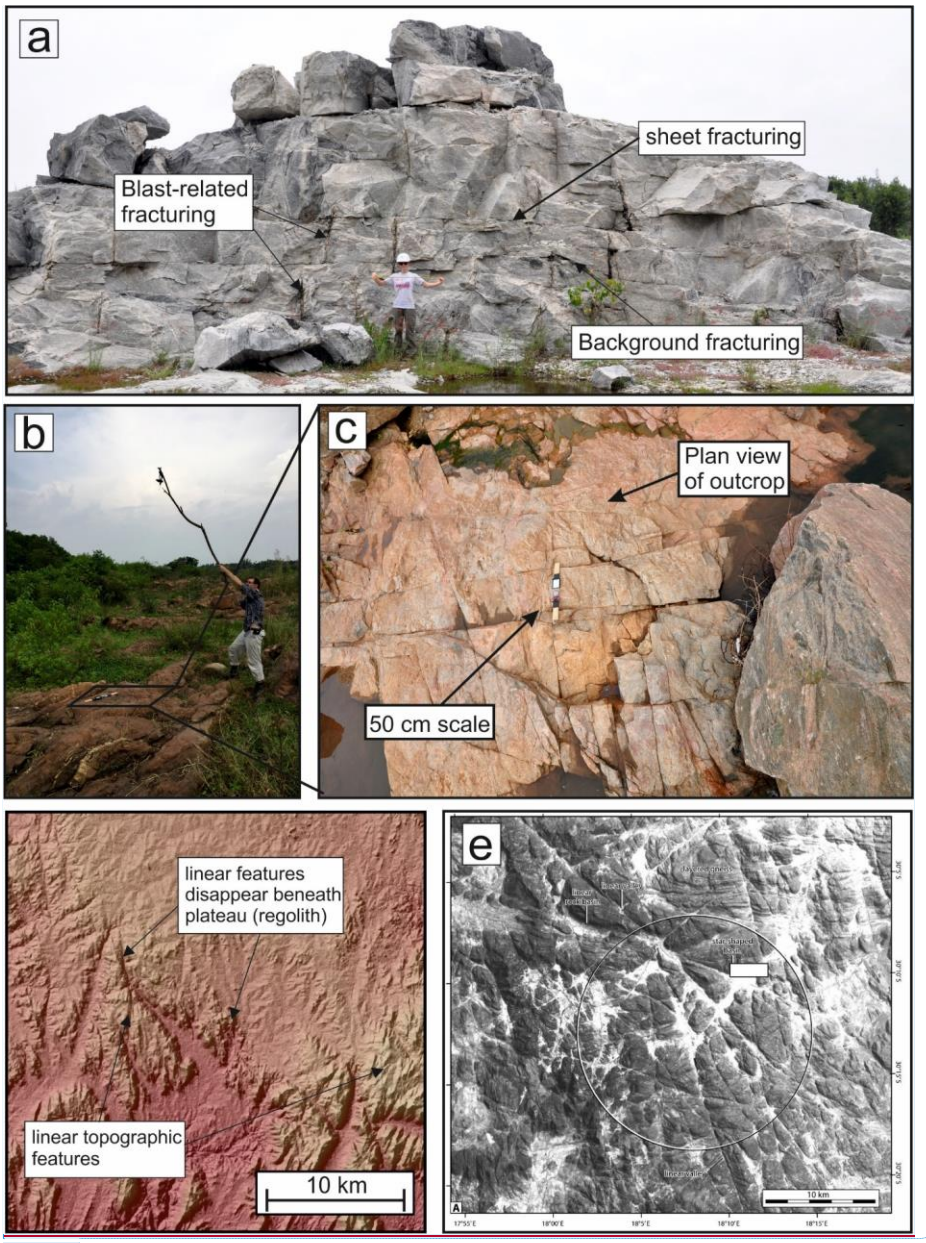

Figure 2: Examples of photographs and DEM images that can be used for digitising 2D linear features, including: (a-c) photographs of fracture networks of various scale from southern India and improvised methods for taking parallel photographs; (d) a DEM image from southern India of larger kilometre scale features that could also be digitised; and (e) an aerial photography from Namibia (adapted from Krabbendam and Bradwell, 2014).

Commented [KM4]: A: 'sheet jointing' better than 'sheet fracturing'?
B: white lines would work better: I can barely see the black lines…
D. 'D' is missing… also, not sure what linear topo features points to (?arrow has moved?)

2.3 Georeferencing the images

Commented [KM5]: Move this up (to be section 2.2.)? it is not relevant for the DEM imagery…

To aid robust georeferencing, the photograph needs to have a square of known size (e.g. 1 x 1 m) embedded in it. This can be done by importing the photograph into a graphics software package (such as Inkscape), and drawing a square based on the scale included in the original photograph (Figure 3). The photograph with the embedded 1 x 1 m square is then imported into a new GIS project file. The GIS project file needs a projection in metres; we recommend a Mercator projection, (such as EPSG:3857). Within the GIS project, a 'vector grid' (fishnet grid) is created, with a grid extent that is larger than the imported photograph and with a vertical and horizontal spacing of 1.0 m. Finally, georeference the square on the photograph to a square on the fishnet grid, thus creating a georeferenced photograph within the GIS project (Figure 3a).

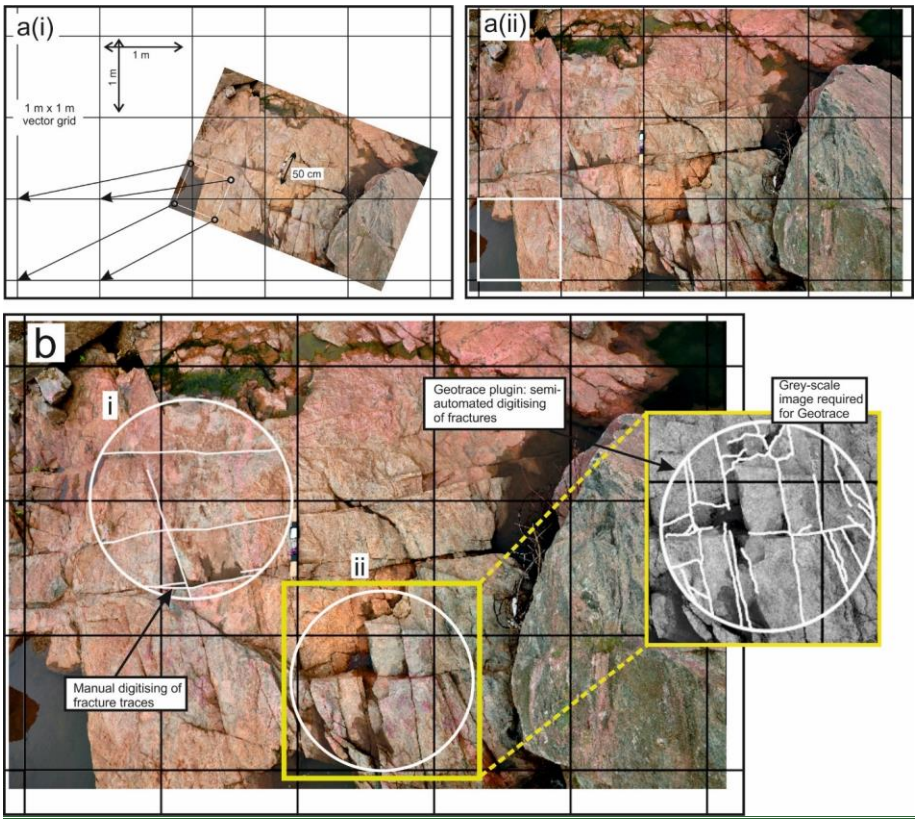

Figure 3: Images showing (a (i-ii)) how to georeference an image to a fishnet grid (black) from a square of a known scale (white); and (b) the tools available for digitising fractures in QGIS, including (i) a fully manual method; and (ii) a semi-automatic method such as Geotrace.

~~. allow corrections to be made for fracture orientations.~~

Commented [KM6]: I think 'corrections' is not appropriate.

2.~~2~~ Using DEM, satellite and airphoto images

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DEMs (Digital Elevation Models) (and their hill-shaded derivatives), satellite images and (orthorectified) aerial photographs commonly show good topographic lineaments that likely represent fracture zones, or master joints (Fig. 2d,e). Such imagery if georeferenced can be used directly without further preparation. It should be noted however that aerial photographs, DEMs and satellite images do not directly show fracture traces, rather they show the topographic expression of these. Thus, fracture density is likely to be underestimated, because fractures ~~with no~~without topographic expression will not be captured. Figure 2d is an example of a DEM image from southern India showing kilometre-scale 2D topographic lineaments: in some parts lineaments are well developed, in other parts fracture zones have no expression and presumably occur beneath a continuous layer of regolith. Furthermore, such imagery is limited by the on-ground resolution, so that smaller-scale (smaller aperture) fractures may not appear. Hill-shade DEM images, as well as satellite imagery and ~~airphotosareal~~aerial photographs have the problem of bias by a particular direction of illumination, so that lineaments of one orientation may be clearer than others. For DEM~~S~~s, hill-shades derivatives with different illumination direction can be made; for satellite imagery, sometimes imagery taken at a different time of day are available. Lineaments in DEM images also have the problem of illumination, which may result in bias depending on the orientation of the lineament relative to the illumination orientation~~ed~~. Hence, f~~F~~or DEM-scale interpretations it is important to take a multi-data type approach (e.g. geological maps and satellite images) to guide digitisation, similar to that of Pless (2012).

~~**2.3 Georeferencing the images**~~

Commented [KM7]: Move this up (to be section 2.2.)? it is not relevant for the DEM imagery…

~~To aid robust georeferencing, the photograph needs to have a square of known size (e.g. 1 x 1 m) embedded in it. This can be done by importing the photograph into a graphics software package (such as Inkscape), and drawing a square based on the scale included in the original photograph (see Figure 3). The photograph with the embedded 1 x 1 m square is then imported into a new GIS project file. The GIS project file needs a projection in metres; we recommend a Mercator projection, (such as EPSG:3857). Within the GIS project, a 'vector grid' (fishnet grid) is created, with a grid extent that is larger than the imported photograph and with a vertical and horizontal spacing of 1.0 m. This will create a 1 m by 1 m vector grid (i.e. a fishnet grid) in the~~

~~GIS project. Finally, georeference the square on the photograph to a square on the fishnet grid, thus creating a georeferenced photograph within the GIS project (Figure 3a).~~

~~2.5~~ ~~2.4~~ Data capture

~~2.4.1~~ 2.5.1 Select analysis window

Different 2D lineament analysis windows can be used with this method including line scanlines, areal sampling and circular windows. For each of these methods a different shaped sample window is required. For this create a line or polygon shapefile and digitise the area that is to be analysed. An example is shown in Figure 3b as two circular windows, in white, digitised onto a photograph in GIS. It is important to create a different id number for each shape that includes details of the photograph or image that is being digitised.

~~2.4.2~~2.5.2 Digitise linear features

This step aims to create a series of digital line traces from the georeferenced image. Create a new line shapefile in the GIS project to hold the linear trace data. The shapefile needs to include an id column in the attribute table so that the linear traces can be associated with a specific window and photograph. Two methods can be used to create digital traces of the linear features. Firstly, the individual features can be digitised manually in the GIS project, using the "add line features" tool. Alternatively, the plugin tool ~~"~~"GeoTrace~~"~~" can be used to semi-automate the digitising process. The GeoTrace plugin tool in QGIS allows one to click on the start and end of each fracture and GeoTrace creates a line vector between these points. For this method the photograph must be in grey scale, because the plugin follows the linear feature based on low raster values and requires a sharp contrast between the feature and the background. When digitising fracture traces it is important to only digitise in one orientation: if a feature has multiple orientations along its length then multiple line~~s~~ segments should be digitised. Figure 3b is an example of both (i) manual digitisation and (ii) semi-automated digitisation with GeoTrace. In both the manual and semi-automated methods, it is important that connecting fractures are properly snapped against each other, and to the surrounding circular window.

A practical difficulty when analysing field outcrops will depend on whether the outcrop is natural or anthropogenic. In a quarry or excavated section it can be challenging to distinguish natural joints from those arising from quarrying processes, such as blast damage or drilling related fractures. Using field observations, blast damage can be separated from natural joints (Figure 2a). Joints arising from blast damage can easily be distinguished from natural joints as they do not fit with the overall fracture pattern of the section, and are generally surrounded by small radiating fractures. The type of fractures digitised will be depend on the study, and it is

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Commented [KM8]: This section – if you think about it – better belongs in Section 2.5.2 Digitise linear features, because it impacts on HOW you digitise..

important to appreciate the wide range of processes causing fractures that are dependent on the outcrop setting. Some basic initial observations in the field are beneficial for making such distinctions at a later stage; hence, it is recommended that the outcrops that are being analysed are always viewed in the field as well.

2.~~6~~5 Data output and further analysis

The final step is to generate basic parameters and calculate dimensions from the digital traces of the linear features. There are a number of different ways that the vector data can be analysed, which include: 1) using the field calculator in QGIS; 2) as an exported spreadsheet; or 3) using a programming language such as Python or ***R*** to make calculations from the spreadsheet or directly from the shapefile.

Primary parameters can be calculated within the field calculator in the QGIS attribute table, including length and orientation of individual fracture traces. The area of the circular window can also be calculated in the attribute table using the field calculator. For further analysis, the attribute table containing the primary fracture data (length, orientation and reference to the circular window) needs to be exported as a spreadsheet, e.g. in CSV format. Fracture density (D) within the circular window can now be calculated using total length of fractures (ΣL) within the area of the circular window (A), following Singal & Gupta, (1999):

$D = \Sigma L/A$ (in m^{-1}) (1)

Fracture spacing (S) can be easily derived, as this is the reciprocal of fracture density, and is given by (Singal & Gupta, 1999):

$S = A/\Sigma L$ (in m). (2)

Other parameters, that can be derived from the digitised fracture network include the number and distribution of fracture intersections and block size. Fracture intersections (points) within the fracture network can be created as a separate point shapefile with the 'line intersection' tool. The digitised fracture traces can also be used to derive block size parameters, using the 'polygonise' tool to convert the line vectors into polygons. As before, parameters such as area can be derived using the field calculator in the attribute table and exported as a spreadsheet.

~~**3 Advantages and disadvantages**~~

~~The digital method described here is not meant to replace field-based data gathering but used in conjunction, as it may be more suitable for different purposes. There are a number of advantages to using a digital method for gathering fracture data including: speed of gathering data, creating large datasets, flexibility in data gathering approach and consistency of data. Gathering detailed 2D fracture network data in the field can often be a time consuming processes and therefore limits the amount of data that can be gathered during a field campaign.~~

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~~Using the digital methodology allows for fracture network data to be quickly gathered in the office, allowing for more data to be generated from an equivalent amount of time in the field. Field time can be used for detailed study of the outcrop to improve the interpretation of fractures in the office and to gather other key data such as aperture, fracture fill and 3D geometry's. The digital method allows for large, statistically significant datasets to be quickly gathered during a short field campaign. Collecting the data after fieldwork with a broader perspective provides an element of flexibility in terms of the selecting of outcrops for analysis, the type and shape of the sample window and the amount of the data gathered. Finally, the digital method has the potential to be used to improve the consistency and reliability of industry standards that involve fracture networks, such as rock mass strength estimates (Section 4.2) by reducing collector bias by standardising the data collection strategy.~~

~~For more evolved analysis of the fracture data the digital traces can be used in fracture analysis software packages such as FracPaQ (Healy et al., 2017), NetworkGT (Nymberg et al., 2018) and FraNEP (Zeeb et al., 2013). These programmes can be used for topological analysis such as deducing node types, and plotting fracture density heat maps illustrating density variations across a fracture zone.~~

~~A practical difficulty when analysing outcrops such as quarries,or excavated is to distinguish natural joints from those arising from blast damage. However, with experience based on field observations, blast damage can be separated from natural joints: on Figure 2a, some joints arising from blast damage are indicated, and can be easily distinguished from natural joints. Some basic initial observations in the field are beneficial for making such distinctions at a later stage; hence, it is recommended that the outcrops that are being analysed are always viewed in the field as well.~~

~~There are limitations with capturing the data digitally. Firstly, the capturing of data in the field will always be more accurate in terms of seeing the full extent of fractures: for example, fractures may be obscured by vegetation making digitisation of traces more difficult than in the field (Andrews et al., 2019). Secondly, field observations of the character of individual fractures such as roughness, aperture and any secondary fills can be important observations made only in the field and useful when understanding rock mass strength or permeability. It is also possible, of course, to digitise the fracture network, and then return to the outcrop and augment the digital traces with further attribution that requires direct field observation (e.g. fracture aperture, fracture fill); portable PC tablets are ideal for this purpose. Image scale can also be an issue with this method, as smaller fractures can be harder to digitise from a wider perspective photograph, therefore it is important to acquire photographs that cover the appropriate scale of~~

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~~fractures, which will be dependent on the purpose of the study. Estimates of fracture permeability and percolation when using topology alone represent the maximum potential and does not account of closed fractures. Additional observations such as aperture and infilling are import for these types of studies.~~determined

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3~~4~~ Case studies

Below we present a number of case studies that include fracture analysis for groundwater modelling; quantifying rock mass properties for engineering geology; and block size distribution to understand sediment erodibility that help demonstrate the potential broader uses of the digital GIS-based analysis of fracture networks.

3~~4~~.1 Understanding fracture connectivity and permeability, southern India

Characterisation of fracture networks is an important aspect of trying to understand local and regional-scale aquifer properties such as connectivity and permeability. This type of understanding is particularly relevant for groundwater studies in fractured 'hard-rock' aquifers, where fractures are the primary water stores and pathways (e.g. Stober and Bucher, 2007; Singal and Gupta 2010). An example is given here of the Peninsular Gneiss in the Cauvery Catchment in southern India. The groundwater properties of the Cauvery Catchment has been an area of ongoing research (Maréchal et al 2006, Perrin et al 2011, Collins et al. 2020) due to the spatial and temporal variability of groundwater availability and the impact that this has on local communities. Two contrasting basement fracture networks can be identified (Figure 4a-b): firstly, one massive gneiss with few fractures, dominated by a widely spaced 'background jointing' and sheeting joints close to the surface, and secondly 'fracture zones' that are characterised by a very dense fracture network.

Length-weighted ~~R~~rose plots show the variation in orientation of fractures (in a vertical section) in the two identified domains. In the massive gneiss the fractures are generally orientated sub-horizontally, with several short connecting vertical fractures. In contrast, fractures in the fracture zones are generally orientated sub-vertically with short connecting sub-horizontal fractures. The fracture density in the fracture zones is an order of magnitude higher than in the massive gneiss (Table 1). Using NetworkGT (Ny~~m~~berg et al., 2018), the fracture branches and nodes (intersections and fracture trace end-points) were characterised based on the topology of the branch intersections (Sanderson and Nixon, 2015). The massive gneiss is dominated by I-type nodes, whereas the fracture zones predominantly contain a combination of Y- and X-type nodes (Figure 4a-b; for node types see Figure 4g) (Table 1). Heat maps of intersection clustering from the massive gneiss versus a fracture zone illustrate the higher connectivity of the fracture zones. To quantify the connectivity across the Cauvery catchment area the connections per line

and dimensionless intensity (a proxy for intensity that reflects average fracture length) were calculated (following Sanderson and Nixon, 2015), (Table 1; Figure 4h). The connections ~~per line~~, i.e the number of X- and Y-nodes, per line~~,~~ length, is an indication of the percolation potential of a fracture network (Sanderson and Nixon, 2018). The fracture zones have the highest connections per line length and dimensionless intensity, suggesting they have the highest potential connectivity. In contrast, the background gneiss has the lowest connections per line and intensity suggesting a relatively low potential connectivity. The coefficient of variation (Cv) is calculated by dividing the standard deviation of the fracture spacing by the mean fracture spacing (Gillespie et al., 1999; Watkins et al., 2015b~~a~~) and is used to quantify the how clustered a fracture network is (Table 1) (Od~~d~~ling et al., 1999). The Cv ratios quantify the massive gneiss as generally having regularly-spaced fractures, while the fractures in the fracture zones are highly clustered (Table 1, Figure 4h).

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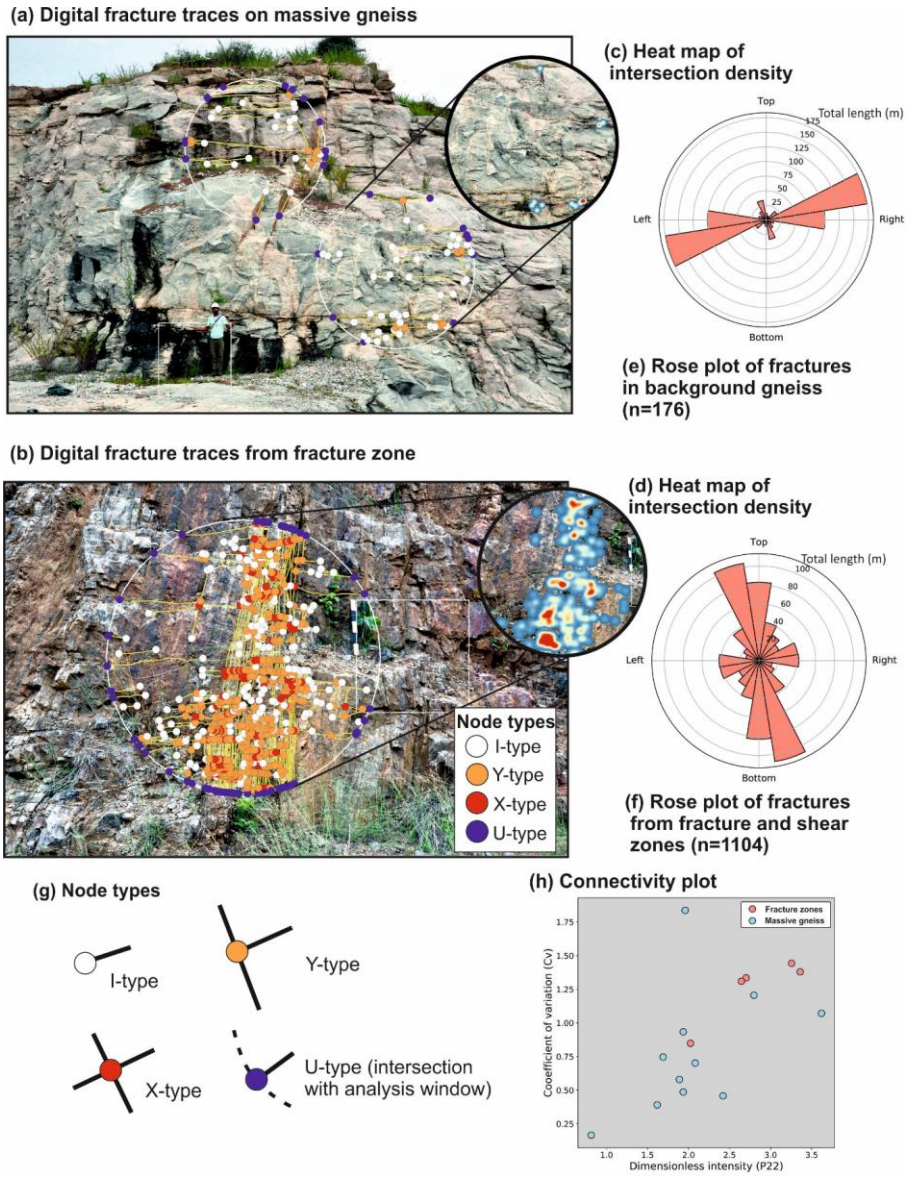

Figure 4: Fracture analysis from the Peninsular Gneiss, South India, including: field photographs with digitised fracture branches and intersection types on (a) a massive gneiss example; and (b) from a fracture zone; (c-d) heat maps illustrate variations in fracture intersection density (massive gneiss: 0-5 nodes/m^2 and fracture zones: 0-18 nodes/m^2); (e-f) length-weighted rose plots showing the variation in orientation of fractures traces in the background gneiss and fracture zones; (g) a schematic illustration of the various types of fracture connections (as defined by Manzocchi, 2002); (h) a plot of connections per line against dimensionless intensity (defined by Sanderson and Nixon, 2015) to show variations in connectivity.

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At the near-surface, the Peninsular Gneiss has a bimodal fracture density distribution with ~~areas~~ fracture zones with~~of~~ high fracture density that make up a relatively small proportion of the bedrock, and the majority of the crystalline basement ~~comprises~~ containing a low-density fracture pattern. Connectivity proxies, such as connections per line, indicate that the fracture zones have the highest potential permeability, whereas the permeability potential of the background gneiss is highly variable but still significantly lower.

In this case study, field time was limited and the digital method provided a quick and flexible way of gathering fracture network data. It was possible to carry out a reconnaissance survey ~~the~~ covering an area ~~that spans~~ over 30,000 km^2 and then retrospectively select the most suitable sites for fracture analysis. Key fracture parameters such as fracture length, orientation and density, which impacts on aquifer characteristics such as connectivity and permeability across the Peninsular Gneiss in the Cauvery River catchment, where then calculated and used to constrain local and regional-scale groundwater models (Collins et al. 2020).

3~~4~~.2 Rock mass strength estimates (Geological Strength Index)

Structural discontinuities are an important control on the engineering behaviour of a rock mass (Müller, 1974; Hoek 1983~~94~~, Hoek & Brown 1997). Slopes, foundations and shallow underground excavations in hard rock can be strongly be affected by the presence of discontinuities, for example, the intersection of structural features can lead to falling and sliding of blocks or wedges from the surface.

In the last decade, rock mass classification systems have been applied extensively in engineering design and construction (Liu, 2007). The ~~GSI (~~Geological Strength Index (GSI) system provides a numerical representation of the overall geotechnical properties of a rock mass, which is estimated using a standard matrix chart and field observations of (a) the 'blockiness' of a rock mass and (b) the surface conditions of any discontinuities. The GSI Index is based upon an assessment of the lithology, structure and condition of discontinuity surfaces in the rock mass and it is estimated from visual examination of the rock mass exposed in surface excavations such as roadcuts, in tunnel faces and in borehole core (Marinos and Hoek, 2000). Both the 'blockiness' and surface conditions, however, are determined in a qualitative and descriptive manner, which is subjective and dependent on the interpreter. Sönmez and Ulusay (1999; 2002) suggested that the 'blockiness' or Structure Rating can be quantified by using the Volumetric Joint (fracture) Count (Jv, in m^{-1}). This parameter is defined as the sum of the

number of joints per meter for each joint set present (Sönmez & Ulusay, 1999), and can be estimated by the following expression:

$$Jv = \frac{1}{S1} + \frac{1}{S2} + \cdots \frac{1}{Sn} \quad (3)$$

where *S* is the spacing of the joints in a set and *n* is the number of joint sets. The 2D fracture digitisation method can clearly be applied to determine a more accurate representation of Jv from an image.

The procedure for quantifying rock mass strength parameters in jointed rocks is illustrated using massive and fractured gneiss exposures in India (Figure 4). Using the qualitative method (Hoek, 1983) the massive gneiss, with 'good' fracture surfaces, has a GSI index of 70-85 whereas the fractured gneiss, with 'fair' fracture surfaces, has a GSI index of 30-45 ~~(Figure 5a)~~. To quantify this, the modified GSI methodology after Sönmez & Ulusay (1999) is used ~~(Figure 5b)~~. In this example, the massive gneiss has horizontal joint spacing of 0.81 m (J1) and vertical joint spacing of 6.19 m (J2). The fractured gneiss has a horizontal joint spacing of 0.17 m (J1) and vertical joint spacing of 0.08 m (J2). Thus, using equation 3, this gives a Jv value of 1.4 for the massive gneiss and 17.7 for the fractured gneiss ~~(Figure 5b)~~. Based on similar estimates of roughness (5), weathering (3) and infill (6) the fracture surface condition rating (SCR) is 14 in both the massive gneiss and the fracture zones. Finally, the GSI values calculated are $c\sigma$. 76 for the massive gneiss and only $c\sigma$. 44 for the fractured gneiss, demonstrating an accurate representation of the rock mass strength differences of the massive and fractured gneiss.

When determining rock mass strength properties the digital method can provide a fast, accurate and consistent result. Understanding rock mass strength properties is relevant for both academic and industry users, in both cases, available field time can often be limited. In addition, particularly in industry there is likely to be multiple interpreters making rock mass strength estimates, and therefore this method can help improve consistency in the results by undertaking analysis digitally.

34.3 Block size and rock erodibility, Southern Scotland

Fracturing is a significant factor in the preconditioning of rock masses for erosion at the Earth's surface (e.g. Roy et al., 2016; Clarke and Burbank, 2010). As well as influencing the volume of material available for mobilisation and transport, fracturing of bedrock is a key control on the clast size distribution of eroded material entering geomorphic systems from hillslopes, particularly in upland landscapes (e.g. Sklar et al. 2016).

The 2D fracture digitisation method is here used to assess the spatial distribution of block-size and fracture intensity of metasandstone of low metamorphic grade in the Southern Uplands, southern Scotland. Block density can be expressed as blocks per square metre, which is easily derived from a polygonised set of fracture traces. It should be noted that whether this 2D block size measure is representative for the true 3D block size depends on the anisotropy of the fracture system and the average block shape. Despite consistent bedrock type (metasandstone) across the study area, the anisotropic fracture pattern gives rise to strong variations in block-size as shown by variation in the number of blocks sampled per unit measuring area from <50 to >1000 blocks per m^2 (F~~igure 6~~igure 5). This data can help to quantify key controls on the influence of facture intensity on block size, which may be used to inform modelling erosion and sediment movement within landscapes.

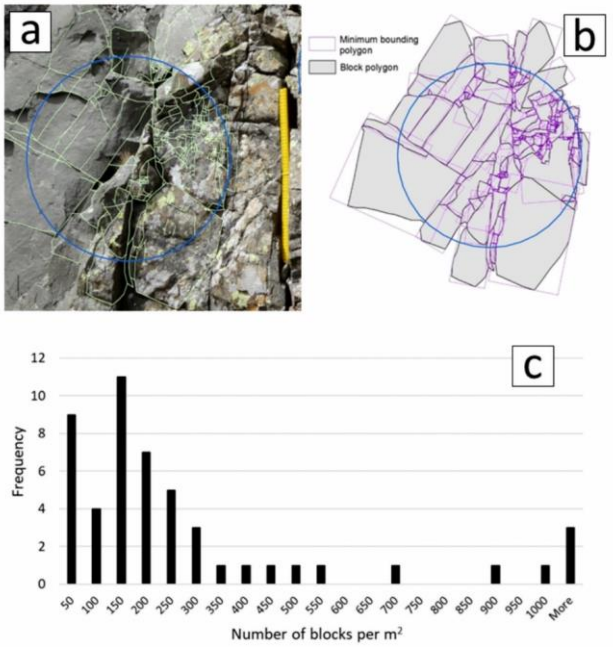

Figure 5. Derivation of block-size metrics for Wacke sandstone in the Southern Uplands of Scotland. Field photograph of sandstone outcrop with fracture delineation (a), polygons for blocks sampled by the circular window (b), number of blocks sampled per m^2 for dataset of 50 measuring sites from the study area.

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For this study, a large amount of fracture and block data was required from several outcrops, and the digital method provided an accurate and efficient way for gathering large amounts of fracture and block size data. Due to the requirements of the study, photographs were taken close

to the outcrop to improve the accuracy of digitisation (F~~igure 6~~igure 5a), resulting in a large and accurate dataset.

3.4 Case studies summary

~~Numerous~~The case studies ~~are~~ presented ~~that~~ here demonstrate the broad range of benefits of a digital method during both ~~the~~ data collection and ~~the~~ data analysis phases. The Cauvery Catchment case study demonstrates how the digital method provide~~d~~s flexibility to gather data while on a short reconnaissance-style field-campaign ~~that covers a large area~~, with fracture data collected retrospectively from photographs taken at key localities. The~~such~~ digital dataset allows for further evolved quantitative and graphical data analysis, such as heat maps of fracture intersections to better understand connectivity. For engineering geology purposes, the digital method is shown to provide a more accurate and consistent representation of the geological strength index (GSI) of a rock mass. We build upon the well-used method for estimating GSI (Hoek, 1983; Sönmez & Ulusay, 1999), to calculate a more accurate GSI based on fractures exposed in outcrop. Finally, the block size and erodibility case study is used to demonstrate the benefits of being able to rapidly generate a large digital dataset that would otherwise be impractical to ~~do so~~gather in the field.

4 Advantages and disadvantages

The digital method described here is not meant to replace field-based data gathering but used in conjunction, as it may be more suitable for different purposes. There are a number of advantages to using a digital method for gathering fracture data including: speed of gathering data, creating large datasets, flexibility in data gathering approach and consistency of data.

Gathering 2D fracture network data in the field can often be a time consuming processes and therefore limits the amount of data that can be gathered during a field campaign. Using the digital methodology allows for fracture network data to be quickly gathered in the office, allowing for more data to be generated from an equivalent amount of time in the field. Field time can be used for detailed study of the outcrop to improve the interpretation of fractures in the office and to gather other key data such as aperture, fracture fill and 3D geometry's. The digital method allows for large, statistically significant datasets to be quickly gathered during a short field campaign. Collecting the data after fieldwork with a broader perspective provides an element of flexibility in terms of the selecting of outcrops for analysis, the type and shape of the sample window and the amount of the data gathered. Finally, the digital method has the potential to be used to improve the consistency and reliability of industry standards that involve fracture networks, such as rock mass strength estimates (Section 3.2) by reducing collector bias by standardising the data collection strategy.

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For more evolved analysis of the fracture data the digital traces can be used in fracture analysis software packages such as FracPaQ (Healy et al., 2017), NetworkGT (Nymberg et al., 2018), FraNEP (Zeeb et al., 2013) and DigiFract (Hardebol and Bertotti 2013). These programmes can be used for wide range of types of fracture analysis including topological analysis such as deducing node types, and plotting fracture density heat maps illustrating density variations across a fracture zone.

There are limitations with capturing the data digitally. Firstly, capturing data in the field will always be more reliable in terms of seeing the full extent of fractures: for example, fractures may be obscured by vegetation making digitisation of traces more difficult than in the field (Andrews et al., 2019). Secondly, field observations of the character of individual fractures such as roughness, aperture and any secondary fills can be important observations made only in the field and useful when understanding rock mass strength or permeability. It is also possible, of course, to digitise the fracture network, and then return to the outcrop and augment the digital traces with further attribution that requires direct field observation (e.g. fracture aperture, fracture fill); portable PC tablets are ideal for this purpose. Image scale can also be an issue with this method, as smaller fractures can be harder to digitise from a from a single photograph covering a large outcrop extent, therefore it is important to acquire photographs that cover the appropriate scale of fractures, which will be dependent on the purpose of the study. Estimates of fracture permeability and percolation when using topology alone represent the maximum potential and does not account of closed fractures (Laubach et al., 2019). Additional observations such as aperture and infilling are import for these types of studies.

Characterising the architecture of a fracture network is useful for understanding relative age history of fracture sets, this can be significant when making larger scale interpretations particularly for fluid flow modelling (Hancock 1985; Peacock et al 2018). Relative age relationships are best determined in the field and can be challenging to gather digitally. It is important to appreciate the limitations of the method, as it may not be suitable for all studies or may need supplementary field data.

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5 Conclusions

The aim of this paper is to review and evaluate the methodology for digitising 2D fracture networks in GIS, and make it more accessible to a broader range of users in both academia and industry. We present a breakdown of the key steps in the methodology, which provides an understanding of how to avoid error and improve the accuracy of the final dataset.

The digital method can be used to interpret traces of 2D linear features of a wide variety of scales from the ~~micro~~local metre-scale to the ~~kilometre~~ kilometre scale, including ~~lineations or~~

~~mineral cleavages from a photomicrograph~~, fractures at outcrop scale to regional-scale structural lineaments that are visible on aerial photographs or DEMs.

An important aspect of applied geosciences, such as hydrogeology and geotechnical engineering is the accurate parameterisation of fracture networks in bedrock. The methodology that is commonly used is a qualitative description and can be time consuming. The digital 2D fracture trace capture method is an accurate and rapid way of quantifying 2D linear networks such as fracture zones using open access software packages. It offers a robust, cost-effective methodology that can used in academy and industry to gather accurate 2D fracture network data.

Acknowledgements

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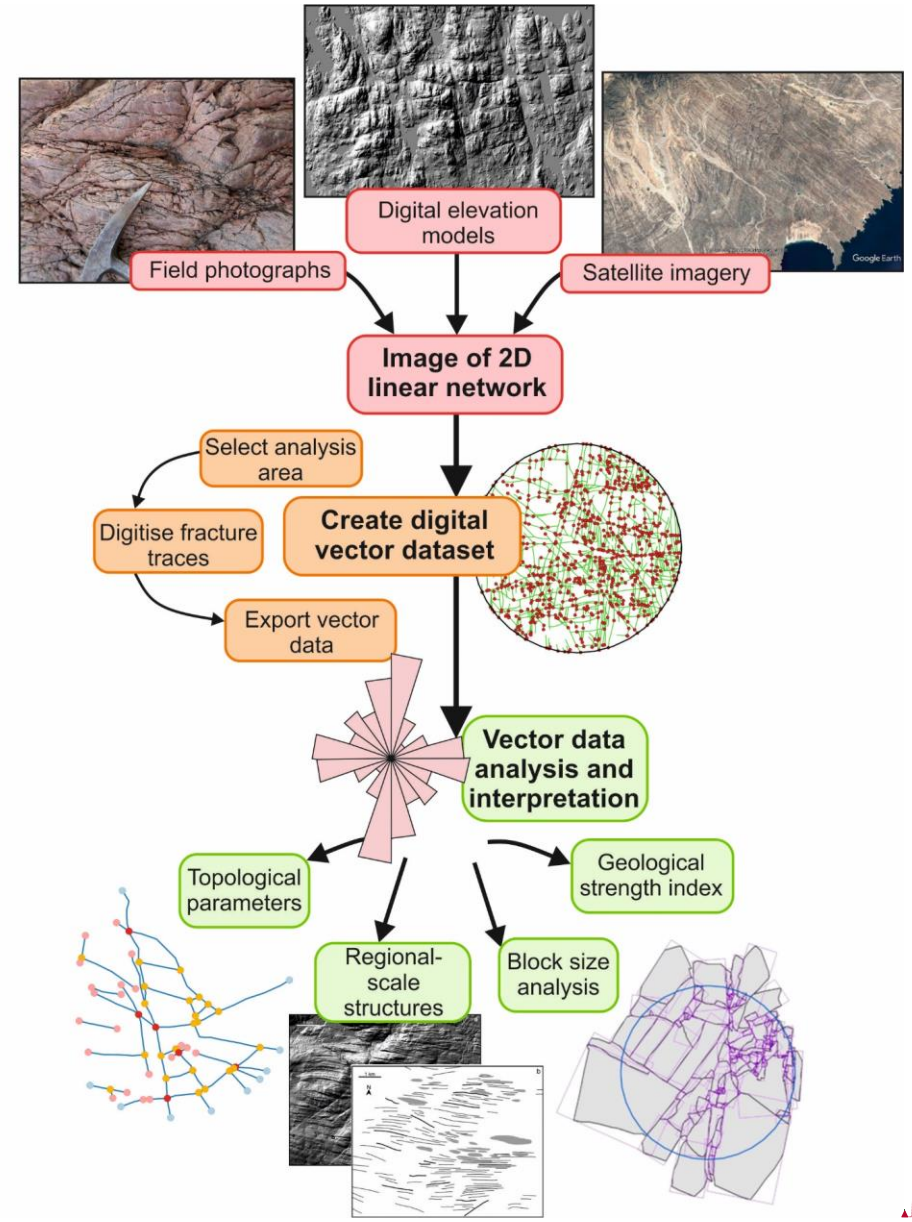
~~Figures~~



~~**Figure 1:** Flowchart providing an overview of the methodology used for digitising linear features, from preparing an image, digitising the features to output of data. Digital elevation model examples are~~

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~~taken from Next map © in Scotland, and the satellite image of Oman example is taken from Google Earth ©.~~

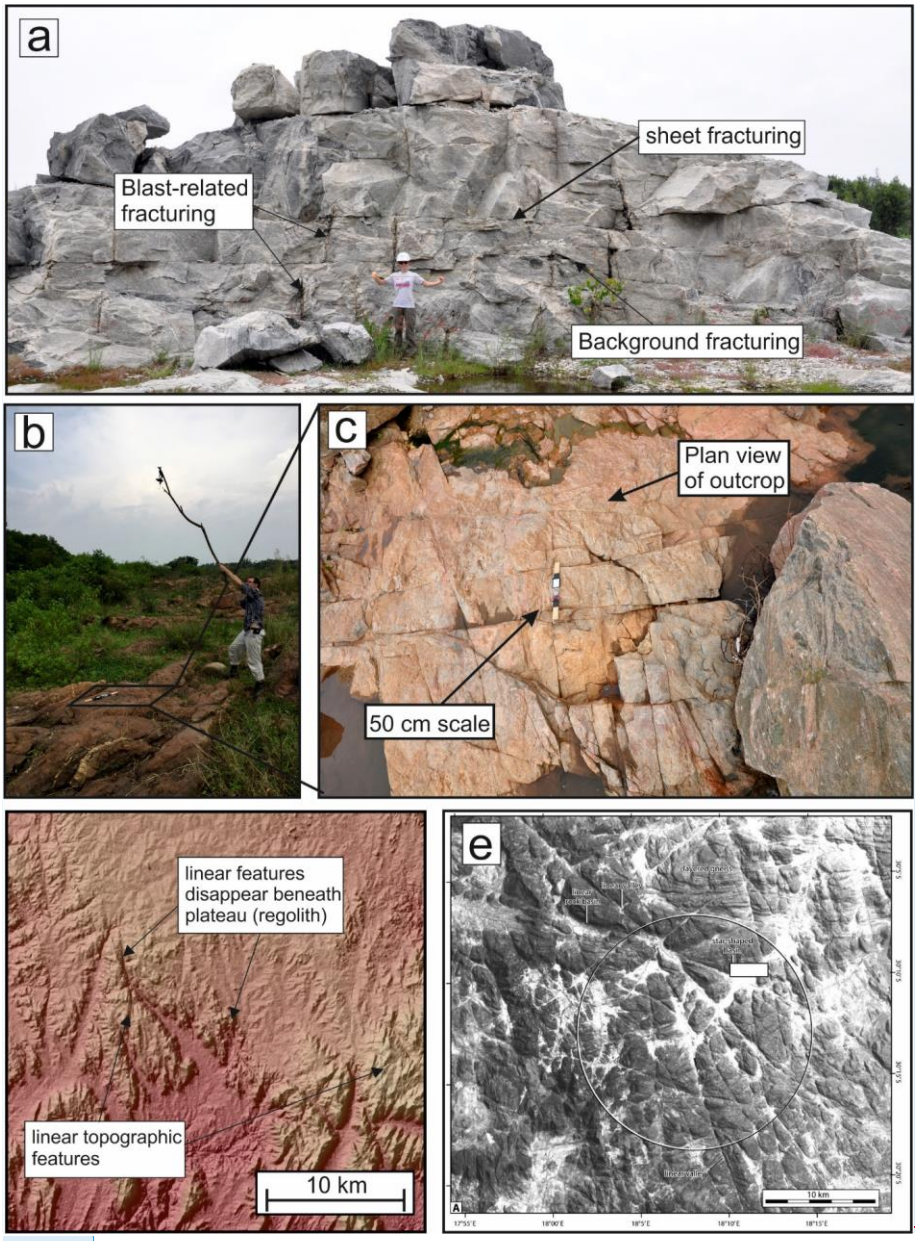

Figure 2: ~~Examples of photographs and DEM images that can be used for digitising 2D linear features, including: (a-c) photographs of fracture networks of various scale from southern India and improvised~~

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Commented [KM25]: A: 'sheet jointing' better than 'sheet fracturing'?
B: white lines would work better: I can barely see the black lines…
D. 'D' is missing… also, not sure what linear topo features points to (?arrow has moved?)

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methods for taking parallel photographs; (d) a DEM image from southern India of larger kilometre scale features that could also be digitised; and (e) an aerial photography from Namibia (adapted from Krabbendam and Bradwell, 20..2014).

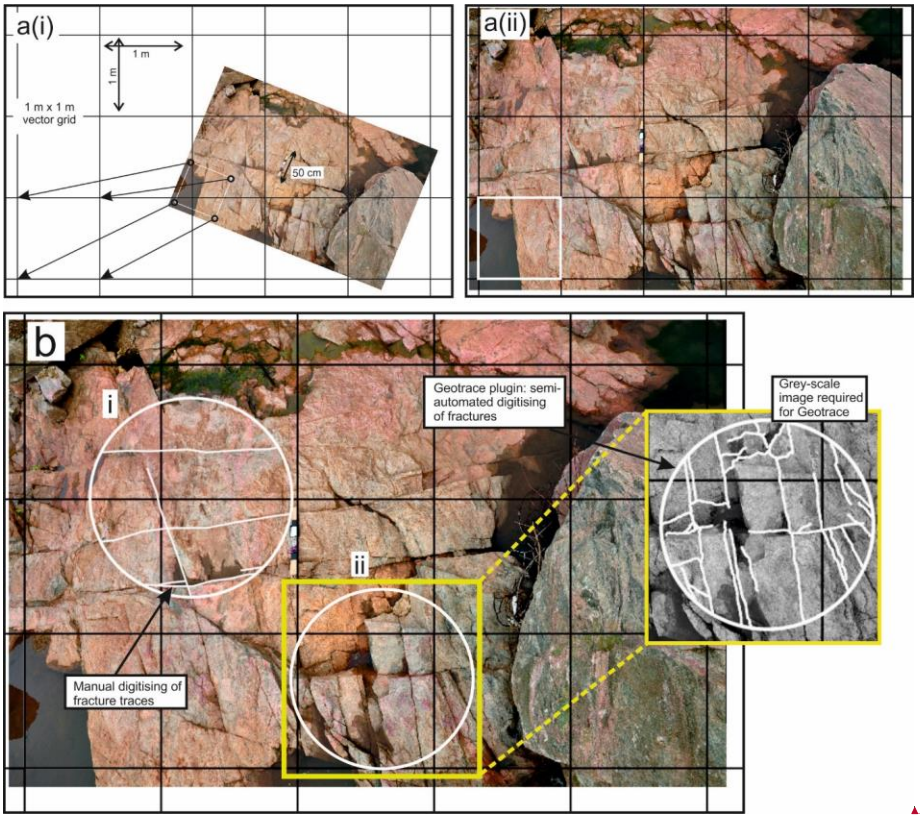

Figure 3: Images showing (a (i–ii)) how to georeference an image to a fishnet grid (black) from a square of a known scale (white); and (b) the tools available for digitising fractures in QGIS, including (i) a fully manual method; and (ii) a semi-automatic method such as Geotrace.

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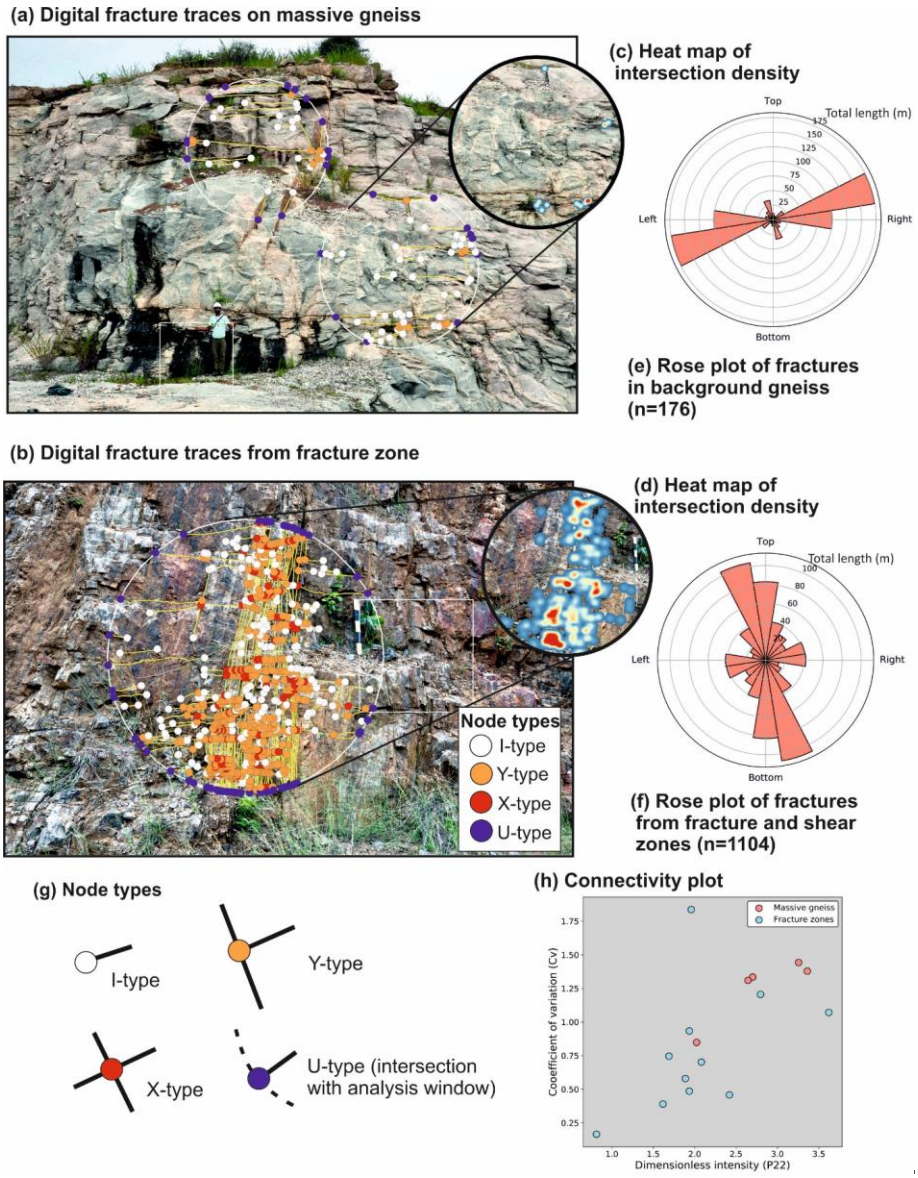

~~**Figure 4:** Fracture analysis from the Peninsular Gneiss, South India, including: field photographs with digitised fracture branches and intersection types on (a) a massive gneiss example; and (b) from a fracture zone; (c-d) heat maps illustrate variations in fracture intersection density (massive gneiss: 0-5 nodes/m^2 and fracture zones: 0-18 nodes/m^2); (e-f) length-weighted rose plots showing the variation in orientation of fractures traces in the background gneiss and fracture zones; (g) a schematic illustration of the various types of fracture connections (as defined by Manzocchi,~~

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2002); (b) a plot of connections per line against dimensionless intensity (defined by Sanderson and Nixon, 2015) to show variations in connectivity.

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Figure 5. Usage of the GSI chart after Hoek (1983) (a) and the modified GSI chart after Sönmez & Ulusay (1999) (b).

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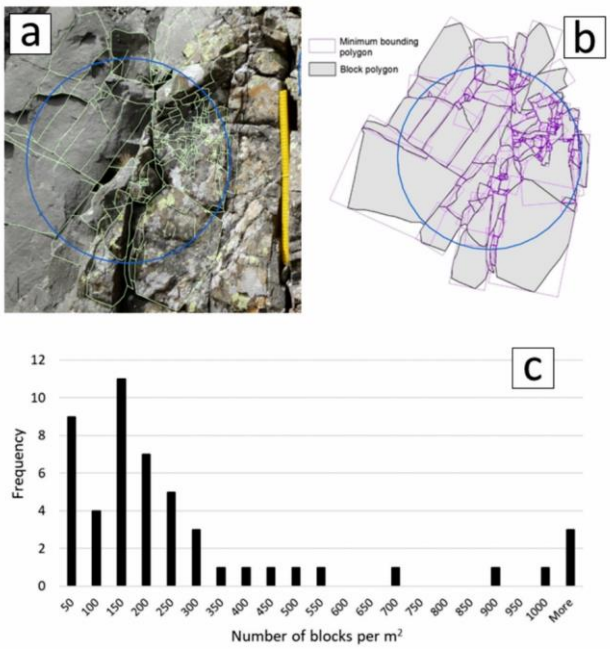

Figure 6. Derivation of block-size metrics for Wacke sandstone in the Southern Uplands of Scotland. Field photograph of sandstone outcrop with fracture delineation (a), polygons for blocks sampled by the circular window (b), number of blocks sampled per m^2 for dataset of 50 measuring sites from the study area.

Supplementary material

Calculating geometries in QGIS field calculator

Area: $area

Length: $length

Orientation: Degrees(azimuth(start_point($geometry), end_point($geometry)))

Calculating basic fracture parameters in Python

#Import key modules including geopandas, numpy and pandas

Import geopandas as gpd

Import numpy as np

Import pandas as pd

You may need install geopandas using either:
#Anaconda install
conda install -c conda-forge geopandas
or
#pip install
pip install geopandas

#Import fracture trace shape file and analysis window shapefile as Geopandas dataframes.

(Terms in italics and capitals need to changed).

df=gpd.read_file(r"*LINK TO SHAPE FILE LOCATION OF FRACTURE TRACES*")

aoi=gpd.read_file(r"*LINK TO SHAPE FILE LOCATION OF AREAS*")

#Group dataframe by each analysis window.

df2=df[df[*'ANALYSIS_WINDOW'*]== *'ANALYSIS_WINDOW_REFERENCE'*]

aoi2=aoi[aoi[*'ANALYSIS_WINDOW'*]== *'ANALYSIS_WINDOW_REFERENCE'*]

For making individual density and spacing calculations

#Make python array of lengths and area from shapefile geometries.

df2_length=np.array(df2.geometry.length)

aoi2_area=np.array(aoi2.geometry.area)

#Calculate sum of lengths.

df2_length_sum=np.sum(df2.length)

#Finally, calculate fracture density based total fracture length and area.

density=df2_length_sum/aoi2_area

#In addition, as before calculate spacing, which is the reciprocal of Density.

spacing=aoi2_area /df2_length_sum

For making density and spacing calculations for multiple groups of data

#Add length from the geometry column to a new column

df['length']=df.geometry.length

#Group dataframe based on digitisation areas

df_group=df.groupby(df. *ANALYSIS_WINDOW*)

#Calculate the sum lengths for each group and convert to pandas dataframe

df_group_lengths=pd.DataFrame(np.sum(df_group.length))

#Add Location column to dataframe

df_group_lengths['Location']=df_group_lengths.index

#Merge main data frame with area dataframe based on location

df3=pd.merge(df_group_lengths, aoi, how='inner', on=*'ANALYSIS_WINDOW'*)

#Calculate density and intensity in new a columns

df3['density']=df3.length/df3.area

df3['spacing']=df3.area/df3.length

#Export as excel file

df3.to_excel(r''*LINK TO LOCATION TO CREARE EXCEL FILE IN*'')