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29 June 2020

Dear Professor Federico Rossetti,

We are now resubmitting a revised version of our manuscript, originally entitled “A review and evaluation of the methodology for digitising 2D fracture networks and topographic lineaments in GIS”.

The original focus of the manuscript was to provide an insight into each step of the method and the potential pitfalls, improving the quality of data in future studies and making the method more accessible to a wider range of users. We never meant this manuscript as a review of all fracture data capture methods, and perhaps this led to unrealistic expectations for the reviewers. In the revised manuscript, we have refocussed on the detail of the methodology and its potential uses rather than a review of digital fracture analysis, therefore, we are retitling the manuscript: “Data acquisition by digitising 2D fracture networks and topographic lineaments in GIS: further development and applications”. The paper is primarily *aimed at workers without access to expensive software or equipment and scientists outside of structural geology*, such as geotechnical engineers, geomorphologists and groundwater modellers.

We have reorganised the manuscript to 1) provide a clearer understanding of where this method fits within the current literature, 2) provide a better understanding of the potential contribution that the method will make to large-scale digital fracture datasets and 3) provide an important outline of good practice for gathering digital fracture data for future studies.

Changes to the manuscript are in two parts, 1) a reorganisation of the introduction to address issues around the novelty of the method, and 2) a development of the discussion to demonstrate the usefulness of the method. The aim of this manuscript is to provide a detailed description and discussion of the digital fracture network analysis methodology and to set out an important standard for future studies. Furthermore, we aimed to make the technique more accessible to a wider audience (in particular in developing countries), which is reason for the presentation of the method using open-access software and publishing in an open-access journal. In the new title and the restructured introduction, we have refocused the emphasis of the paper onto the methodology, with some context in terms of how the methodology fits with 1D to 3D fracture network analysis.

To address points 3 and 4, in regard to the usefulness of the technique we have added a new case study, which is an example of how the method can be used on historic photographs of sections that are no longer available and therefore it would otherwise be impossible to gather fracture network data. Furthermore, we have developed the discussion to focus on the on digital benefits of the method, in terms of generating large datasets across large areas, which is particularly relevant in modern geoscience field campaigns. The refocussing of the discussion onto the benefits in terms of digital data acquisition and management for broad range of studies helps demonstrates the useful of the method for wide range of studies in a range of circumstances where conventional analogue fracture network analysis is not applicable.

The review suggests the technique has limited useful as it does provide data on surface orientation. In the various examples provided the parameters that are derived from digital fracture network analysis include length, spacing, density and relative orientation. In these case studies these fracture network parameters provide an important understanding in terms of rock mass strength, groundwater properties and erodibility. We strongly disagree with the point as there are number the 2D geometric and topological parameters that are used to understand fracture networks in broad range of contexts.

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

Yours sincerely,

Dr Romesh Palamakumbura
On behalf of the co-authors

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 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~~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.~~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.~~

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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 ~~e~~Earth sciences, 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 (Clarke and Burbank, 2010). Fracture network data are essential for assessing future sites of nuclear waste repositories (Follin ~~et al.~~*et al.* 2007), predicting rock slope

Commented [PRN2]: Better swden reference stability (Selby, 1982; Park ~~et al.,~~*et al.* 2005) and understanding intact rock strength for engineering of infrastructure (Hoek and Brown, 1997; Zhan ~~et al.,~~*et al.* 2017; Ren ~~et al.,~~*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 (~~cf.~~ Schrodt ~~et al.,~~*et al.* 2019).

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

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

The ready availability of digital cameras and suitable open-source software means that the 2D digital capture methods have 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). Whilst advanced 3D methods for outcrop imaging and fracture analysis are now available (~~CITE~~Tavani *et al.* 2016; Bisdom *et al.* 2017).~~,~~ L~~l~~imited access to necessary hardware, software and training technology ~~and practical constraints on deployment,~~ may limit the wider adoption of these high-cost techniques in many applied research contexts. ~~Furthermore~~ S~~, s~~ystematic 2D digital capture methods have 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

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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 ~~utilising~~using micro (e.g. thin section) to macro (e.g. satellite) scale images.

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

~~[ALTERANTIVE TO PARA ABOVE…] 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. From this dataset, numerous key spatial relationships and parameters can be calculated. The only equipment needed are a 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.~~

~~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 wider potential of this method for other users, for example geotechnical engineers, groundwater modellers and geomorphologists (Figure 1).~~

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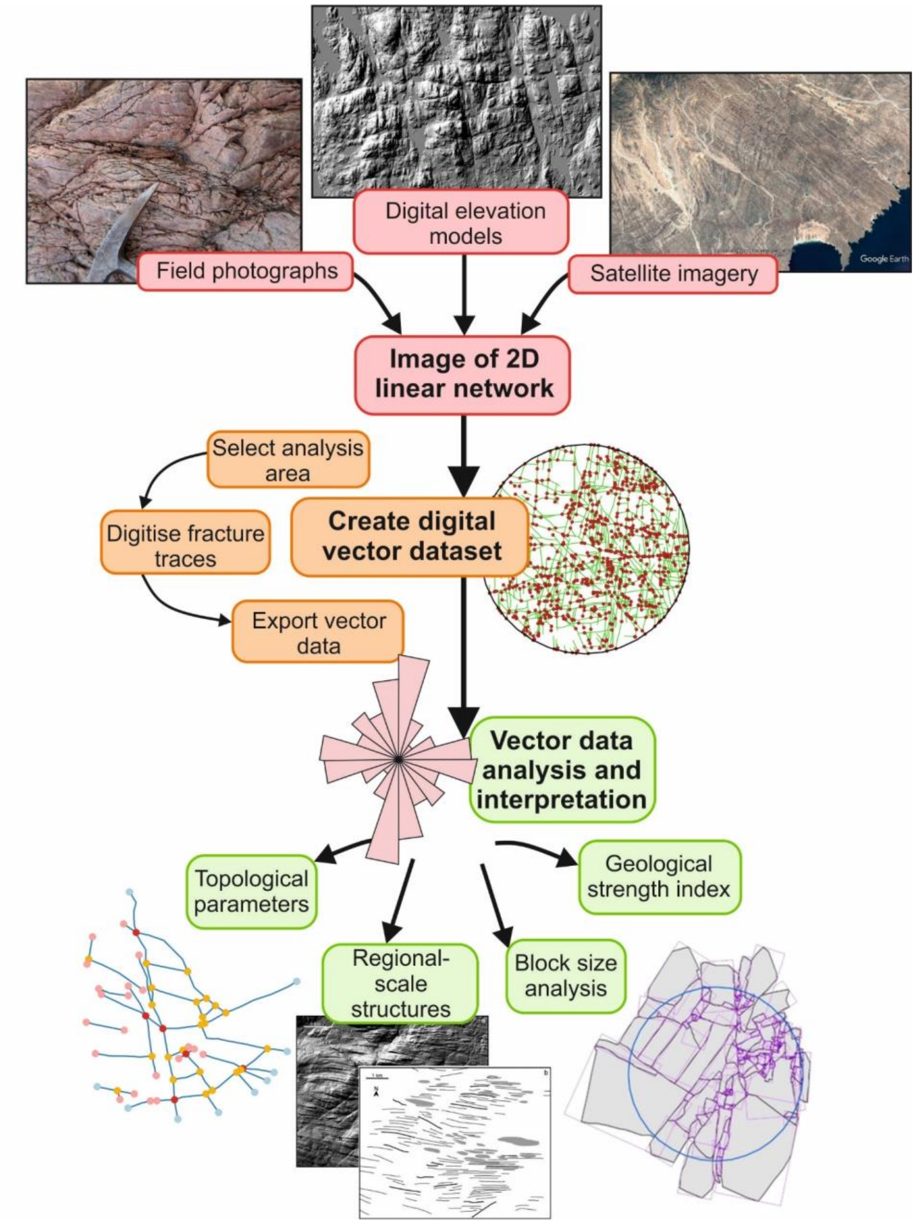

Figure 1: Flowchart providing an overview of the methodology used for digitising linear features, from preparing an image, digitising the features to output of data. Digital elevation model examples are taken from Next map © in Scotland, and the satellite image of Oman example is taken from Google Earth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

2. Summary of fracture data capture methods

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~~A complete u~~Understanding ~~of~~the effect of a fracture network on the properties~~, for example for detailed analysis of fluid flow,~~ of a rock mass requires ~~observations~~acquisition ~~of many parameters~~ a range ~~of~~various measured parameters such as length, orientations, density and spacing (Singhal and Gupta, 2010).~~;~~ N~~n~~etwork topology~~, such as~~ 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, 2019). Finally, ~~; and~~ fracture ~~character, such as~~ aperture, ~~fracture~~ fill and paragenesis history provide an important understanding of the fracture network history, fluid flow and fracture strength (Carlsson, 1979; Laubach ~~et al.,~~*et al.* 2019).~~ Some of these parameters, such as fracture aperture and fill can only be acquired by direct observation, whilst others can be derived from analysis of images – and can thus be potentially captured using~~ ~~relating to fracture geometry, topology and character (e.g. aperture size and fill), and both field and digital capture methods typically need to be combined to derive suitable datasets (e.g. Laubach et al., 2019).~~ ~~digital image methods (e.g. Watkins et al. 2015; Healy et al. 2017). However, depending on the application, not all these parameters are necessarily required: for some application fracture connectivity is important, for others fracture orientation is important.~~

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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 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 cannot directly constrain ~~certain~~ parameters such as fracture length and connectivity. ~~; i~~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.~~*et al.* 2013b; Watkins ~~et al.~~*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).~~

In 2D fracture network analysis, a circular ~~scanline or~~ sampling window is commonly used~~As a compromise, many studies employ a 2D approach. Normally, this uses some form of characterisation within a circular window on a rock outcrop~~ (Davies et al, 1996; Rohrbaugh ~~et al.~~*et al.* 2002; Watkins ~~et al.~~*et al.* 2015a).~~;~~ I~~i~~n the field, ~~. Generally, for 2D analysis a circular scanline or window approach is taken.~~ ~~this is commonly carried out by using~~ a circular ‘chalk line’ is drawn on an outcrop, within which the fractures and ~~their~~ ~~attributes~~key geometry’s are captured. Connectivity within two-dimensional fracture networks 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 many 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 typical sampling window diameters of 1 – 2 m being commonly used (e.g. Watkins ~~et al.,~~*et al.* 2015; ~~CITE others~~Procter and Sanderson, 2018). This limitation means that 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.~~*et al.* 2001), in which only those fractures are captured that intersect the particular circular scanline; in a sense it is similar to the 1D approach. The ~~In the former, fractures intersecting the a circular line are recorded, whereas in the latter, fractures within the window area are recorded. C~~circular scanline ~~methods are~~analysis is more rapid than the full 2D circular ~~circular~~ window analysis~~methods~~ and ~~have~~ has less length and orientation bias compared to 1D methods (Mauldon ~~et al.,~~*et al.* 2001).~~-~~ The circular scanline method ~~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.~~*et al.* 2001). This method~~,~~ provides~~ing~~ a time~~n~~ efficient means of deriving basic fracture parameters. The Mauldon *et al.* 2001 method only provides length and density proxies from the data collected in the field, if other parameters are needed further field work would be required. ~~However, the validity of these proxies depends on the variability and anisotropy of the fracture network, and fracture connectivity in particular cannot be accurately captured.However, circular scanline methods lack the full analysis of a completethe 2D circular window approach is needed where more complex parameters such as those related to fracture connectivity are required~~. ~~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 understand fluid 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).~~

~~The 2D circular scan line and sampling window methods can be applied in both analogue (in situ) and digital contexts. Field-based 2D fracture network analysis is commonly carried out by using a circular ‘chalk line’ drawn on and outcrop, and a range of parameters can be derived describing the 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 fracture geometry and network parameters, such as length, orientations, density and spacing (Singhal and Gupta, 2010); network topology, such as percolation potential and clustering (Sanderson and Nixon, 2019), and; fracture character, such as aperture and paragenesis history (Laubach et al., 2019). However, there are a number ofField-based data capture~~

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~~provides direct observations and is particularly important for describing aperture fill and paragenesis as well as capture of 3D orientation data, however many important geometric and topological characteristics of fracture networks can be captured using digital methods (e.g. CITE).~~ ~~limitations when gathering fracture network data in the field. Firstly thisField-based capture can be very time consuming, particularly when collecting largedata from multiple sites are required datasets across a large field area. Secondly, and may be impractical, or impossible for some many outcrops, such as quarries, cliffs and coastal platforms or unstable cliffs may not be impractical or unsafe to access for making fracture measurements. Field-based methods are also limited in their scale of application, with typical sampling window diameters of 1 – 2 m being commonly used (e.g. Watkins et al., 2015; CITE others). This limitation means that variability in fracture properties at scales greater than 5-10 m may be difficult to capture using field-based sampling alone. By contrast, digital data capture methods can be used at a greater range of scales, permit data capture from inaccessible sites, and provides a reproducible approach from which a digital dataset suitable for numerical and statistical analysis can be readily derived.~~

~~Digital 2D data capture methods are based on the same principles as field-based sampling, but utilise 2D imagery such as photographs of an outcrop or thin section, aerial photographs, or satellite imagery (CITE). The 2D digital capture methods typically rely on GIS-type functions for the visualisation and analysis of images, and can be undertaken using standard GIS tools, as well as enhanced software applications such as 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 (Nymberg et al., 2018). These tools provide enhanced functions for efficient capture of data from images, and are targeted for application in structural geology research contexts.~~

~~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.~~

Ideally, for any application, a full 3D characterisation of the rock mass is achieved. However, t~~t~~rue 3D characterisation of a rock mass is currently only possible using CT scanning, and is restricted to very small samples (Voorn ~~et al.~~*et al.* 2015). ~~Digital capture of fracture network parameters is also possible from h~~High resolution ‘3D’ images of outcrop surfaces (more like ‘2.5D’) can be captured ~~using~~ by ~~from~~ laser scanning, which can be ground based or UAV (e.g. ~~Pless et al., 2015.~~ Bisdom ~~et al.,~~*et al.* 2017; Gao ~~et al.,~~*et al.* 2017~~; Senger et al., 2015~~; Wüstefeld ~~et al.,~~*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.,~~*et al.* 2014). These can provide additional information on fracture orientation through the use of advanced image analysis techniques (Wüstefeld

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Commented [PRN18R17]: I removed some but there rest are okau *et al.* 2018~~e.g. Pless et al., 2015~~). These~~is~~ methods have~~s~~ been used ~~), and are therefore valuable to inform~~for advanced fracture network analysis and modelling for applications related to fluid flow, gas migration and engineering/construction (e.g. Bisdom ~~et al.,~~*et al.* 2017; Menegoni ~~et al.,~~*et al.* 2019; Strijker ~~et al.,~~*et al.* 2012; Tavani ~~et al.,~~*et al.* 2016). ~~, however~~ These 3D scanning techniques require sophisticated hardware, proprietary software and training that~~,~~ potentially limit~~ing on ~~s their applicability. In addition~~,~~ ~~whereas~~there are ~~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).~~

~~A complete understanding of fracture network properties, for example for detailed analysis of fluid flow, requires observations of many parameters relating to fracture geometry, topology and character (e.g. aperture size and fill), and both field and digital capture methods typically need to be combined to derive suitable datasets (e.g. Laubach et al., 2019). However,~~ practical limitations at ~~potential~~ sites, such as access and restrictions on the use of UAVs, that may further limit their use (e.g. Senger ~~et al.,~~*et al.* 2015)~~, or lack of access to suitable technology, may restrict the use of high-resolution 3D 'virtual outcrop' technique~~)s.

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

~~2D digital methods for fracture data capture can be deployed alongside field-based (1D or 2D) capture and/or 3D 'virtual outcrop' analysis to compliment detailed or high-resolution studies, or can be deployed as the primary method of data capture where the geometric and topological parameters that are readily captured by the method are suitable and sufficient for the nature of the analysis.~~

~~2D digital analysis methods provide a valuable approach for geometric and topological parametrisation of fracture networks that can be used alone, or in conjunction with in-field capture and/ or 3D analysis techniques (Krabbendam and Bradwell, 2014; Pless et al., 2015; Watkins et al., 2015a; Krabbendam et al. 2016; Healy et al., 2017).~~ In its basic form the 2D digital method ~~The accessibility of the method, which~~ requires only a digital camera, a measuring stick and access to GIS (such as open-source QGIS).

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~~, and this~~The low-cost~~, low threshold~~ nature~~also can be used systematically on a range of types of image,~~ 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 practise for 2D digital fracture capture and analysis. In~~,~~ particular~~ly~~ we focus~~ing~~ on the practical aspects of image capture, preparation and analysis using QGIS and ~~available~~other open-source tools and plugins. ~~We then present f~~Four case studies ~~that~~are presented to illustrate the wide applicability of the method.

We demonstrate some simple fracture analysis tools that can be applied to the captured data. Finally, w~~We~~e ~~then~~ evaluate the benefits and drawbacks of ~~2D digital capture~~a digital method for capturing fracture data.~~ compared to other (1D or 3D) methods.~~

~~2 Method Background~~

~~The digital fracture trace method has been used for data collection in a range of structural geology studies,Digital methods are used in a wide range of studies to gather fracture network data including multiscale fracture network models (Strijker et al., 2012), the development of 3D fracture models (Tavani et al., 2016; Menegoni et al., 2019) and and developing discrete fracture networks (DFNs) to model fluid flow (Bisdom et al., 2017). These studies often use equipment such as drones to image an outcrop (Gao et al., 2017), LIDAR to scan and generate high resolution outcrop surfaces (Wüstefeld et al., 2018) and photorealistic georeferenced models (Bisdom et al., 2017).. This type of equipment is able to produce high quality digital representation of an outcrop that can be use generally a highly accurate dataset, however this is also expensive and can require specialist training and licences, such as a UAV pilot licence. However, gradually equipment has become cheaper and more accessible to users, for example inexpensive drones and smart phones are now used to generate high quality orthorectified images.~~

~~A number of free software packages are available for digital fracture analysis that range from data acquisition (DigiFract (Hardebol and Bertotti, 2012)), to basic processing in Matlab (FracPaq (Healy et al., 2017)), and finally to typology-type analysis in ESRI ARC GIS and QGIS (Network CT (Nymberg et al., 2018)). The free open-access software provides the basic tools for fracture data acquisition and processing. Although even several of the open access require paid for software to run such as FracPaq which requires Matlab and Network CT which requires ARC GIS. The open-access software is generally aimed at structural geology type studies rather than applied geology such as groundwater modelling and geotechnical modelling.More evolved fracture analysis and modelling can be done with commercial software such as SKUA-GOCAD (i.e. Spahić et al., 2013), MOVE (i.e. Watkins et al., 2018) and Petrel (i.e. Lepillier et al., 2020). Commercial software provides the capability for more evolved analysis of fractures from various datasets including boreholes and seismic data and the ability~~

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~~to 3D fracture network models. However, commercial software is often expensive and requires extensive training and experience to use.~~

~~Over the past few years photogrammetry technology such as UAV, high-quality digital cameras and GPS devices have become more accessible and inexpensive. As these technologies become more prolific and accessible a wider range of users are able to undertake basic fracture network analysis, who do not necessarily have access to more expensive software for example in developing countries or academics and students. Fracture network data is used range applied geology fields, such as groundwater modelling of a fractured hard rock aquifer (Maréchal et al., 2014) where field measurements of fracture could help understand the hydrodynamic properties. A more accessible open access method is needed for users to carry out fracture network analysis.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.~~

~~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 an open-access method for capturing a 2D fracture network as a digital (GIS) dataset from outcrop photographs. From this dataset, numerous key spatial relationships and parameters can be calculated. The only equipment needed are a 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.~~

3~~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.

3~~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 (Watkins *et al.* 2015a). The outcrop selected will depend on the nature of the study being undertaken and the type

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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).

3~~2~~.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); 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.

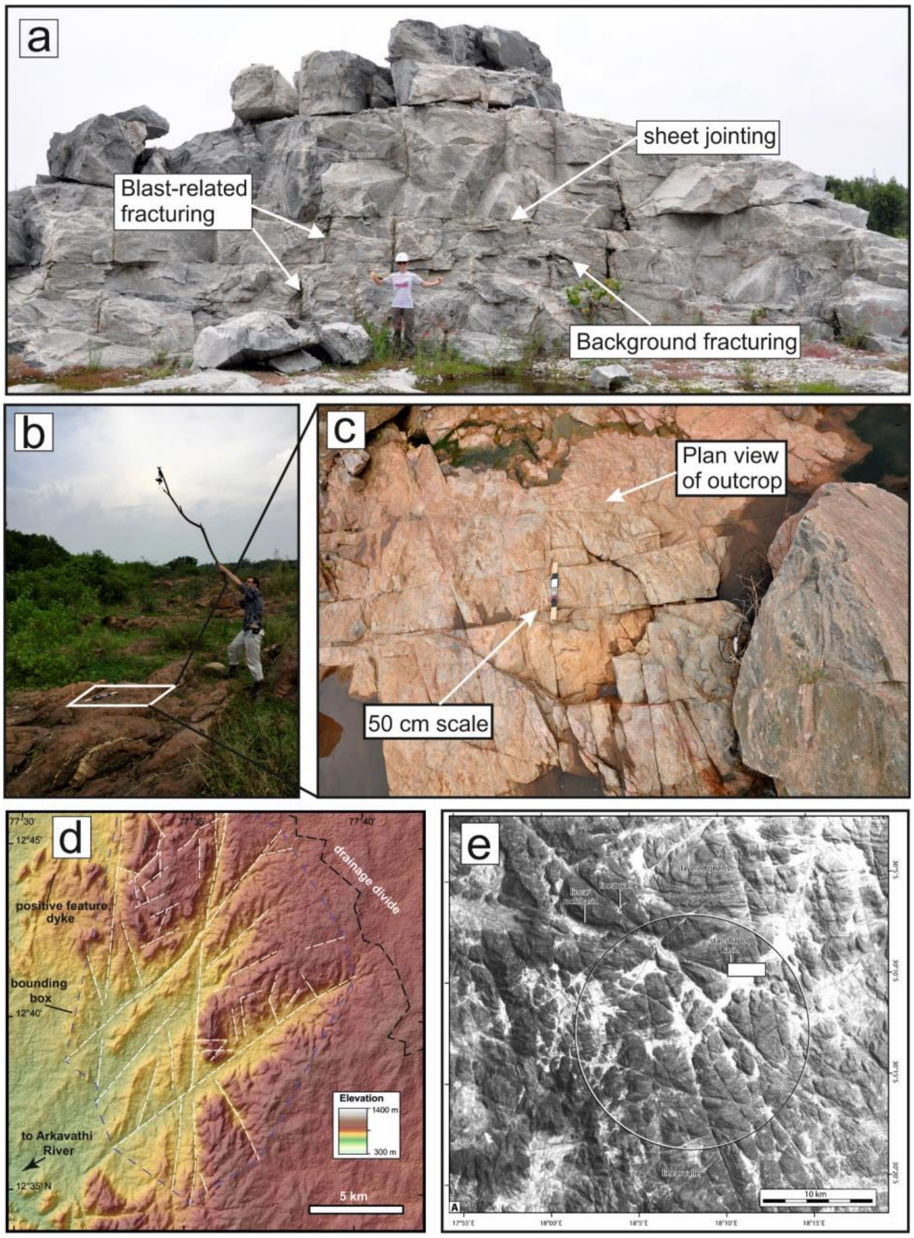
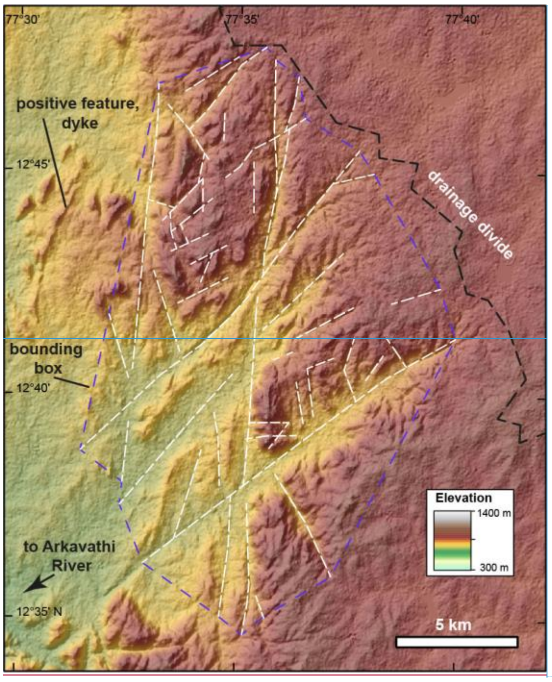


Figure 2: Examples of photographs and DEM images that can be used for digitising 2D linear features, including: (a-c) photographs of fracture networks of various scale from southern India and improvised methods for taking parallel photographs; (d) a DEM image from southern India of larger kilometre scale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



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3~~2~~.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 ~~can be done~~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, ~~georeference~~ the square on the photograph is georeferenced to a square on the fishnet grid~~, thus creating a georeferenced photograph within the GIS project~~ (Figure 3a).

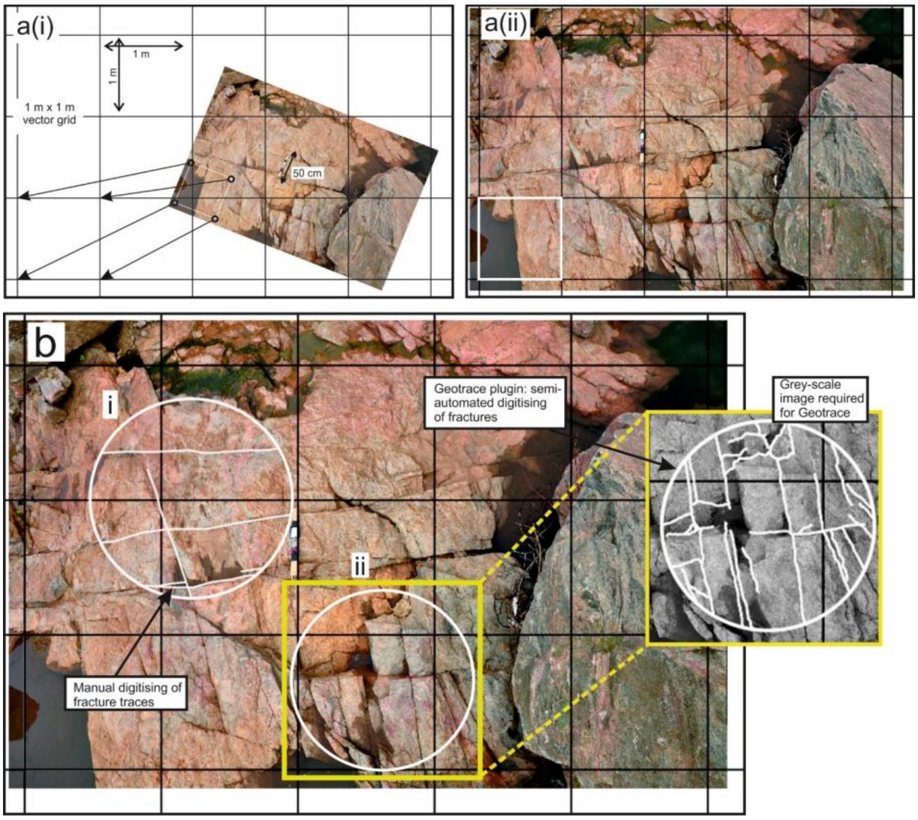

Figure 3: Images showing (a (i-ii)) how to georeference an image to a fishnet grid (black) from a square of a known scale (white); and (b) the tools available for digitising fractures in QGIS, including (i) a fully manual method; and (ii) a semi-automatic method such as Geotrace.

3~~2~~.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 ~~si~~is commonly already ~~if~~ georeferenced and 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 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. 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. Hence, for 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).

~~2.5~~ 3.5 Data capture

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3~~2~~.5.1 ~~Select~~ Create 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 c~~Create a line or polygon shapefile and digitise around 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.

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~~2.5.2~~3.5.2 Digitise linear features

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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 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.

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 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.~~

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3~~2~~.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):

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

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

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

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~~3~~ Case studies

To illustrate the use of systematic 2D digital fracture analysis methods to enhance applied geoscience investigation we present a number of case studies selected 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).

~~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.~~

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

Characterisation of fracture networks is ~~an important aspect of trying~~essential ~~-~~to understand local and regional-scale aquifer properties such as connectivity and permeability, in particular ~~. 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; Singhal 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~~have been an area of ongoing research (Maréchal ~~et al.,~~*et al.* 2006, Perrin ~~et al.,~~*et al.* 2011, Collins ~~et al.~~*et al.* 2020) as the spatial and temporal variability of groundwater availability for irrigation has great implications for communities. 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.,~~*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

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within the fracture zones. To quantify the connectivity, 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 number connections (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) was calculated by dividing the standard deviation of the fracture spacing by the mean fracture spacing (Gillespie ~~et al.,~~*et al.* 1999; Watkins ~~et al.,~~*et al.* 2015b) and was used to quantify the how clustered a fracture network is (Table 1) (Odling ~~et al.,~~*et al.* 1999). The Cv ratios show that the massive gneiss generally has ~~having~~ 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)
Fracture zone	4.6	0.2	17.8	157.0	61.0	121.0	517.0	3.3	3.8	1.4
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
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
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
Fracture zone	9.2	1.5	1.4	4.0	6.0	0.0	6.0	2.1	2.4	0.7
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

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

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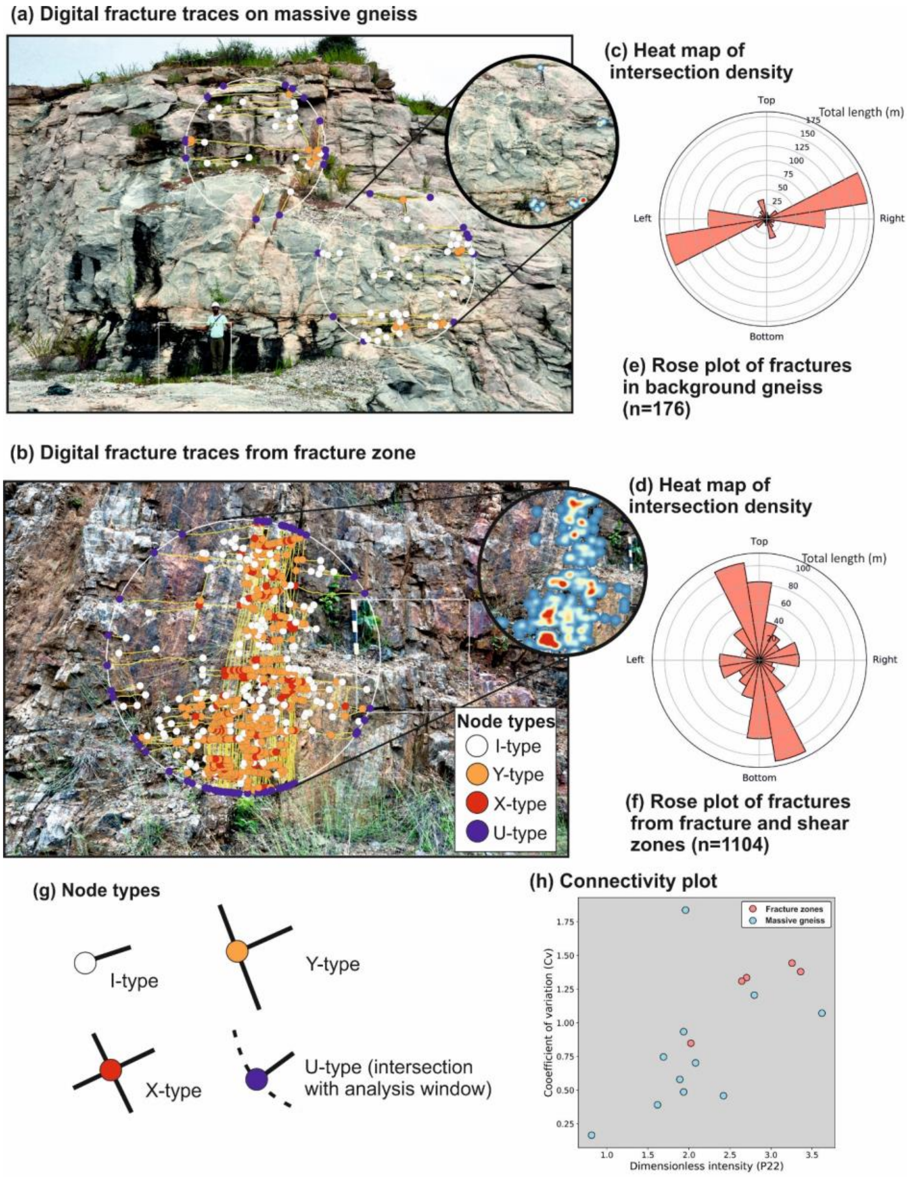

Figure 4: Fracture analysis from the Peninsular Gneiss, South India, including: field photographs with digitised fracture branches and intersection types on (a) a massive gneiss example; and (b) from a fracture zone; (c-d) heat maps illustrate variations in fracture intersection density (massive gneiss: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

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 c~~C~~onnectivity parameters ~~proxies, such as connections per line,~~ indicate the highest potential permeability is found in ~~that~~ the fracture zones ~~have the highest potential permeability~~, whereas the ~~permeability potential of the~~ background gneiss ~~is~~ has significantly lower potential permeability~~highly variable but still significantly lower~~.

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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 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.~~*et al.* 2020).

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

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Structural discontinuities are an important control on the engineering behaviour of a rock mass (Müller, 1974; Hoek 1983, 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 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):

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

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~~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 calculated are *c*. 76 for the massive gneiss and only *c*. 44 for the fractured gneiss, demonstrating an accurate representation of the rock mass strength differences of the massive and fractured gneiss.

~~The 2D digital method can provide a fast, accurate and consistent results for determining rock mass strength properties. 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.~~

4~~3~~.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. Roy ~~et al.,~~*et al.* 2016; Clarke and Burbank, 2010).~~, and a~~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 fracture~~ds~~ rocks, and by the size distribution of sediment grains entering the geomorphic systems ~~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.~~*et al.* 2016). To understand the controls exerted by the rock mass properties on geomorphic systems,

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The 2D fracture digitisation method is here used to assess the spatial distribution of block-size and fracture ~~intensity~~ density of metasandstone of low metamorphic grade in the Southern Uplands, southern Scotland (Figure 5). The use of the 2D digital method allowed~~s~~ for a nested sampling approach, to characterise variability ~~at~~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). ~~It should be noted that w~~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 ~~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 (Figure 5D). ~~This~~ These data ~~can~~ help to quantify the way in which rock mass parameters such as fracture density influence key geomorphic process elements such as block size.~~,~~ ~~providing parameterisationkey controls on the influence of facture intensity on block size, which may be used to~~This type of data can be used to inform modelling of erosion and sediment movement within landscapes.

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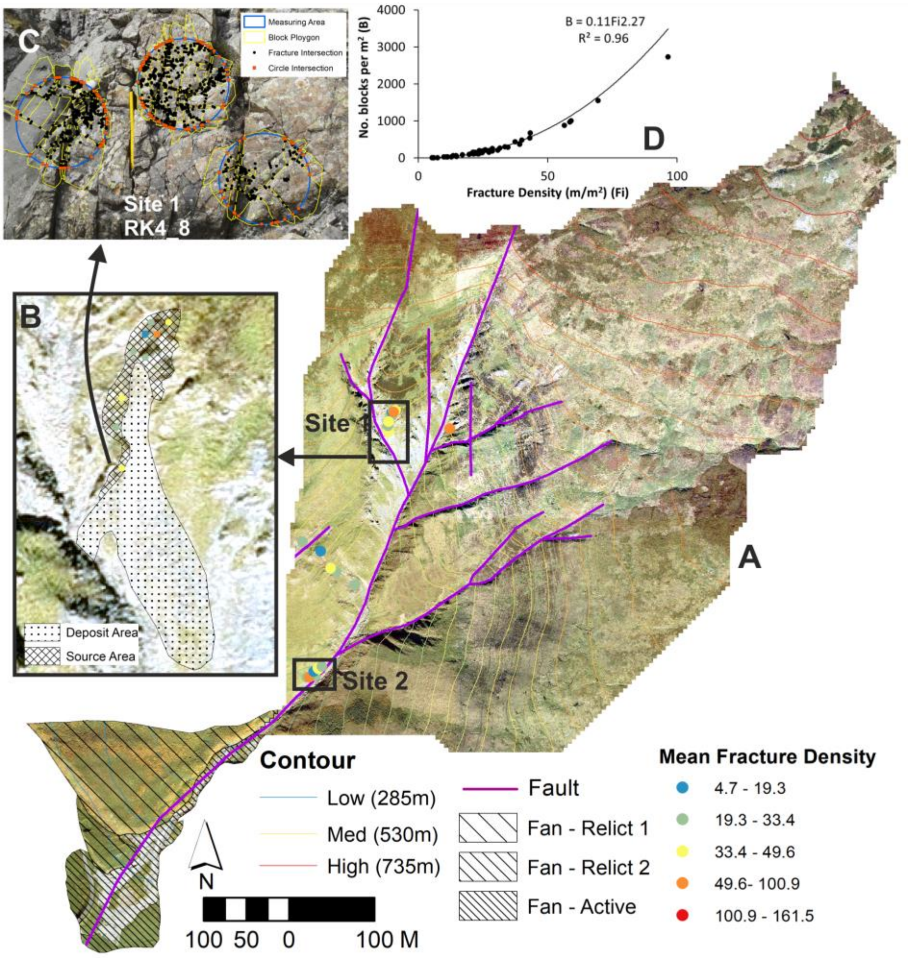

Figure 5. Multi-scalar fracture network and block-size analysis ~~Derivation of block-size metrics~~ for the Codleteith Burn catchment ~~Wacke sandstone~~ in the Southern Uplands of Scotland (A). Sites 1 (B) and 2 (not shown) are sub-catchment hillslope source areas sampled at high resolution. Variability at the outcrop-scale was captured using multiple sampling windows per image (C). ~~Field photograph of sandstone outcrop with fracture delineation (a), polygons for blocks sampled by the circular window (b),~~ The number of blocks sampled per m^2 ~~for dataset of 50 measuring sites from the study area~~is strongly related to the fracture density (D).

~~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 (Figure 5a), resulting in a large and accurate dataset.~~

~~3.3 >> Swedish example: Add section on use of historical images…~~

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. Many aspects of this shallow fracture network were documented at the time, including ~~fracture~~ aperture and roughness, ~~fracture~~ density, ~~fracture~~ orientation, ~~fracture~~ coatings (chlorite, epidote etc), as well as a characterisation of the sediment fills (Stephansson & Ericsson 1975; Carlsson and Olsson, 1976; Carlsson 1979). Since these studies, the original excavations were graded, or concreted over or filled with water and not available for study anymore, even though they remained of interest to establish the potential of groundwater overpressure and hydraulic jacking of basement fractures (e.g. Pusch et al, 1990; Talbot 1999; Lönnqvist & Hökmark, 2013; Talbot 2014), relevant for the safety of a proposed deep nuclear waste repository nearby.

Interest in these fracture networks was rekindled as it was recognised that the sediment-filled fractures play a major role in a newly recognised erosion mechanism, termed glacial ripping (Hall ~~et al.~~*et al.* 2020). This research is ongoing, and 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 photos were provided from the archive of SKB, the Swedish Nuclear Fuel and Waste Management Co. All photos ~~had a good ruler or tape measure~~contain a scale, such a measuring stick, and could thus be georeferenced accurately. ~~-~~Digitisation followed the methods described in this paper. Fractures aperture characteristic were attributed to the digital traces based on their appearance in the photograph. The shapefile of fracture traces was imported into python, where spatial parameters such as orientation were calculated and fractures were separated into subhorizontal and subvertical. Total fracture trace length was calculated for each 1 m depth interval and fracture density for each interval was subsequently also calculated. The results are plotted as a density-depth profile, and a cubic interpolation is used to smooth the curve (Figure 6). ~~ROMESH; SAY SOMETHING ABOUT THE SMOOTHING!!.~~ Results show a clear difference in fracture density between different sections (Figure ~~-~~ 6~~X~~A~~A~~, B~~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.

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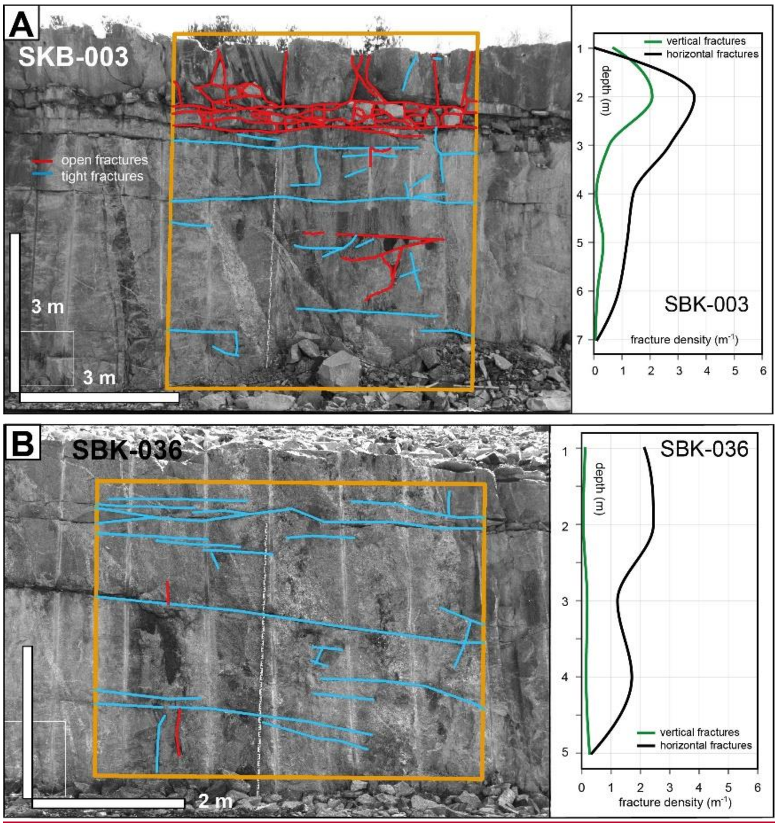

Figure 6. 2D fracture analysis applied to historic photographs of excavations during the construction of the Forsmark nuclear power plant, eastern Sweden. Open and tight fractures (red/blue) were digitised. Fracture density was calculated separately for subvertical and horizontal fractures.

5~~ MK: I think this can be culled or left out…~~

~~3.4~~5 ~~Case studies summary and dDiscussion~~

5 Discussion

5.1 Overview of case studies

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 presented here ~~demonstrate~~ highlight ~~the broad~~a range of benefits ~~of~~ from the use of the 2D ~~a~~ digital method for

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Commented [WK51]: Could this be integrated within an expanded ‘Case studies summary and discussion section’?

At the moment this section is very generalised and needs a lot of tightening up.

I think the key point is that the field-based and 3D methods are typically used in studies at relatively small scales… i.e. for a single site, or a limited number of sites

So the main point of this section will be to demonstrate that the number of sites these studies use is relatively limited -> My main recommendation would be to get some specifics from the papers about the numbers of sites they are looking at and/or the scales over which they are working

Can we make the case that this practical limitation is restrictive of what is being achieved with respect to understanding fracture systems in the current literature?

Can we make the case that consistency and reproducibility would facilitate meta-analysis through compilation of data from many studies (– as happens a lot in biology and palaeontology) in the future?

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Commented [WK53]: This kind of statement gets repeated a lot, so it is very repetitive. At the moment, the statements about limitations and benefits are still too vague.

Commented [WK54]: The main point is that a limited dataset means that spatial variability in fracture parameters may be underestimated. This is particularly a problem for larger scale studies. Do these papers specifically highlight:
- lack of data / small datasets as a problem?
- Lack of consistency between datasets collated from other sources?

If these things are not easily drawn out, is it possible to make the point by pulling together some metrics from the paper ...

Commented [KM55]: We’ve said this now before.

Commented [KM56]: We’ve said this before.

Commented [KM57]: We’ve said this before. ..

Commented [WK58]: Again, this statement needs to follow on from a more explicit treatment of the limitations of the analogue studies: ...

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different applications~~ during both data collection and data analysis phases~~. The Cauvery Catchment case study demonstrates how the digital method provided flexibility to gather data for estimation of regional aquifer properties ~~while ~~on a short reconnaissance-style field-campaign, with fracture data collected retrospectively from photographs taken at key localities. The 2D 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, 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, giving rise to increased uncertainties, potentially leading to 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 & Ulusay, 1999)~~. 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~~. 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.,~~*et al.* 2016; Sklar ~~et al.,~~*et al.* 2017). The Codleteith Burn Catchment study demonstrates the potential of the 2D digital method for multi-scalar fracture analysis in challenging terrain, such analyses can provide a key foundation for enhanced process modelling. In eastern Sweden, the historic photographs were the best source for assessing the fractures in the shallow basement, and the 2D digital method is the only possible way to retrospectively gather this data.

~~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 gather in the field.~~

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 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 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 fractures geometries when modelling slope processsres (Pradhan and Siddique, 2020).~~<<Add sentence about the Swedish study>>~~

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~~<<?? Add here the paragraphs from the 'other case studies' section -> widen out to consider publish studies: demonstrate how they relate to the key benefits of the 2D digital methods identified particularly – larger datasets for understanding variability over regional scales. If possible, can we demonstrate that the scales of previous studies are generally quite limited? Can we really review enough literature to demonstrate this properly?>>~~

~~There are a number of studies that rely upon accurate fracture network data, however the collection of large field-based fracture data sets is too expensive, time consuming and outside of the main scope of the study. An open-access method for fracture data acquisition and processes would enable such studies to rapidly generate high quality data that could be used improve rock mass strength estimates and discrete fracture network models that are used for modelling hydraulic conductivity.~~

5.2 ~~54 Advantages and disadvantages~~Benefits and limitations

~~As demonstrated in the discussion and case studies presented, fracturing is a critical property of rock masses with significant implications for practical decision making in resource and environmental management and engineering contexts. Adequate characterisation of rock mass fracturing is notoriously difficult due to extremely high variability in parameters over a range of spatial scales, the restrictions of limited exposures for adequate observation in many settings, and the time intensive nature of sampling. Whilst these difficulties affect structural geology research contexts, they are particularly acute for many applied studies, where time and resourcing for intensive field sampling may be limited. As such it is common for applied studies, out with the realm of structural geology research, to utilise qualitative approaches for characterising fracturing, as seen in many engineering and geomorphic studies (e.g. Wohl and David, 2008; Whittaker et al, 2008; Roy et al, 2016; CITE – engineering studies). This qualitative sampling may be inconsistently applied by practitioners, and typically provide metrics that are of limited value for advanced analysis or modelling. A further problem of inadequate sampling is high uncertainty associated with upscaling small-scale or local observations to regional scales, which may affect projections of groundwater flow rates, engineering costs, and geohazard risks, amongst other impacts.~~

The case studies demonstrate that ~~T~~the 2D digital method described herein represents a valuable tool for ~~enhancing the characterisation of~~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

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secondary fills. –These factors ~~and~~ are useful ~~when~~ for understanding rock mass strength or permeability~~.~~~~, for instance estimates of fracture permeability and percolation from fracture topology alone represent the maximum potential and does not account of closed fractures~~ (Carlsson, 1979; Laubach ~~et al.,~~*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.

~~There are a number of 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 from an image 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. Additional observations such as aperture and infilling are import for these types of studies. However, It is also possible, of course, to digitise the fracture network, and then return to the outcrop and augment the digital traces can A further limitation is the iImage 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.~~

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 it – a 3D scanning survey could be ~~added~~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.

~~The method can be used in conjunction with field-based data capture, and with the use of 3D methods at suitable sites, offering a means to expand data capture capability that is particularly advantageous where, or when, practical limitations of time, cost and site access may be restrictive to the study.~~

Commented [KM63]: We need to be honest about this!!

Commented [PRN64R63]: This is the issue with all 2D fracture analysis though?

~~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 2D 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.with Field field time can be useddirected for detailed study capture of contextual information of the outcrop to improve the interpretation of fractures in the office and to gatherand other key data such as aperture, fracture fill and 3D geometry's. This increase in efficiency can enhance the amount of data captured in a given study, such that The digital method allows for large, statistically significant datasets to can be quickly gatheredgenerated even during a short field campaign. In addition, cCollecting 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 ~~use of~~ 2D digital method is ~~particularly suitable for~~the only method to capture ~~gathering~~ ~~valuable information~~data from historic images ~~(Section XX).~~ , ~~This capability is~~ valuable for the retrospective analysis of temporary sections during construction ~~and development works~~ or quarrying, which can be crucial if existing~~,~~ ~~and can support more extensive analysis in areas of limited~~ exposure is limited. ~~,~~ ~~even allowing studies to be undertaken in the absence of modern field sites. 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.~~

~~The capture of fracture data in digital form also provides the opportunity fFor more evolved analysis of the fracture data the digital traces can be used in using 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.~~

~~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.~~

6~~5~~ Conclusions

Commented [KM65]: Repetition!

Commented [WK66]: Could we add the prospect of meta-analysis in here?

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The aim of this paper is to describe, evaluate and develop a simple but robust, low-cost ~~The aim of this paper is to review and evaluate the~~ method~~ology~~ for ~~digitising~~ capturing 2D fracture network data~~s~~ 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 local metre-scale to the kilometre scale, including, 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. 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.

Acknowledgements

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