Data acquisition by digitising 2D fracture networks and topographic lineaments in GIS: further development and applications

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Abstract. Understanding the impact of fracture networks on rock mass properties is an essential part of a wide range of 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 field work 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 a 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. Advantages and limitations compared to other fracture network capture methods are discussed.

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 applications in the Earth sciences, such as understanding the behaviour of fluid flow in groundwater aquifers (Singhal and Gupta, 2010) and hydrocarbon reservoirs, and the erodibility and slope stability of rock masses (Clarke and Burbank, 2010; Krabbendam and Glasser, 2011). Fracture network data are essential for assessing future sites of nuclear waste repositories (Follin *et al.* 2014), predicting rock slope stability (Selby, 1982; Park *et al.* 2005) and understanding rock mass strength for engineering of infrastructure (Hoek and Brown, 1997; Zhan *et al.* 2017; Ren *et al.* 2017). Thus, fracture network analysis is a critical component of applied geological characterisation required for ensuring water and energy security, supporting infrastructure development, and protecting human health, which are identified as key Sustainable Development Goals (Schrodt *et al.* 2019).

To characterise fracture networks, a range of fracture network parameters need to be acquired, including the fracture density, connectivity, and orientations (e.g. Singhal and Gupta, 2010). These properties can be highly spatially variable over a range of scales, which cannot be accurately predicted (Long *et al.* 1987). The comprehensive capture of observational data is typically required to characterise fracture network variability over large areas. Due to the limited distribution of suitable rock exposures in many settings, understanding the spatial variability of fracture network parameters at regional scales requires sampling at multiple sites (e.g. McCaffrey *et al.* 2020). Practical constraints on data collection are therefore critical factors. Constraints on the number of sites that can be analysed in a given study increases uncertainty in estimations of fracture properties of the wider rock mass. This uncertainty limits the scales at which analyses can be reasonably applied.

The need for efficient and robust methods for quantitative capture of fracture data is well recognised, and methods using statistically-based observational techniques (Mauldon *et al.* 2001), and systematic regional sampling (e.g. Watkins *et al.* 2015a) have been proposed previously. We build on previous developments in fracture sampling by focusing on a method for digital data capture from 2D outcrop images.

Advanced 3D methods for outcrop imaging and fracture analysis are now available (Tavani *et al.* 2016; Bisdom *et al.* 2017), but limited access to necessary hardware, software and training technology may limit the wider adoption of these high-cost techniques in many applied research contexts. In contrast, the ready availability of digital cameras and suitable open-source software means that the 2D digital capture method has potential for wider adoption across applied geoscience fields where traditional, low-cost 1D and analogue sampling methods are still widely used (Siddique *et al.* 2015; Panthee *et al.* 2016). Systematic 2D digital capture has particular relevance for studies (1) where large datasets are required from multiple sites, (2) where advanced outcrop scanning or unmanned aerial vehicle (UAV) systems are not available or are impractical to use; (3) where historic images (such as from quarries, canal excavations or road cuttings) provide a valuable data source, or (4) for multi-scalar analysis using micro (e.g. thin section) to macro (e.g. satellite) scale images.

Here we describe good practice in the use of a low-cost 2D digital method for efficient capture and visualisation of a range of fracture parameters and illustrate how these methods can be used across a range of applied geoscience fields (Figure 1). Although the method has been used before (Krabbendam and Bradwell, 2014; Watkins *et al.* 2015a; Krabbendam *et al.* 2016; Healy *et al.* 2017) no comprehensive description of the method has been published.

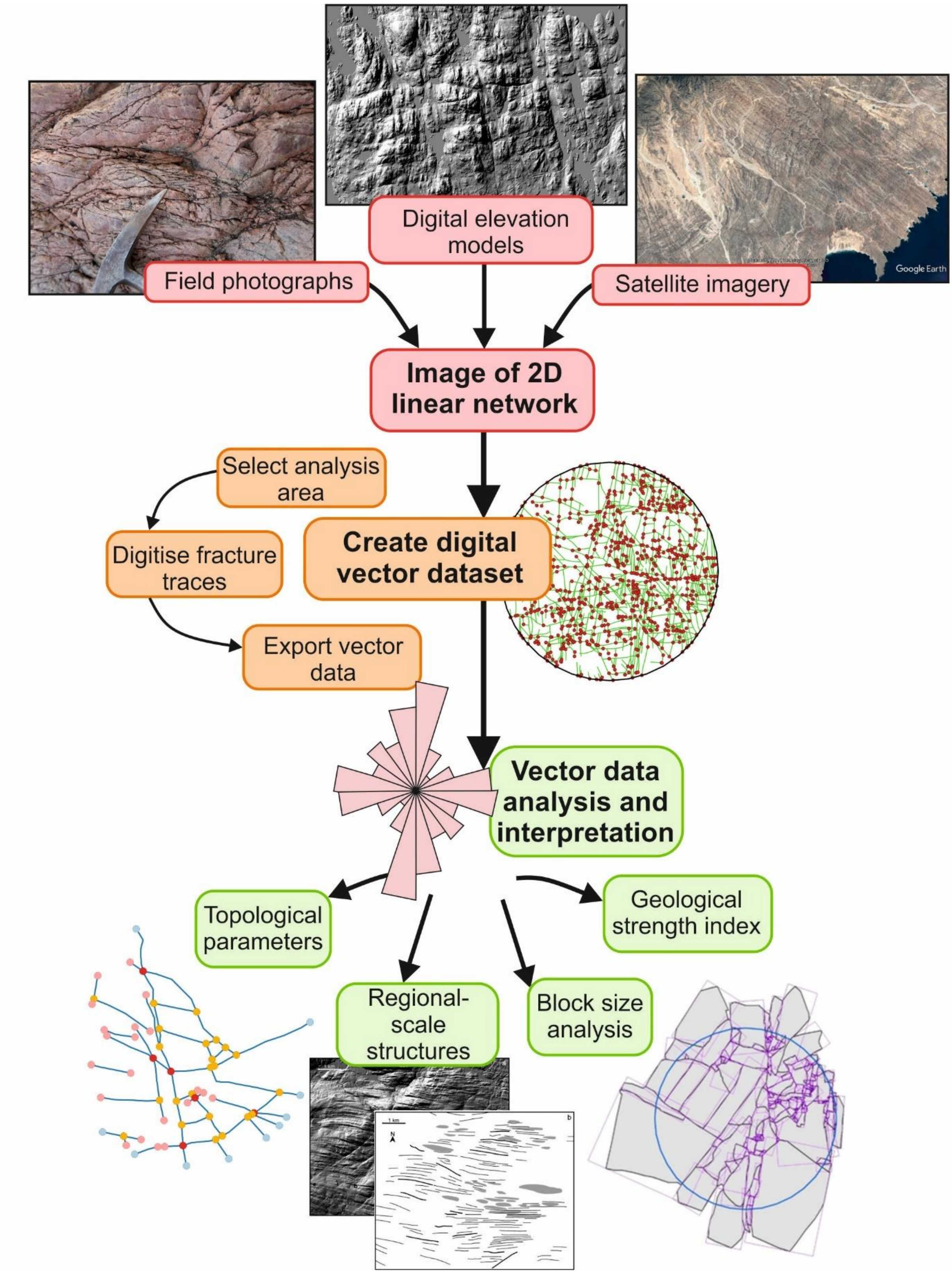

Figure 1: Flowchart providing an overview of the 2D digital capture method y used for digitising linear features, from preparing an image, digitising the features to output of data. Digital elevation model examples are taken from Next map © in Scotland, and the satellite image of Oman example is taken from Google Earth ©.

2. Summary of fracture data capture methods

Understanding the effect of a fracture network on the properties of a rock mass requires acquisition of various parameters such as length, orientations, density and spacing (Singhal and Gupta, 2010). Network topology is used to understand how connected a fracture network is and can be characterised by derived parameters such as fracture connectivity, percolation potential and clustering (Manzocchi, 2002; Sanderson and Nixon, 2015). Finally, fracture aperture, fill and paragenesis history provide an important understanding of the fracture network history, fluid flow and fracture strength (Carlsson, and Olsson, 1976; Laubach *et al.* 2019).

Fracture networks can be characterised in different dimensions using a number of approaches. 1D approaches include outcrop-based scanline surveys and (by necessity) borehole fracture analysis, typically represented by the number of fractures per unit length, i.e. frequency. 1D approaches are relatively rapid, but do not directly constrain parameters such as fracture length and connectivity. If the fracture network is anisotropic, which is 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.* 2013; Watkins *et al.* 2015b).

In 2D fracture network analysis, a circular sampling window is commonly used (Davies et al, 2011; Rohrbaugh *et al.* 2002; Watkins *et al.* 2015a). In the field, a circular 'chalk line' is drawn on an outcrop, within which the fractures and key geometries are captured. Connectivity within the fracture network can be parameterized by characterising the different types of fracture terminations and intersections, which can be used to understand fluid percolation potential (e.g. Manzocchi, 2002). Full field-based capture is very time consuming, particularly when data from multiple sites are required, and may be impractical or impossible for some outcrops, such as quarries, cliffs and coastal platforms. Time constraints normally mean that field-based methods are also limited in their scale of application, with sampling window diameters of 1 – 2 m being commonly used (e.g. Watkins *et al.* 2015a; Procter and Sanderson, 2018). This limitation means that spatial variability in fracture properties at scales greater than 5-10 m are typically not captured.

To overcome the time-constraints of the full 2D window approach, a circular scanline method was developed (Mauldon *et al.* 2001), in which only those fractures that intersect a particular circular scanline are captured; in a sense it is similar to the 1D approach. The circular scanline analysis is more rapid than the full 2D circular window analysis and has less length and orientation bias compared to 1D methods (Mauldon *et al.* 2001). The circular scanline method can be used to calculate proxies for (but does not directly measure) fracture density and length based on the ratio of the types of trace intersection (Mauldon *et al.* 2001), however if other parameters are needed further field work would be required.

Ideally, for any application, a full 3D characterisation of the rock mass is achieved. However, true 3D characterisation of a rock mass is currently only possible using CT scanning, and is restricted to very small samples (Voorn *et al.* 2015). High resolution '3D' images of outcrop surfaces (more like '2.5D') can be captured by laser scanning, which can be ground based or acquired by UAV (e.g. Bisdom *et al.* 2017; Gao *et al.* 2017; Wüstefeld *et al.* 2018). From the laser scans, 3D images of the outcrop surface (3D 'virtual outcrop') can be generated using techniques such as structure from motion (SfM) photogrammetry (Vasuki *et al.* 2014). These can provide additional information on fracture orientation through the use of advanced image analysis techniques (Wüstefeld *et al.* 2018). These methods have been used for advanced fracture network analysis and modelling for applications related to fluid flow, gas migration and engineering/construction (e.g. Bisdom *et al.* 2017; Menegoni *et al.* 2019; Strijker *et al.* 2012; Tavani *et al.* 2016). These 3D scanning techniques require sophisticated hardware, proprietary software and training that potentially limits their applicability. In addition, there are practical limitations at sites, such as access and restrictions on the use of UAVs, that may further limit their use (e.g. Senger *et al.* 2015).

The 2D fracture network can be captured in the field as well as from image tracing (e.g. Watkins *et al.* 2015a). Digital 2D data capture can be applied to photographs of an outcrop or thin section, aerial photographs, or satellite imagery. 2D digital data capture methods can thus be used at a great range of scales, permit data acquisition from inaccessible sites, and provides a reproducible approach from which a digital dataset suitable for numerical and statistical analysis can be readily derived. The 2D digital capture typically relies on GIS-type functions for the visualisation and analysis of images, and uses standard GIS tools. More sophisticated analysis can be carried out using software applications such as proprietary DigiFract which is based on customised QGIS functions (Hardebol and Bertotti, 2012), the open-source tool FracPaq for Matlab (Healy *et al.* 2017) and NetworkGT for QGIS (Nyberg *et al.* 2018). These tools provide enhanced functions for efficient capture of data from images and advance data analysis, but are targeted for application in structural geology research contexts.

In its basic form, the 2D digital data capture method requires only a digital camera, a measuring stick and access to GIS, such as open-source QGIS. The low-cost nature of the method means that this is potentially a powerful tool for enhancing geological investigations across a range of applied studies, such as engineering geology and hydrogeology. We comprehensively describe good practice for 2D digital fracture capture and analysis. In particular we focus on the practical aspects of image capture, preparation and analysis using QGIS and other open-source tools and plugins. Four case studies are presented to illustrate a number of practical applications. We demonstrate some simple fracture analysis tools that can be applied to the captured data. Finally, we evaluate the benefits and drawbacks of 2D digital data capture compared to other approaches for capturing fracture data.

3 Digital 2D fracture analysis method

The 2D digital capture 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.

3.1 Outcrop selection

A suitable outcrop for digital fracture analysis must be first selected. The outcrops selected will depend on the nature of the study being undertaken and the type of fracture network parameters required (Watkins *et al*. 2015a). 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 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 (Laubach et al 2019; Ukar et al 2019).

3.2 Outcrop image preparation

The first step is to capture or 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. This also applies to historic photographs. 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); drones 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.

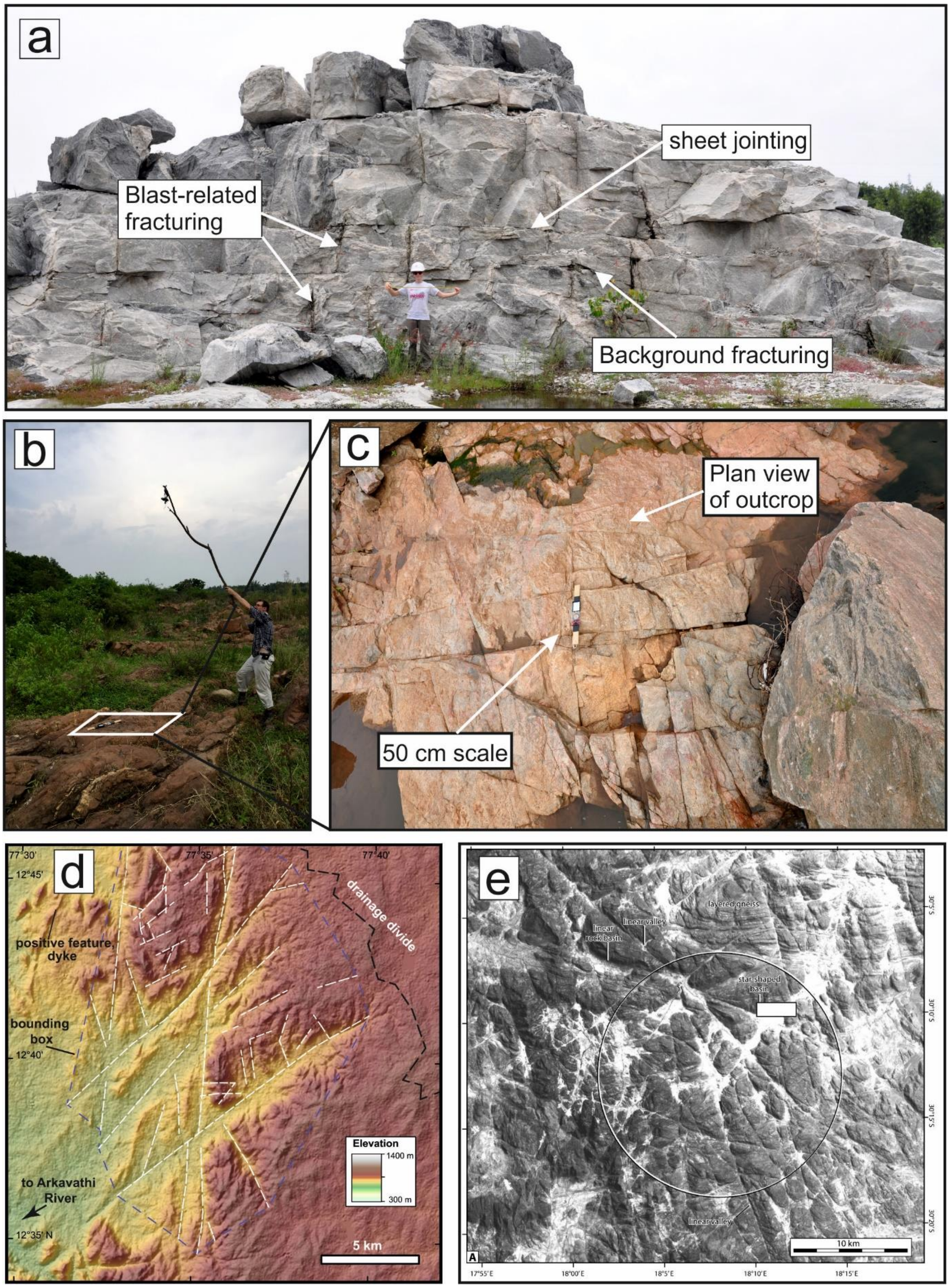

Figure 2: Examples of photographs and DEM images that can be used for digitising 2D linear features, including: (a-c) photographs of fracture networks of various scale from southern India and improvised methods for taking photographs parallel to the outcrop; (d) a DEM image from southern India of larger kilometre scale features that

could also be digitised; and (e) an aerial photography from Namibia (adapted from Krabbendam and Bradwell, 2014).

3.3 Georeferencing the images

To aid robust georeferencing, the photograph needs to have a square of known size (e.g. 1 x 1 m) embedded in it. This is 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, the square on the photograph is georeferenced to a square on the fishnet grid (Figure 3a).

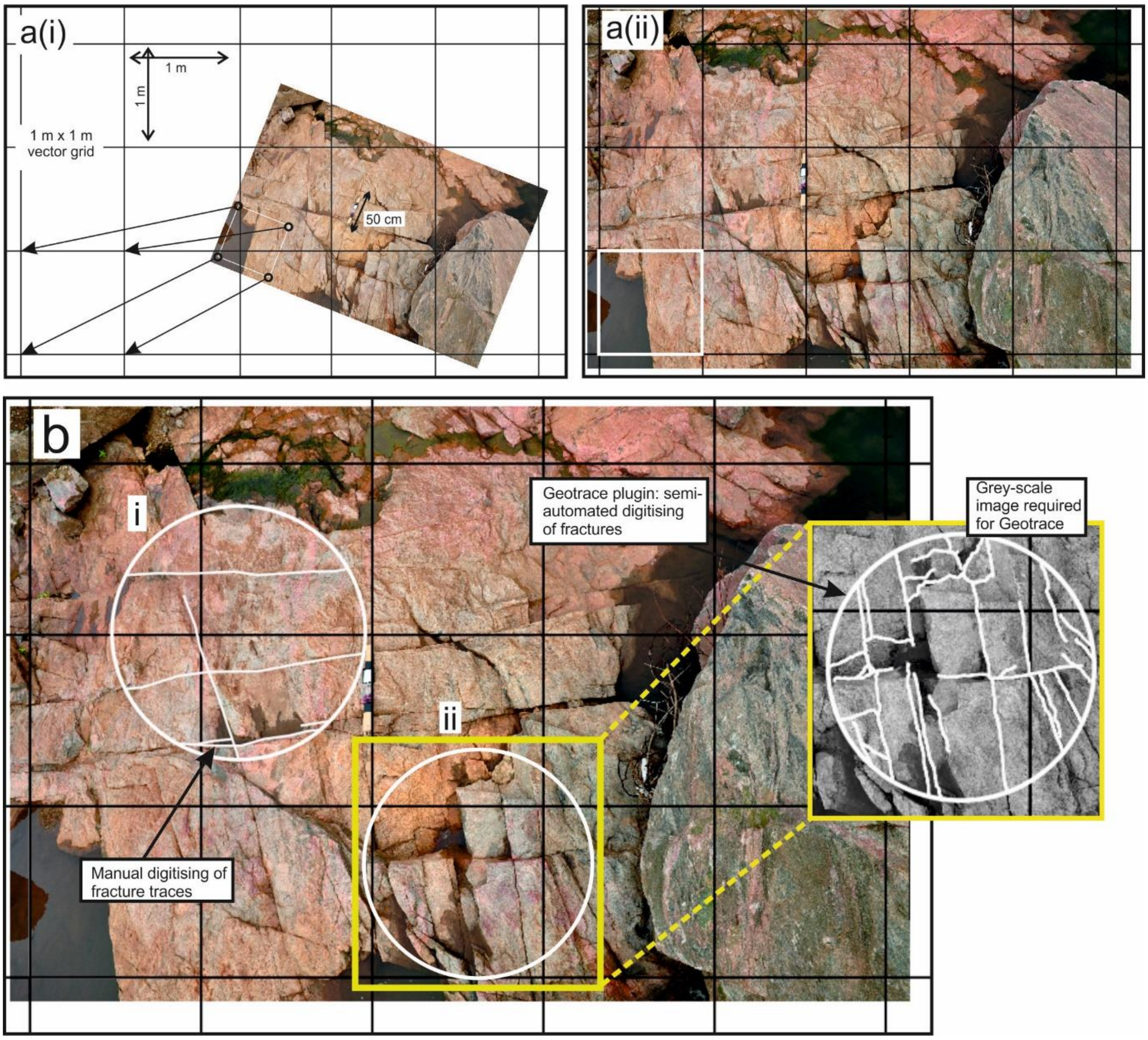

Figure 3: Images showing (a (i-ii)) how to georeference an image to a fishnet grid (black) from a square of a known scale (white); and (b) the tools available for digitising fractures in QGIS, including (i) a fully manual method; and (ii) a semi-automatic method such as Geotrace.

3.4 Using DEM, satellite and air photo images

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 is commonly already georeferenced and can be used 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 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 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 DEMs, hill-shades derivatives with different illumination direction can be made; for satellite imagery, sometimes imagery taken at a different time of day are available. Hence, for DEM-scale interpretations it is important to take a multi-data type approach (e.g. DEMs and satellite images) to guide digitisation, similar to that of Pless (2012).

3.5 Data capture

3.5.1 Create analysis window

As a first step, create a polygon shapefile and digitise the area (window) 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. Multiple windows can be used on the same imagine, in particular if the image shows spatial variability of the fracture network.

3.5.2 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 its specific window polygon. 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 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, connecting fractures should be properly snapped against each other, and to the surrounding circular window.

In quarries or excavated sections, 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, and are generally surrounded by small radiating fractures.

3.6 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 processed, 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 such length and orientation of individual fracture traces can be calculated within the field calculator in the QGIS attribute table. The area of the circular window can also be calculated in the attribute table using the field calculator. For further processing, 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 Singhal & Gupta, (1999):

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

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

$$S = A/\Sigma L \ \text{(in m).} \tag{2}$$

Fracture intersections (points) within the fracture network, important to constrain connectivity (Manzocchi, 2002) 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.

4 Case studies

To illustrate the use of systematic 2D digital fracture analysis methods for applied geoscience investigation we present a number of case studies to highlight a range of geoscience applications and illustrate key benefits, including: (1) Rapid data collection to support regional hydrogeological assessment (India); (2) Enabling quantitative, rather than typical qualitative, assessment of key parameters for engineering Rock Mass Strength evaluation (India); (3) Analysing catchment-scale variability in sediment source characteristics for applied geomorphic studies in erosional terrains (Scotland), and; (4) Fracture network analysis from historical images for sites where modern exposures are unavailable (Sweden).

4.1 Understanding fracture connectivity and permeability, southern India

Characterisation of fracture networks is essential to understand local and regional-scale aquifer properties such as connectivity and permeability, in particular in fractured 'hard-rock' aquifers, where fractures are the primary water stores and pathways (e.g. Stober and Bucher, 2007; Singhal and Gupta 2010; Guihéneuf *et al*. 2014). An example is given here of the Peninsular Gneiss in the Cauvery Catchment in southern India. The groundwater properties of the Cauvery Catchment have been an area of ongoing research (Maréchal *et al.* 2006, Perrin *et al.* 2011, Collins *et al.* 2020) as the spatial and temporal variability of groundwater availability has profound implications for the sustainability of irrigation and hence food security. Two contrasting basement fracture networks can be identified (Figure 4a-b): firstly, 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. Data were collected during a very short, reconnaissance-type fieldwork.

Length-weighted rose plots show the variation in orientation of fractures (in a vertical section) in the two identified domains (Figure 4c, d). 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 (Nyberg *et al.* 2018), the fracture branches and nodes (intersections and fracture trace end-points) were characterised based on the topology of the branch intersections (Manzocchi, 2002; 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 illustrate the higher fracture connectivity within the fracture zones. To quantify the connectivity, the connections per line and dimensionless intensity (a representation of intensity that uses average fracture length) were calculated (following

Sanderson and Nixon, 2015), (Table 1; Figure 4h). The number of connected (X- and Y) nodes per fracture 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, indicating 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) was calculated by dividing the standard deviation of the fracture spacing by the mean fracture spacing (Gillespie *et al.* 1999; Watkins *et al.* 2015b) and was used to quantify the how clustered a fracture network is (Table 1) (Odling *et al.* 1999). The Cv ratios show that the massive gneiss generally has regularly-spaced fractures, while the fractures in the fracture zones are highly clustered (Table 1, Figure 4h).

Rock type	Area (m^2)	Mean length (m)	2D density (m^{-2})	I	U	X	Y	Dimensionless intensity	Connections per line	Coefficient of variation (Cv)
Massive gneiss	15.0	0.6	1.4	41.0	10.0	1.0	11.0	0.8	0.9	0.2
Massive gneiss	11.9	1.0	1.9	19.0	15.0	0.0	10.0	1.9	1.4	0.6
Massive gneiss	26.8	0.5	3.9	136.0	32.0	18.0	157.0	2.0	2.4	0.8
Massive gneiss	8.5	0.3	8.8	130.0	40.0	38.0	204.0	2.7	2.9	1.3
Massive gneiss	137.8	2.9	0.7	21.0	10.0	6.0	23.0	1.9	2.6	0.9
Massive gneiss	359.4	11.9	0.2	5.0	4.0	1.0	1.0	2.0	1.3	1.8
Massive gneiss	31.1	5.3	0.7	3.0	5.0	0.0	0.0	3.6	0.0	1.1
Massive gneiss	13.3	2.1	0.9	2.0	8.0	0.0	2.0	1.9	2.0	0.5
Massive gneiss	10.5	1.9	0.9	2.0	5.0	2.0	1.0	1.7	4.0	0.7
Massive gneiss	119.6	2.1	0.8	41.0	12.0	4.0	27.0	1.6	1.8	0.4
Massive gneiss	95.4	2.3	1.0	29.0	19.0	5.0	30.0	2.4	2.4	0.5
Fracture zone	4.6	0.2	17.8	157.0	61.0	121.0	517.0	3.3	3.8	1.4
Fracture zone	45.2	0.9	3.9	139.0	38.0	45.0	174.0	3.4	2.8	1.4
Fracture zone	38.5	1.7	1.6	139.0	38.0	45.0	174.0	2.6	2.8	1.3
Fracture zone	81.6	2.6	1.1	23.0	16.0	6.0	25.0	2.8	2.6	1.2
Fracture zone	9.2	1.5	1.4	4.0	6.0	0.0	6.0	2.1	2.4	0.7

Table 1: Summary fracture network statistics from the Peninsular Gneiss in the Cauvery Catchment, southern India.

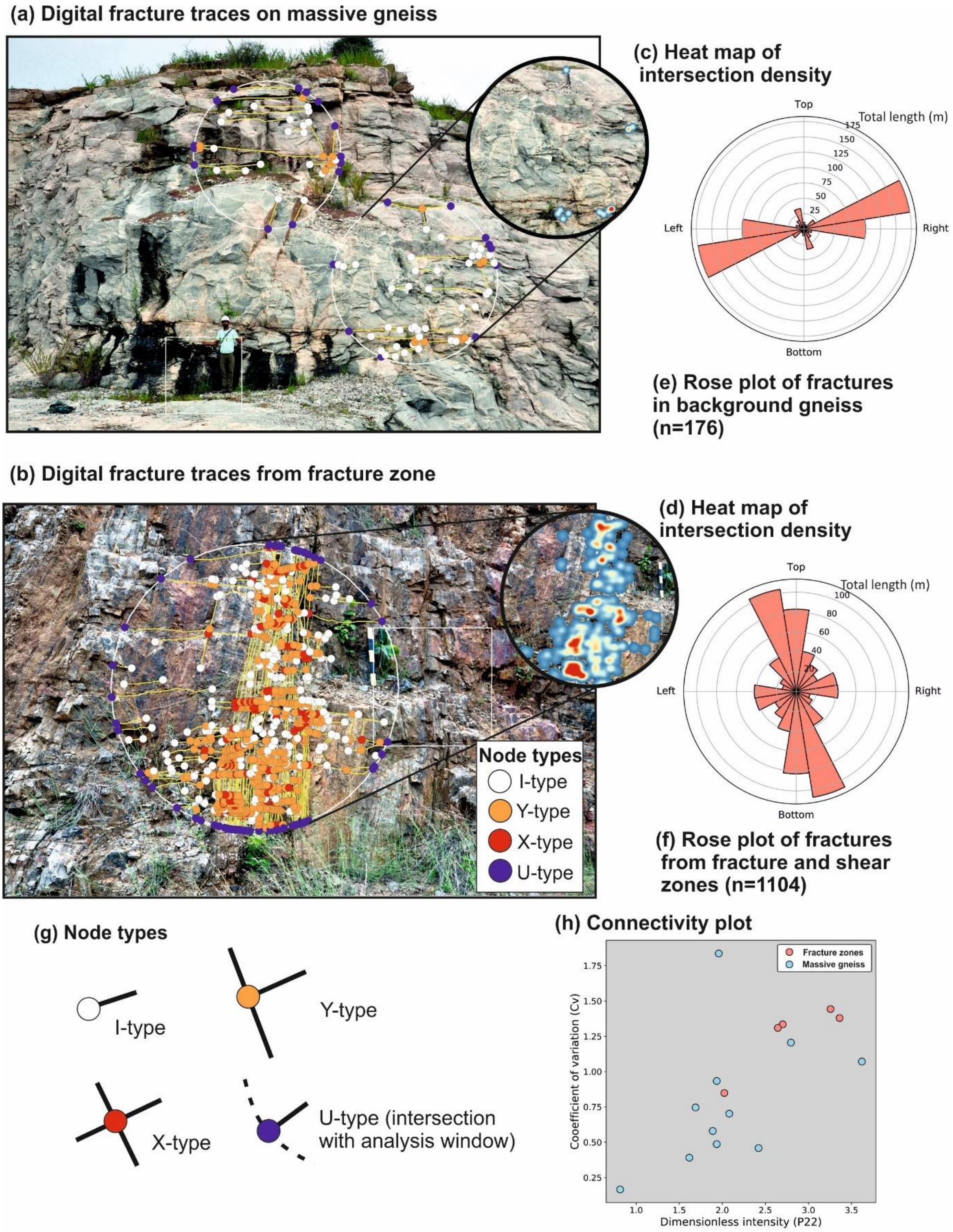

Figure 4: Fracture analysis from the Peninsular Gneiss, South India, including: field photographs with digitised fracture branches and intersection types on (a) a massive gneiss example; and (b) from a fracture zone; (c-d) heat maps illustrate variations in fracture intersection density (massive gneiss: 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.

At the near-surface, the Peninsular Gneiss has a bimodal fracture density distribution with fracture zones with high fracture density that make up a relatively small proportion of the bedrock, and the majority of the crystalline basement containing a low-density fracture pattern. Derived connectivity parameters indicate the highest potential permeability is found in the fracture zones, whereas the background gneiss has significantly lower potential permeability.

In this case study, field time was limited and the 2D digital method provided a rapid and flexible way of gathering fracture network data. It was possible to carry out a reconnaissance survey covering an area 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).

4.2 Rock mass strength estimates (Geological Strength Index)

Structural discontinuities are an important control on the engineering behaviour of a rock mass (Barton *et al*. 1974; Müller, 1974; Hoek 1983, Hoek & Brown 1997). Slopes, foundations and 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 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 should 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):

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

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 an 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. To quantify this, the modified GSI methodology after Sönmez & Ulusay (1999) is used. In this example, the massive gneiss has a horizontal joint spacing of 0.81 m (J1) and a vertical joint spacing of 6.19 m (J2). The fractured gneiss has a horizontal joint spacing of 0.17 m (J1) and a vertical joint spacing of 0.08 m (J2). Applying equation 3, this gives a Jv value of 1.4 for the massive gneiss and 17.7 for the fractured gneiss. 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 for the massive gneiss was calculated as *c*. 76 and as *c*. 44 for the fractured gneiss, demonstrating a more accurate representation of the rock mass strength differences of the massive and fractured gneiss.

4.3 Block size and rock erodibility, Codleteith Burn catchment, Southern Scotland

Geohazards related to active geomorphic processes such as debris flows and landslides affect many upland areas. Pre-existing fractures are a significant factor in the preconditioning of rock masses for erosion at the Earth's surface (e.g. Clarke and Burbank, 2010; Dühnforth et al. 2010; Roy *et al.* 2016). Areas of intensely fractured rocks are thus more likely to be associated with higher susceptibility to debris flow and landslide hazards. This susceptibility is likely to be driven both by higher volumes of material being produced from hillslopes underlain by highly fractured rocks, and by the size distribution of sediment grains entering the geomorphic systems (e.g. Sklar *et al.* 2016). To understand the controls exerted by the rock mass properties on geomorphic systems, the spatial variability in fracture networks in bedrock needs to be adequately characterised at catchment scales. This characterisation is challenging in many upland settings as high spatial variability means that large data sets from multiple sites are required, yet practical difficulties accessing sites are common in steep terrain.

The 2D fracture digitisation method is here used to assess the spatial distribution of block-size and fracture density of metasandstone of low metamorphic grade in the Southern Uplands, southern Scotland (Figure 5). The use of the 2D digital method allowed for a nested sampling approach, to characterise variability across a range of length scales, from meter (Figure 5C), to decimetre (Figure 5B), to catchment (Figure 5A). Block density can be expressed as blocks per square metre, which is easily derived from a polygonised set of fracture traces, and is related to the fracture density (Figure 5D). 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, fault-related fracturing gives rise to highly variable fracture density across the study area, and variations in 2D block size estimates from <50 to >1000 blocks per m^2 (Figure 5D). These data help to quantify the way in which rock mass parameters such as fracture density influence key geomorphic process elements such as block size. This type of data can be used to inform modelling of erosion and sediment movement within landscapes.

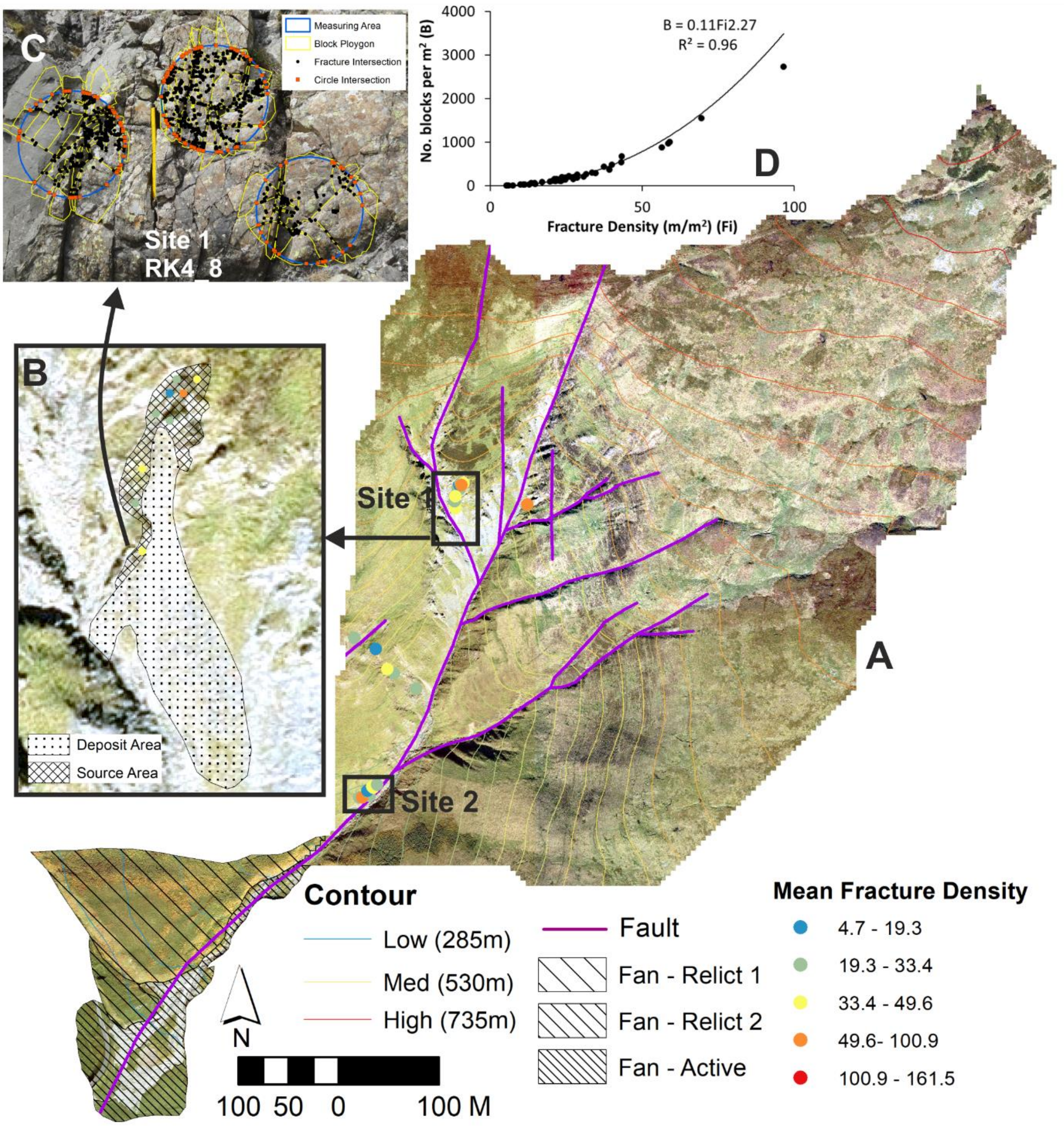

Figure 5. Multi-scalar fracture network and block-size analysis for the Codleteith Burn catchment in the Southern Uplands of Scotland (A). Sites 1 (B) and 2 (not shown) are sub-catchment hillslope source areas sampled at high

resolution. Variability at the outcrop-scale was captured using multiple sampling windows per image (C). The number of blocks sampled per m^2 is strongly related to the fracture density (D).

4.4 Application to historic photographs of shallow basement fractures, eastern Sweden.

During the construction of the Forsmark nuclear power plant in east Sweden in the 1970s, a series of excavations for shafts, tunnels and cooling water canals were dug out in basement gneiss rocks. In these excavations, numerous subhorizontal fractures were encountered, many of which were dilated and filled with water-lain silt and sand. Many aspects of this shallow fracture network were documented at the time, including aperture and roughness, density, orientation, coatings (chlorite, epidote etc), as well as a characterisation of the sediment fills (Stephansson and Ericsson, 1975; Carlsson and Olsson, 1976; Carlsson 1979). As construction was completed the excavations were graded, or concreted over or filled with water and are not available for study anymore. The shallow fracture network remained of interest to establish the potential of groundwater overpressure and hydraulic jacking of basement fractures (e.g. Pusch *et al*. 1990; Talbot 1990; Lönnqvist and Hökmark, 2013; Talbot, 2014), as well as playing a potentially important role in a newly recognised erosion mechanism, termed glacial ripping (Hall *et al.* 2020). For this latter (ongoing) research one relevant issue is the fracture density of subvertical and subhorizontal fractures as a function of depth in sections with and without fracture dilation: data that was not gathered during the original studies in the 1970s.

To acquire this data, high quality historic photos were used. All photographs contain a clearly recognisable measuring stick, and could thus be georeferenced accurately. Digitisation followed the methods described in this paper. Fracture aperture characteristics were attributed to the digital traces based on their appearance in the photographs. The shapefile of fracture traces was imported into python, with which spatial parameters such as orientation were calculated and fractures were separated into subhorizontal and subvertical attitudes. Total fracture trace length was calculated for each 1 m depth interval and fracture density for each interval was subsequently calculated. The results are plotted as a density-depth profile, and a cubic interpolation was used to smooth the curve (Figure 6). Results show a clear difference in fracture density between different sections (Figure 6A, B). A further difference is that in some sections (e.g. SKB-003) both the subvertical and subhorizontal fracture densities increase towards rockhead, whilst in other sections (SKB-036) only the subhorizontal fracture density show a marked increase.

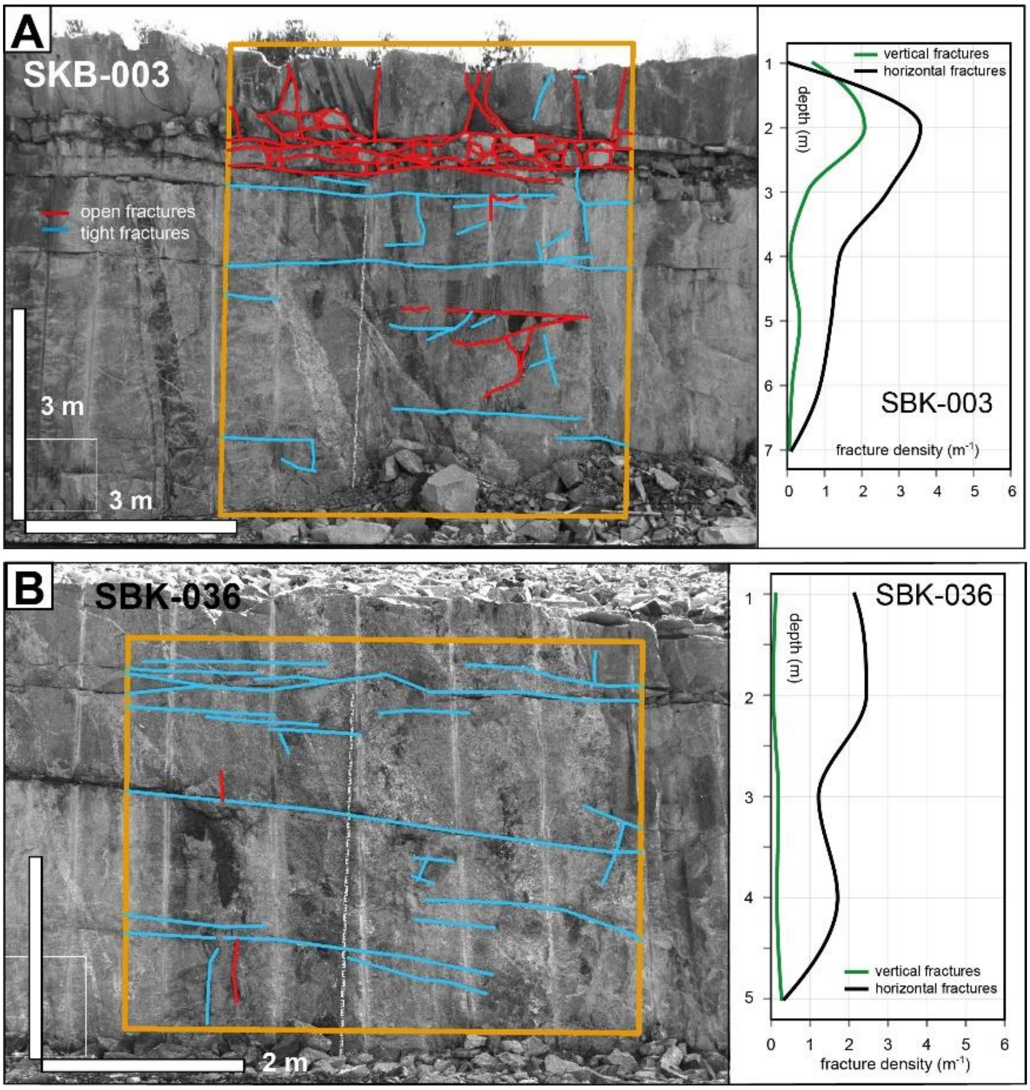

Figure 6. 2D fracture analysis applied to historic photographs of excavations during the construction of the Forsmark nuclear power plant, eastern Sweden. Photos: Göran Hansson. Open and tight fractures (red/blue) were digitised. Fracture density was calculated separately for subvertical and horizontal fractures.

5 Discussion

5.1 Overview of case studies

The case studies presented here highlight a range of benefits from the use of the 2D digital method for different applications. The Cauvery Catchment case study demonstrates how 2D digital capture provided flexibility to gather data for estimation of regional aquifer properties on a short reconnaissance-style field-campaign, with fracture data collected retrospectively from photographs taken at key localities. The 2D digital dataset allows for evolved quantitative and graphical data analysis, such as heat maps of fracture intersections to better understand connectivity. For engineering geology purposes, commonly-used qualitative approaches for estimating key rock mass strength parameters such as the geological strength index (GSI) are subject to variability through interpretation bias and practitioner experience, resulting in increased uncertainty, and potentially in higher project risks and costs. In the case study presented here, the 2D digital method is shown to provide a more accurate and consistent representation of the geological strength index (GSI) of a rock mass than the commonly-used qualitative estimators (e.g. Hoek, 1983; Sönmez and Ulusay, 1999). In geomorphic studies, quantitative characterisation of rock mass strength is increasingly important for parameterisation of process and landscape-evolution models (e.g. Roy *et al.* 2016; Sklar *et al.* 2017). The Codleteith Burn Catchment study demonstrates the potential of the 2D digital method for multi-scalar fracture analysis in challenging terrain. In eastern Sweden, the historic photographs were the best source for capturing specific fracture parameters in the shallow basement, and the 2D digital method is the only possible way to retrospectively gather this data.

A number of modern applied geoscience studies, such as in groundwater modelling (Babadagli, 2001), geothermal energy (Hitchmough et al., 2007) and geotechnical engineering (Bandpey et al., 2019) use field-based-only methods to gather fracture network data. Field measurements of geometry and density of fractures networks are used to understand the mechanical and hydraulic properties of a rock mass (Babadagli, 2001; Maréchal *et al.* 2004; Siddique *et al*. 2015). The 2D digital method described would be ideally suited to such case studies to improve the quality of data collected and allowing for more advanced analysis. In these studies, field time and accessibility of the outcrop are a major consideration for the type and amount of fracture data collected. When time is limited a 1D method is used to collect fracture data (Bandpey *et al.* 2017), whereas the new digital method would allow full 2D fracture traces to be collected efficiently. In studies that look at slope stability on narrow mountain roads in the Himalayas (Siddique et al., 2015), limited fracture data is used in rock quality calculations, which is likely due a combination of time constrains and the inaccessibility of the outcrop. The digital method would provide a more accurate estimate of fracture geometries when modelling slope processes (e.g. Pradhan and Siddique, 2020).

5.2 Benefits and limitations

The capture and publication of digital objects such as digital fracture network traces and derived parameters is an increasingly valuable part of the geoscience research process, facilitating evaluation and supporting ongoing scientific discovery (Gil *et al*. 2016). The case studies demonstrate that the 2D digital method described herein represents a valuable tool for analysing fracture networks, facilitating the efficient capture of quantitative datasets through a systematic and reproducible approach. Nevertheless, there are benefits and limitations compared to other fracture capture methods.

The 2D digital method is as rapid, if not more so, than a 1D scan-line survey. However, the 2D digital method does not capture the direct field observations such as orientation, roughness, aperture and any secondary fills. These parameters are useful for understanding rock mass strength or permeability (Carlsson, 1979; Laubach *et al.* 2019). If such direct observational data are required for the study (and practical on the outcrop in question), it is perfectly possible to first perform the 2D digital fracture capture as described herein, and then return to the study site and augment the dataset with further observational data as attributes; portable PC tablets are ideal for this purpose.

A major drawback of the 2D digital method is that it captures the fractures that are at a high angle to the outcrop plane, but not those that are subparallel to it. It is these fractures that will be particularly important for slope stability studies. This can be mitigated by analysing outcrop faces at different angles, but this may not always be possible. In these cases, an additional scan-line survey, focusing on fracture orientations, may be added to the study, or – if resources allow – a 3D scanning survey could be undertaken. The 3D scanning method does gather more data, including orientation of exposed fracture surfaces. This method is probably preferred for intense, localised studies, such has local, high-value infrastructure projects, or other key sites. However, 3D scanning methods are resource intensive, and likely not cost-effective if a fracture network analysis of multiple sites across a region is required, for instance for long infrastructure projects or regional groundwater studies.

Finally, the 2D digital method is the only method to capture data from historic images, valuable for the retrospective analysis of temporary sections during construction or quarrying, which can be crucial if existing exposure is limited.

6 Conclusions

The aim of this paper is to describe, evaluate and develop a simple but robust, low-cost method for capturing 2D fracture network data 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 2D digital method can be used to interpret traces of 2D linear features of a wide variety of scales from the outcrop scale to the regional-scale, using outcrop photos, aerial photographs, DEMs or satellite imagery.

An important aspect of applied geosciences is the use of fracture network parameters to characterise a rock mass in terms of rock mass strength and fluid flow properties. The field-based methodology for determining fracture network parameters can be time consuming and impractical, when field time is limited or outcrops are inaccessible. 2D digital fracture trace capture is an accurate and rapid method of quantifying 2D linear networks 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. The low-cost nature of the method means that it can be applied to a large number of outcrops, so that in studies where the spatial variability of fracture networks is important, large datasets can be generated cost effectively. Systematic capture and publication of 2D digital fracture datasets has significant potential to enhance future geoscience research by making aggregated analysis (meta-analysis) possible.

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