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Appraisal of fracture sampling methods and a new workflow to characterise heterogeneous fracture networks at outcrop

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ABSTRACT

Characterising fractures at outcrop for use as analogues to fractured reservoirs can use several methods. Four important fracture data collection methods are linear scanline sampling, areal sampling, window sampling and circular scanline sampling. In regions of homogeneous fracture networks these methods are adequate to characterise fracture patterns for use as outcrop analogues, however where fractures are heterogeneous, it is more difficult to characterise fracture networks and a different approach is needed.

We develop a workflow for fracture data collection in a region of heterogeneous fractures in a fold and thrust belt, which we believe has applicability to a wide variety of fracture networks in different tectonic settings. We use an augmented circular scanline method, along with areal sampling to collect a range of fracture attribute data, including orientation, length, aperture, spatial distribution and intensity. This augmented circular scanline method more than halves the time taken for data collection, provides accurate, unbiased data that is representative of local fracture network attributes and involves data collection of a wider range of fracture attributes than other sampling techniques alone.

1. Introduction

Outcrop studies are used to characterise fracture patterns within potential hydrocarbon reservoir units, with the expectation that these data will positively enhance the development of fractured reservoirs (Stephenson et al., 2007; Bosworth et al., 2012). In homogeneous rock volumes, these methods may be considered sufficient, assuming that fracture attributes are consistent, meaning similar fractures at outcrop are a good representation of subsurface fracture patterns. In heterogeneous rock volumes, fracture attributes can change over very short distances, making them much more difficult to characterise. Using outcrop data to predict the characteristics of subsurface fracture networks in heterogeneous regions is therefore risky, unless an appropriate workflow is used at outcrop to sufficiently characterise fracture attribute variations.

The literature has a number of examples where limited outcrop data are used as analogues for subsurface fracture networks. Wennberg et al. (2007) used an outcrop study of the fractured Khaviz Anticline in SW Iran as an analogue for subsurface reservoirs. Sample sites were located along two transects, spaced over 10 km apart, and oriented parallel to regional compression. In regions of heterogeneous fractures we know fracture patterns can vary significantly along strike. Therefore data collected along these transects may not be a sufficient representation of fracture attributes in outcrop and the subsurface.

Antonellini and Mollema (2000) believed that an understanding of the joint distribution throughout a reservoir is essential for management during production. In their study, fractures from outcrop analogues are analysed along transects perpendicular to major faults to determine changes due to distance from fault cores. Data were collected at outcrop from four transects across three separate faults meaning along strike variability in fracture characteristics was not recorded. It is possible that significant variations in fracture patterns may occur along fault strike, which could significantly affect flow in the subsurface during production. By only sampling single transects at outcrop, variations along fault strike cannot be detected or incorporated into flow simulation models.

To characterise fractured reservoirs using outcrop analogues, several fracture attributes need to be characterised: orientations, degree and distribution of clustering, tracelengths and intensity (Fig. 1). Individually and collectively, these attributes affect the connectivity and permeability of the fracture network in a rock volume (Nelson, 2001; Jolly and Cosgrove, 2003).

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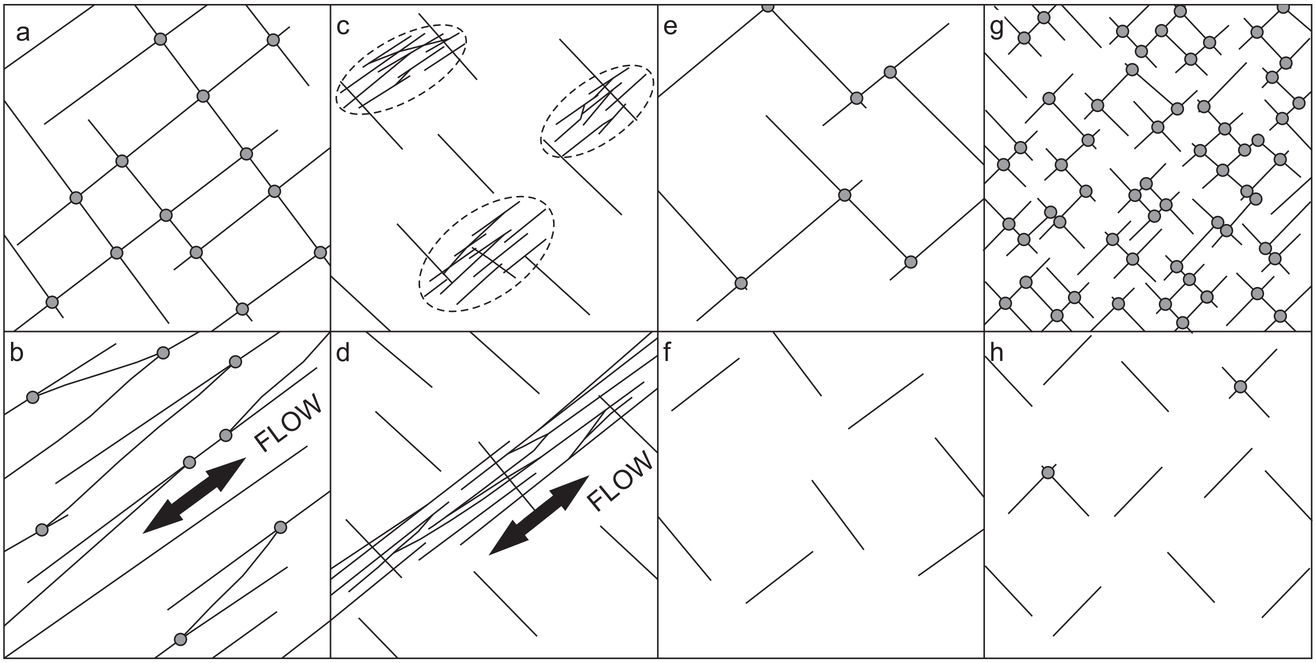


Fig. 1. a) Multiple fracture sets at different orientations increase the number of fracture intersections (grey dots). b) Unimodal fracture orientations with some dispersion to create connectivity result in flow anisotropy. c) Isolated fracture clusters (within dashed lines) are not connected to the rest of the fracture network so do not enhance reservoir quality. d) Fracture corridors create anisotropic flow. e) Long fractures increase the likelihood of fracture intersection, and therefore increase connectivity & reservoir quality. f) Short fractures have a low probability of intersecting and therefore can have poor connectivity. g) High fracture intensity increases the chance of fracture intersection, and therefore increases connectivity & reservoir quality. h) Low fracture intensity decreases the chance of fracture intersection, and therefore decreases connectivity & reservoir quality.

We evaluate current methods for fracture data collection and propose a new workflow, which enables fracture data collection on bedding surfaces of key geometrical fracture attributes important for determining fractured reservoir quality. Our workflow is compared to current methods using a fracture dataset collected at outcrop from bedding surfaces in the folded Torridon Group sandstone, Achnashellach Culmination, NW Scotland.

2. Current methods for fracture sampling

Four main sampling strategies for collecting fracture data are widely used and reported in the literature: the linear scanline method (Priest and Hudson, 1981; Priest, 1993), areal sampling (Wu and Pollard, 1995), rectangular window sampling (Pahl, 1981; Priest, 1993) and the circular scanline method (Mauldon et al., 2001; Rohrbaugh et al., 2002).

2.1. Linear scanline sampling

The linear scanline method tends to be favoured as it is a fast method for recording a wide range of fracture attributes. This method involves laying a tape on an outcrop and measuring attributes (including orientation, length, aperture, intensity, fracture fill and spacing) of each fracture that intersects the tape (Priest and Hudson, 1981; Priest, 1993) (Fig. 2a). Scanlines are oriented so as to best represent the fracture sets present. Usually, the scanline is normal to the strike of the fracture set, and where multiple fracture sets are present, two scanlines are set up parallel and perpendicular to bedding strike to ensure each fracture set intersects at least one scanline (Priest, 1993). Although this method allows a lot of fracture attribute data to be collected quickly, it does create orientation and length bias, and is sensitive to censoring, where large fractures are under-represented in data because their tracelengths are longer than the extent of the outcrop, so they are truncated and only a minimum size is recorded. Data will be most susceptible to orientation bias when multiple fracture sets at different orientations are sampled with a single scanline. Fractures striking at a low angle to the scanline will be under-represented, giving much lower estimates for intensity and overestimates for spacing, compared with fractures that strike normal to the scanline, unless these biases are corrected.

Fig. 2b shows a trace map of three fracture sets, each of equal length, intensity and spacing, but different orientations. Fracture intersections with a linear scanline oriented normal to the N–S fracture set and oblique to the NE–SW and NW–SE record a greater intensity of N–S fractures (8 per metre) than NE–SW or NW–SE (6 per metre) and wider spacing for the NE–SW and NW–SE fracture sets (15 cm spacing) compared with the N–S fracture set (11 cm spacing), when the effect of the orientation bias is uncorrected. Orientation bias can be corrected for by using the Terzaghi method (Terzaghi, 1965), however this adds time and another potential source of error in the data. Ideally, collecting unbiased data in the field is preferred.

Problems with using the linear scanline method are seen in a study about fractures in the Sub-Andean fold-and-thrust-belt, Bolivia (Florez-Niño et al., 2005) where linear scanlines are placed parallel to the strike azimuth of the folds axial surfaces. Data from Florez-Niño et al. (2005) show greater numbers of fractures striking perpendicular to bedding and the regional thrust/fold strike, but this abundance may be an artefact of scanline orientation. A small number of fractures striking parallel and oblique to the scanline are present. So, to properly represent relative abundance between the fracture sets, multiple scanlines at different orientations should be used. Many studies have adopted this method (McQuillan, 1973; Hanks et al., 1997; Wennberg et al., 2007; Ortega et al., 2010; Hooker et al., 2011; Barbier et al., 2012; Ellis et al., 2012; Iñigo et al., 2012) whereby a scanline is set up perpendicular to the strike of each fracture set on the outcrop. For each scanline, fracture attributes are measured for that fracture set only. This method provides much more accurate intensity and spacing measurements

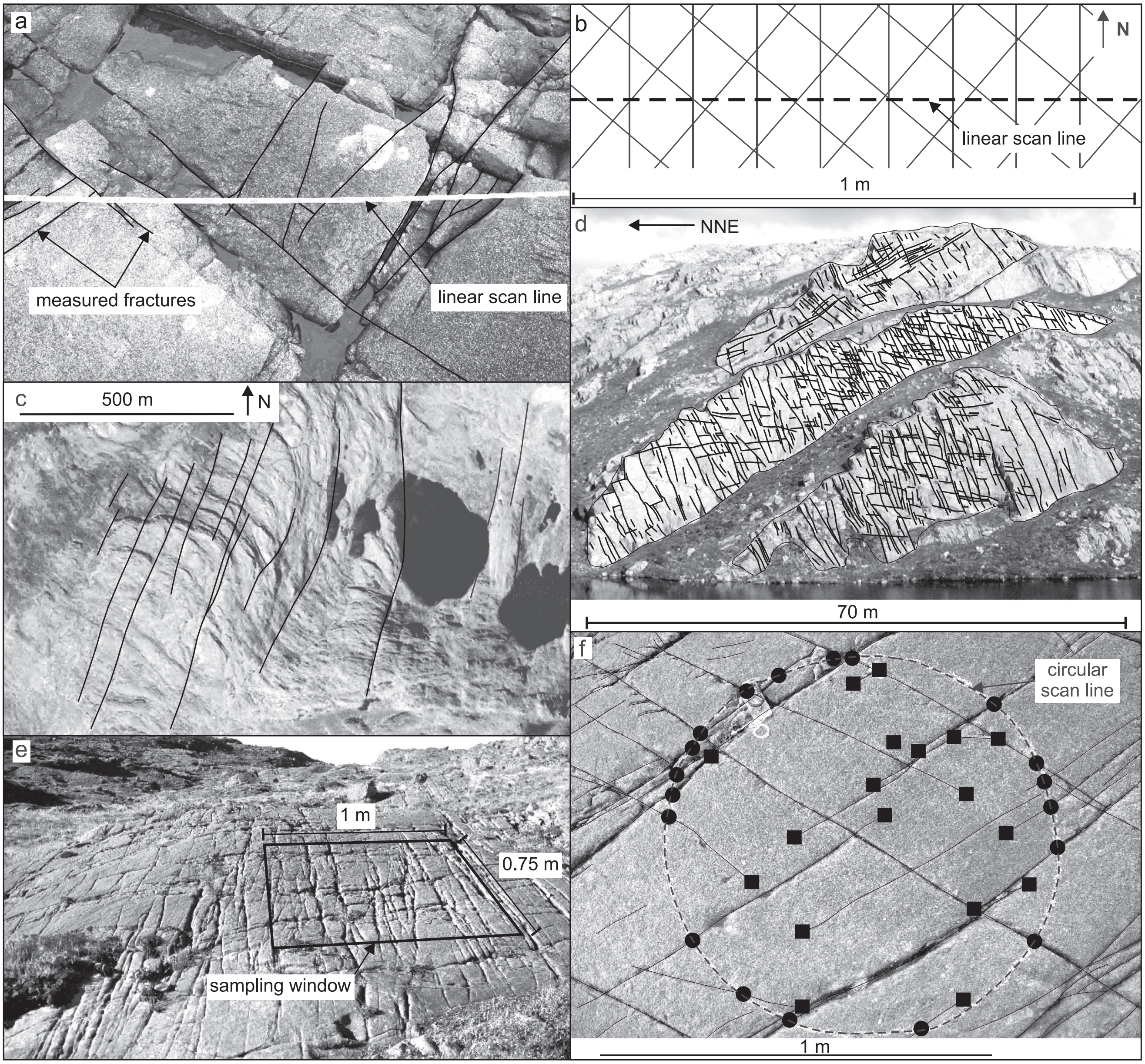


Fig. 2. a) Fractures attributes, including orientation, length, aperture, spacing and fracture fill are measured for each fracture that intersects a linear scan line (tape measure). b) Three evenly spaced fracture sets at different orientations (N–S, NE–SW & NW–SE) recorded on a linear scan line (dashed line). True spacing for each set is 11 cm, and true intensity is 8 per metre; only the true spacing and intensity of fractures perpendicular to the scan line (N–S set) are recorded as the other two sets are oblique to the scan line, giving 15 cm spacing and only 6 fractures per metre. c) Large scale discontinuities mapped using areal sampling from an aerial photograph. d) Fracture traces mapped onto bedding planes from a field photograph. e) Fracture attributes, including orientation, length, aperture, spacing and fracture fill are measured for each fracture within a sampling area (black box) using rectangular window sampling. f) Circular scan line data collection; fracture intersections with the sampling circle (black dots) and fracture terminations within the circle (black squares) are counted to estimate fracture intensity, density and mean trace length (Mauldon et al., 2001).

for all of the fracture sets than a single scanline but data are still taken on 1D lines so variability in fracture attributes in 2D or 3D is not captured. Since this method involves setting up individual lines for each fracture set, it requires recognising and defining individual fracture sets in advance of data collection, meaning data collection may be biased by pre-interpretation of fracture sets. Defining fracture sets before data collection also adds time to the process, especially if a lot of fracture sets are present.

2.2. Areal sampling

Areal sampling involves fracture attribute data collection in 2D, and is especially effective when mapping large-scale fractures or discontinuities. Sampling can be completed remotely through analysis of aerial photographs (Wu and Pollard, 1995) such as Fig. 2c where large-scale discontinuities, inferred to be fracture corridors, are mapped over several hundred metres. Photographs taken in the field are also used for areal mapping at a smaller scale where fracture traces can be mapped onto bedding surfaces such as on Fig. 2d. Areal sampling is a common method used for assessing fracture variability across large-scale structures or on larger outcrops. Photographs/satellite imagery are used to generate 2D fracture trace maps, usually on bedding surfaces or in cross-section view, for extracting fracture trace azimuth, density and intensity data (McQuillan, 1974; Mobasher and Babaie, 2008; Ghosh and Mitra, 2009). Spatial distribution data can also be extracted by calculating the coefficient of variation to ascertain whether fractures are evenly distributed or clustered (Cox and Lewis, 1966; Odling et al., 1999). This method is fast for collecting large amounts of data, however results are highly dependent on source-image data resolution, which causes data truncation, as smaller fractures are under-represented, and quality control between photographs and outcrops is required, which can be time-consuming.

2.3. Rectangular window sampling

Rectangular window sampling utilises a rectangle, which is placed on an outcrop and selected fracture attributes are measured within the area of the rectangle (Fig. 2e) (Priest, 1993). Rectangular window sampling reduces orientation bias, compared with linear scanline sampling, because all fractures within the area are measured, and allows for a simple estimation of mean trace length (Pahl, 1981). The method can be very time consuming if many attributes are to be measured for each fracture within the window area. Data are also affected by censoring due to outcrop size, and quality of exposure. Mean trace length estimation involves analysing fracture end points, but if the outcrop has significant vegetation cover, data may be unreliable (Priest, 1993).

2.4. Circular scanline sampling

A fourth fracture sampling strategy is the circular scanline method, outlined by Mauldon (1998), Mauldon et al. (2001) and Rohrbaugh et al. (2002). Rather than directly measuring fracture attributes, the method involves counting the number of fracture intersections with the edge of a circular line placed on an outcrop, and the number of fracture terminations within the circle (see Fig. 2f). These values are used as inputs into a series of equations, from which estimates of fracture density, intensity and mean trace length within the area of the circle can be calculated. Since this method counts fracture intersections with and terminations within each circle, rather than direct measurements of fracture attributes, it is not affected by length censoring, unlike the linear scanline, areal sampling and rectangular window sampling methods. Using this method also eliminates orientation bias of layer-parallel fractures in 2D (in 3D fractures oblique to bedding will still be under-sampled, which is true for all four sampling strategies) as fractures are not sampled along a single orientation, as in the linear scanline method.

To calculate a representative estimate for fracture density, intensity and mean trace length, Rohrbaugh et al. (2002) suggested a sampling circle should be large enough to contain a minimum of 30 end points. Clearly the size of the circle is dependent on fracture intensity at each sampling site, meaning for outcrops where only a few fracture end points are present within a given area, sampling circles will need to be large, and therefore sampling would be restricted to larger outcrops. The circular scanline method is a quick approach for collecting data, however the method, as outlined by Mauldon et al. (2001) does not provide calculated estimates for other fracture attributes, for example orientation, length, aperture, spacing or fracture fill. This estimator is ideal for density, intensity and mean trace length calculations where fractures are evenly distributed, however it only gives average values and does not give information on how fractures are distributed within the circle (i.e. whether fractures are evenly spaced, randomly distributed, or clustered), unlike the linear scanline or rectangular window/areal sampling methods. The circle does provide an area within which the nature of fracture clustering could be noted by the operator, if this information is required.

3. A new method for characterising heterogeneous fracture networks

We use bedding surface outcrops of the Torridon Group sandstone in the Achnashellach Culmination to test fracture sampling strategies and develop a workflow for characterising heterogeneous fracture networks. The consideration of whether a network is spatially homogeneous or heterogeneous is dependent on the scale of observation. It is possible for a network that is heterogeneous at a smaller scale to be homogeneous at a larger scale because the heterogeneity replicates from point to point at the larger scale. Correspondingly, the opposite is also possible. We use the term heterogeneous networks where fracture attributes vary considerably on a single bedding surface outcrop, or between adjacent sampling sites. The structural context for our study is presented by Butler et al. (2007) and Watkins et al. (2014). The Achnashellach Culmination is located in the southern Moine Thrust Belt (Fig. 3a), which formed during the Caledonian Orogeny (c. 439–410 Ma, Mendum et al., 2009). The fold and thrust belt formed in the footwall of the Kishorn/Kinlochewe Thrusts, which are themselves in the footwall to the Moine Thrust (Butler et al., 2007). Thrusting within the culmination initiated on a lower detachment within the Torridon Group (Butler et al., 2007; Watkins et al., 2014) and propagated in a WNW-directed foreland-propagating sequence, parallel to regional compression. Fracture data are collected from the Torridon Group, which has very low porosity (1–2%) and permeability (0.002–0.004 mD) within the study area, and therefore makes an ideal analogue for a tight sandstone.

3.1. Sampling site selection

None of the four main fracture sampling methods described above is sufficient for characterising fractures as they are all subject to one or more sampling biases or do not describe all fracture attributes. We use an augmented circular scanline method to characterise fractures on bedding surfaces. The first stage in our workflow is to select sampling site localities, prior to fracture data collection. Data presented in this paper have been recorded from sampling sites chosen using the following selection methods. Sampling site localities were initially chosen using aerial photographs to identify areas where bedding surfaces are well exposed. These areas are gridded with a 200 m spacing, and sampling sites are chosen at the corner of each grid square (Fig. 4a and c). If an outcrop is present at the pre-selected grid reference, it was used for data collection. If no outcrop is present, the nearest exposed bedding surface was used to collect data, as long as exposure quality is good, and it falls within a 200 m squared area centred on the pre-selected grid reference (see i, Fig. 4a). If no suitable outcrops are present within this area, no data were collected (see j, Fig. 4a).

Following sample site selection using the grid square method, a number of sites were chosen at closely spaced intervals along transects, to identify heterogeneity at a scale smaller than the 200 m grid square spacing. These closely spaced sites are sampled at intervals between 10 and 100 m along pre-selected transect orientations (Fig. 4b and c), usually parallel to regional strike or dip (providing outcrop is available and steep topography does not prevent sampling). These transects are selected to test how fracture data varies at a resolution higher than that sampled by the grid method. The transect sampling sites also test how representative the grid data are by determining whether fracture variations occur gradually on a large scale or over short distances that cannot be detected using a 200 m grid.

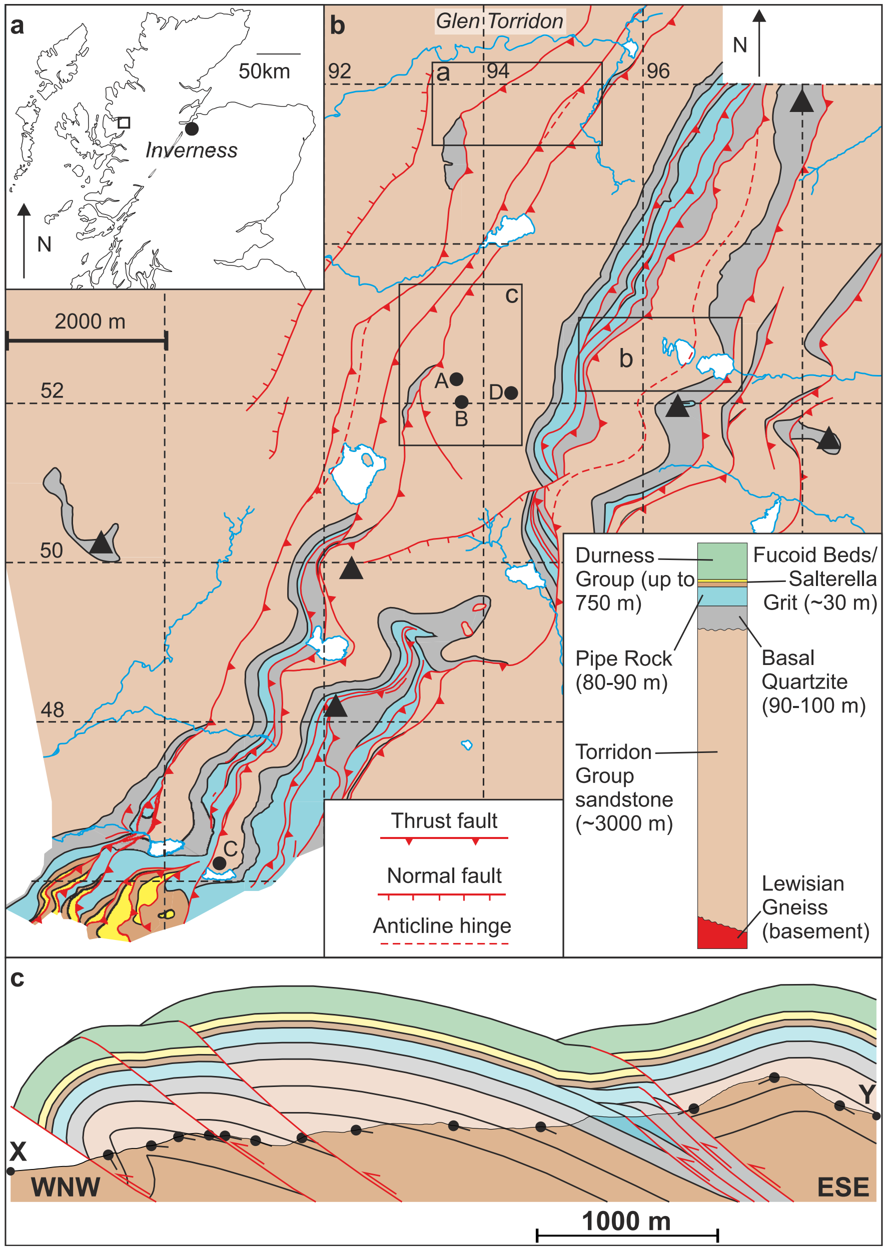


Fig. 3. a) Location of the Achnashellach Culmination field area (black box) in NW Scotland. b) Geological map of the Achnashellach Culmination showing fracture sampling sites A–D (black dots). Locations of aerial photographs on Fig. 4 are shown in boxes a, b & c, black triangles represent mountain tops. c) Cross section through the Achnashellach Culmination (section line X–Y on Fig. 3b) showing fold geometries.

3.2. Data collection at outcrop: an augmented circular scanline method

At each sampling site, selected either by gridding or transects, a circle of known radius is drawn onto the bedding surface using a length of rope with a stick of chalk tied to the end (for example, regularly spaced circles along a transect on Fig. 5). The circular scanline sampling method of Mauldon et al. (2001) is used to count the number of fracture intersections with the edge of the circle (n) and the number of fracture terminations within the circle (m) (Fig. 6a and c). These values are then inputted into a series of equations (Mauldon et al., 2001). In this paper, we use the Mauldon equation to estimate values of fracture intensity:

$$I = n/4r$$

where I = intensity (m/m^2), n = number of fracture intersections with the circle, and r = circle radius (m) (Mauldon et al., 2001). The circle radius was chosen, partly based on the minimum m count of Rohrbaugh et al. (2002), who recommended that a minimum m count of 30 is sufficient to ensure reliable fracture estimates. Smaller numbers of m points can lead to significant errors, especially if an estimate for mean trace length is required (see Rohrbaugh et al., 2002).

Our workflow involves combining the circular scanline method of Mauldon et al. (2001) with methods used in the linear scanline workflow by measuring fracture orientation (strike, dip, and dip direction), length, aperture, fracture fill and spacing (perpendicular distance to nearest fracture of the same orientation) of each fracture that intersects the edge of the sampling circle (Fig. 6b), in addition to n and m point counting. Our workflow has the advantage of allowing individual fracture attribute data to be collected

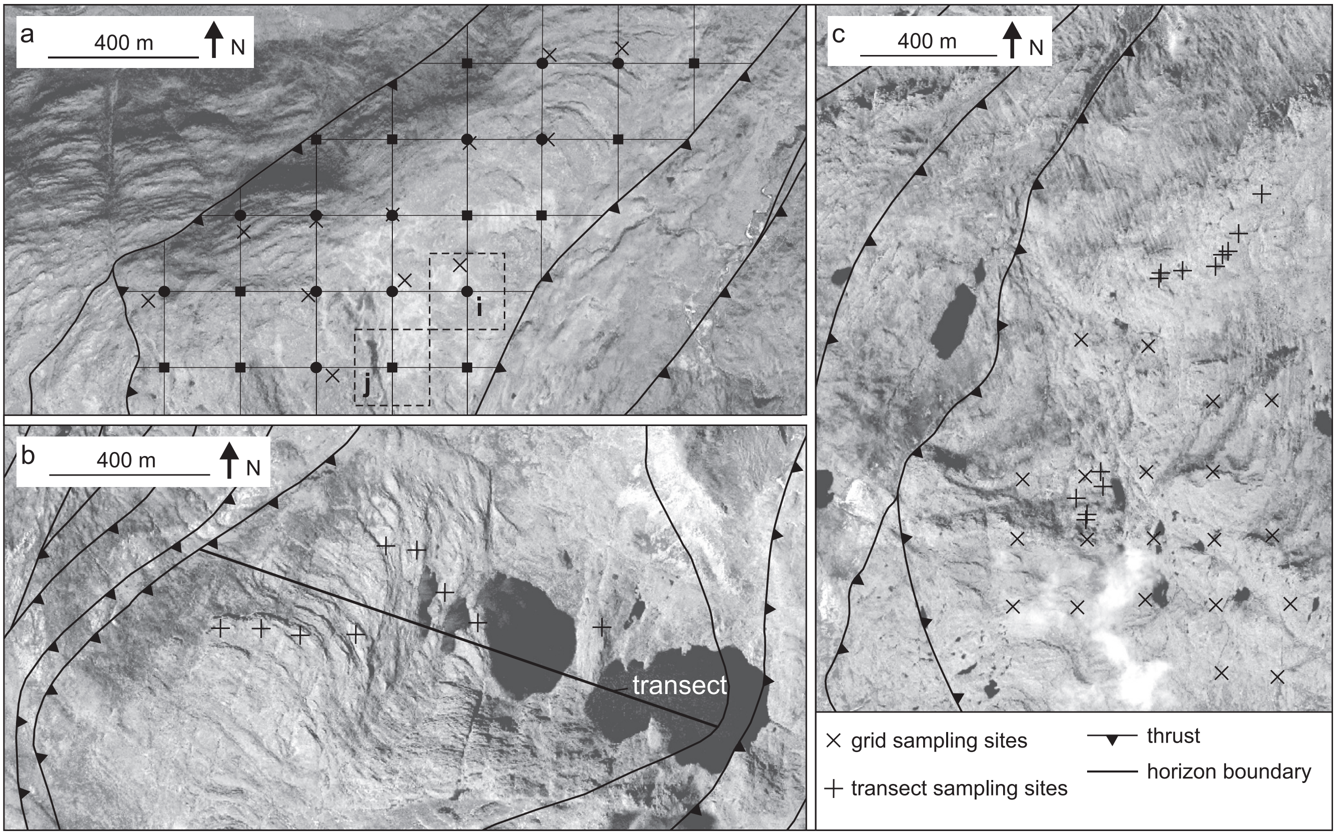


Fig. 4. a) Areas of good bedding plane exposure are identified on aerial photographs and divided using a 200 m spaced grid. Sampling site localities are chosen at the corner of each grid. Sampling is undertaken at the nearest outcrop to this pre-selected grid reference (cross) within a 200 m squared area of this site (i). If no outcrop is located within this 200 m square then no sampling is undertaken (j). Black dots show pre-selected grid references for which data was collected and black squares show where no outcrop was available or the outcrop was inaccessible. b) A transect parallel to regional transport direction is chosen. Sampling is undertaken along this transect; for transect sampling sites are 10–100 m apart. c) A combination of grid and transect sampling is used throughout the study area.

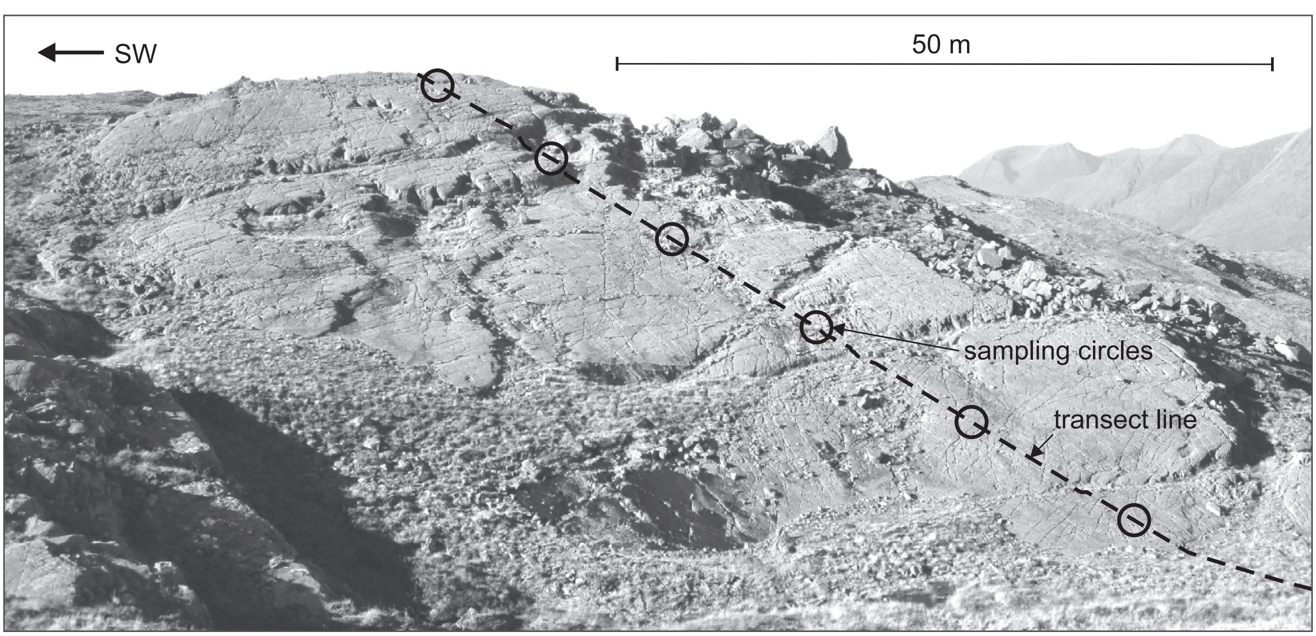


Fig. 5. Sampling circles are placed at regular intervals along a transect line to determine small-scale variations in fracture patterns; fracture data is collected from each of the sampling circles.

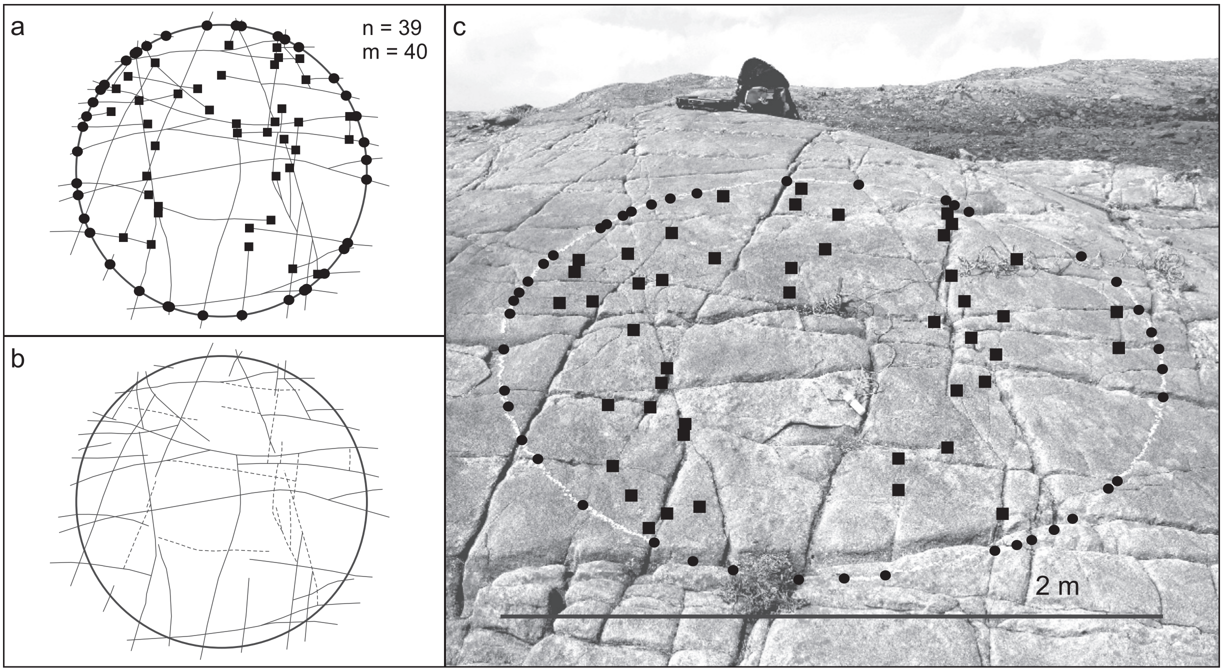


Fig. 6. a) The Mauldon et al. (2001) data collection method: *n* (circles) are fracture intersections with the circle and *m* (squares) are fracture terminations within the circle. b) Attribute data (orientation, length, aperture, spacing to nearest fracture of the same set) is collected for fractures which intersect the sampling circle (solid lines). c) A photograph of a sampling site on a Torridon Group bedding plane showing *n* & *m* points.

without any orientation bias of layer-perpendicular fractures, as is incurred by using only the linear scanline method.

As well as using circles large enough to contain 30 *m* points, as suggested by Rohrbaugh et al. (2002), the circles need to be large enough so that enough fracture orientations are measured to define fracture set clusters. In regions of heterogeneous networks, orientations of a given fracture set can show significant dispersion. Therefore, a greater number of fractures measured allows for better determination of the average orientation of each fracture set. We found that defining individual fracture sets/data clusters is difficult if fewer than 20 fractures are measured per sampling site. Data clustering becomes more apparent with 20–30 fracture measurements and is generally well defined with over 30 measurements. Therefore, a minimum *n* value of 30 was required, where possible. It

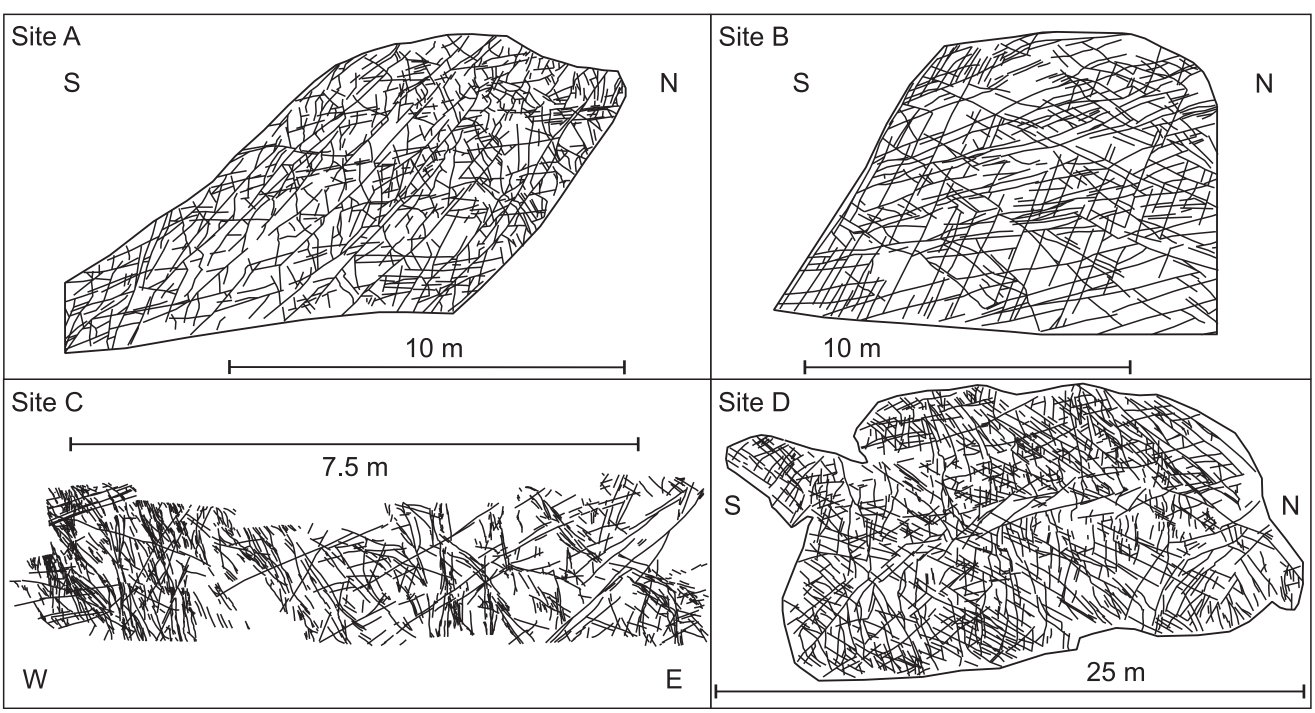
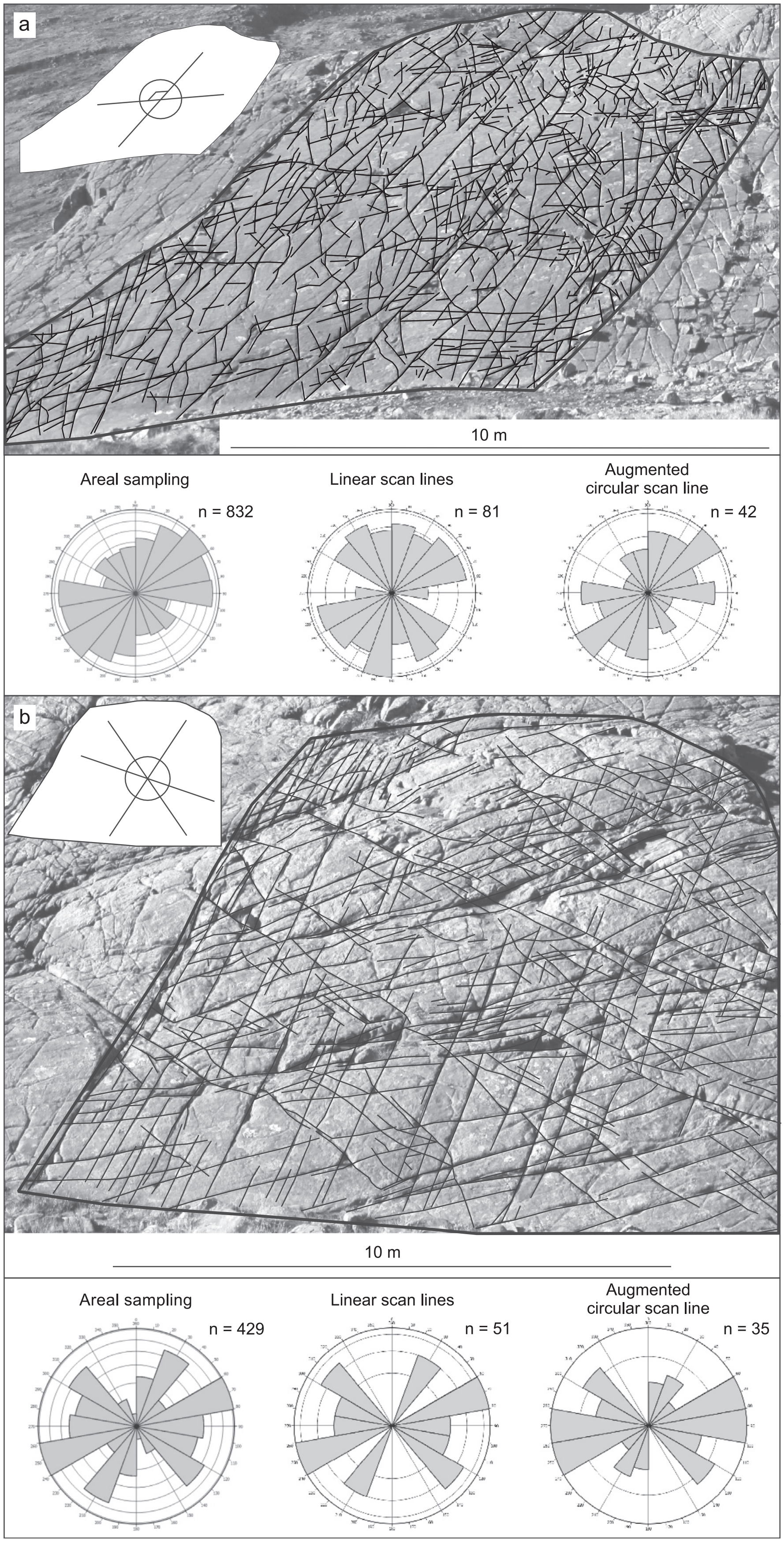


Fig. 7. Fracture trace maps from sampling sites A–D showing heterogeneous fracture networks. Fracture orientation dispersion is common (sites A & C), as well as variations in fracture intensity and length over short distances (sites C & D).


a
10 m
Areal sampling
n = 832
Linear scan lines
n = 81
Augmented
circular scan line
n = 42
b
10 m
Areal sampling
n = 429
Linear scan lines
n = 51
Augmented
circular scan line
n = 35

is also noted that, where fracture intensity is high, fracture set orientation dispersion is much smaller, and therefore fewer fracture orientation measurements are required to define data clusters.

3.3. Overview of field fracture data

We present data from four sampling sites (see Fig. 3b for locations), which were chosen using the sampling site selection workflow described in section 3.1. These data are used to illustrate advantages and disadvantages of the four sampling strategies, and to compare with our augmented circular scanline method. The bedding surface at site A (Fig. 7a) contains multiple fracture sets, which exhibit weak modal orientations due to orientation dispersion. Fracture intensity varies spatially on the bedding surface, as do fracture lengths. Site B (Fig. 7b) exhibits three main fracture sets which show little orientation dispersion on the bedding surface. Fractures at Site C (Fig. 7c) show significant orientation and tracelength dispersion. Fracture intensity is much higher at the western end of the bedding surface than at the eastern. Site D (Fig. 7d) exhibits four fracture sets, each of which has variable intensity on the bedding surface. Two of the fracture sets are clustered and are not present across the whole outcrop. Fracture orientation dispersion, along with variable tracelengths and intensities on individual bedding surfaces make these four sites ideal for testing fracture sampling strategies in regions where fracture networks are heterogeneous. These small scale heterogeneities on individual bedding surfaces also highlight the necessity to use high density sampling sites, such as those closely spaced sites along transects; small scale changes in fracture networks would not be detected using the 200 m grid square method. The differences in fracture trace patterns between the four sampling sites (A–D) also highlight the heterogeneity of fracture networks across the larger study area.

4. Comparison of sampling strategies

We now use fracture data and photographs of outcrops in the field area to test the effectiveness of each data collection method, and to compare sampling strategies to determine which method is most effective in recording heterogeneous fracture networks.

4.1. Orientation

Our workflow for fracture data collection has several advantages with respect to the four techniques. Firstly this method eliminates orientation bias of bedding-perpendicular fractures. While it is recommended by Priest (1993) that two linear scanlines parallel and perpendicular to bedding strike dip should reduce this orientation bias, we tested this method against our proposed workflow for an outcrop at site A (see Fig. 3b for site location), containing at least three fracture sets (Fig. 8a). For this test we use areal sampling results to represent the distribution of fracture orientations for the whole outcrop, because this provides the most complete sample, and also the largest dataset, which is an order of magnitude higher than linear scanline or augmented circular scanline sampling data. Fracture orientation data for areal sampling at site A is shown as a rose plot (Fig. 8a); the dataset has an NE–SW modal orientation. The augmented circular scanline data qualitatively matches the areal sampling data better than the linear scanline data because it clearly shows the same modal orientation as areal sampling (NW–SE), whereas the linear scanline data has only a weak N–S modal orientation. Areal and augmented circular scanline sampling both show low data frequency for NW–SE orientations, whereas linear scanline sampling does not.

To quantitatively compare fracture orientation results from linear and augmented circular scanlines to areal sampling, data is normalised by calculating the number of data points in each rose plot 'petal', where each petal represents 20°. Coefficients of correlation (R^2) are then calculated to determine how well normalised datasets for linear and augmented circular scanline sampling correlate to those data for areal sampling. We find linear scanline data has a poor correlation to areal sampling results ($R^2 = 0.0661$), which is probably because scanlines are not oriented normal to fracture traces, meaning data are subject to orientation bias and some fractures, oriented oblique to scanlines, may be sampled twice. Augmented circular scanline data has a better correlation to areal sampling results ($R^2 = 0.1902$), although the correlation coefficient is still quite low. This outcome is probably because only a small area of the outcrop was sampled, meaning the augmented circular scanline data do not reflect the fracture orientation dispersion seen across the whole outcrop. We found that orientation data from two linear scanlines parallel and perpendicular to bedding strike resulted in unrealistic fracture set orientation distributions, when compared with areal sampling results from the entire outcrop (Fig. 8a). In contrast to this, orientation data measured using the augmented circular scanline method represents the relative fracture set orientation distributions much better as it compares better to areal sampling results from the entire outcrop (Fig. 8a).

To reduce orientation bias for linear scanlines many authors (McQuillan, 1973; Hanks et al., 1997; Wennberg et al., 2007; Ortega et al., 2010; Hooker et al., 2011; Barbier et al., 2012; Ellis et al., 2012) use a technique where a separate scanline is set up perpendicular to each fracture set present. We tested this method against our proposed workflow (Fig. 8b). Considering the fracture network at site B (see Fig. 3b for site location), we again compared the results of the two scanline methods to the data from the areal sampling method, which again was almost an order of magnitude greater in data amount (Fig. 8b). The linear scanline data qualitatively matched the three orientation modes of the areal mapping data better than the augmented circular scanline method. To quantitatively compare results, data are normalised by calculating the number of datapoints in each 20° petal segment of the rose plots. Statistically, the fit of the linear scanline methods ($R^2 = 0.8716$) was slightly better than that of the augmented scanline method ($R^2 = 0.7523$), and therefore relatively speaking, the linear scanline method more accurately represents fracture orientation distributions of the whole outcrop. However, the linear scanline method is more time-consuming because it requires identification and execution of multiple scanlines, which may also be subject to error or uncertainty if the fracture sets are not easily identified when a fracture population has weak orientation modes. By using the augmented circular scanline, we eliminated the need for determining the orientations of multiple scanlines, reducing the time for data collection, as it is not necessary to pre-define individual fracture sets prior to data collection.

Fig. 8. a) Fracture trace map at site A showing orientation data from areal sampling (whole outcrop), two perpendicular linear scan lines (6.8 m length) and an augmented circular scan line (1.1 m radius) (locations on schematic) are plotted. Fracture intensity calculated using circular scanline estimator: 9.55 m/m^2, areal fracture intensity within circle: 10.39 m/m^2, areal intensity of whole outcrop: 7.82 m/m^2. b) Fracture trace map at site B showing orientation data from areal sampling (whole outcrop), three linear scan lines (9.05 m length, each oriented perpendicular to a fracture set), and an augmented circular scan line (1.45 m radius) (locations on schematic) are plotted. Fracture intensity along linear scanlines: 6.63 per m, fracture intensity calculated using circular scanline estimator: 6.03 m/m^2, areal fracture intensity within circle: 7.04 m/m^2, areal intensity of whole outcrop: 5.75 m/m^2. Site locations are shown on Fig. 3b. Rose diagrams apply area scaling.

Although augmented circular scanline data does not correlate as well as linear scanline data to areal sampling results, the R^2 value is still high (0.7523), suggesting the results are accurate when compared to whole outcrop data (Fig. 8a). Since areal sampling takes into account all fractures on the outcrop, it is the most representative of fracture orientation distributions. However, this method is slow to implement, especially when fracture trace maps are created, and orientation data are recorded manually. For this reason we find the augmented circular scanline method more efficient in sampling representative fracture orientations at outcrop.

Since rectangular window sampling involves recording the orientation of all fractures within a given area, orientation data are not biased. However our workflow does have two main advantages over rectangular window sampling. Firstly, window sampling is time consuming. Fig. 9 shows a fracture trace map on a bedding surface at site B (see Fig. 3b for site location), where the outcrop is only 1.5×1 m in area but contains over 375 individual fractures. By using our method of recording only fractures that intersect a circular scanline, we reduce the time taken to estimate fracture orientation distributions. Data collection using the rectangular window sampling method took 2–3 times longer than our augmented circular scanline method. Secondly, for rectangular window sampling, fracture traces are often not straight; Fig. 9 shows changes in azimuth for non-straight fracture traces (dashed lines) of up to 90°. These changes in azimuth cannot be recorded using the rectangular window sampling technique or our proposed workflow, however our method defines clearly where on the fracture trace the orientation should be measured (i.e. where the fracture intersects the edge of the sampling circle) and the rectangular window sampling technique does not. Statistically, these variations in orientation should be accounted for in a circular scanline, mitigating sampling bias.

4.2. Spatial distribution

One advantage of using linear scanlines over circles to characterise fractures in regions of heterogeneous networks is that linear scanlines are more likely to capture fracture variations as they cover longer tracts of outcrop and the position where each fracture intersects the scanline is recorded (Fig. 10). If a circle (representing both the circular and augmented circular scanline methods) was placed at the western end of this outcrop at site C (see Fig. 3b for site location) it would give a much higher fracture intensity value than if it were placed at the eastern end. Although the use of two circles would show the existence of fracture heterogeneity, attributes of the change in fracture intensity between the two circles would not be characterised. A linear scanline of the same length as the circumference of each circle (to ensure roughly the same number of fracture intersections) covers a larger extent of outcrop, although only in one dimension, and, since the exact position of each fracture is recorded along the line, this method is able to capture the change in fracture intensity between the two circles. Therefore, the linear scanline provides more information about the spatial variation and clustering characteristics of each fracture set. Had we replaced the two circular scanlines with rectangular windows the result would be the same. The western rectangle would record higher fracture intensity than the eastern, but nothing would be known of how fracture attributes change in between the rectangles. To record the variability in fracture characteristics using either the circular scanline or augmented circular scanline method, it would be necessary to use circles at different positions on the bedding surface between the first two circles.

We tested this method of using multiple augmented circular scanline surveys to record fracture orientation variations on a large bedding surface at site D (Fig. 11, see Fig. 3b for site location). Rose plots for five equally sized circular scanlines on this bedding surface indicate fracture intensity is greatest along scanline 1 ($I = 6.5$ m/m^2), intensity then decreases into the centre of the outcrop ($I = 4.875$ m/m^2 for scanlines 2 & 4) and increases again in scanlines 3 ($I = 5.375$ m/m^2) and 5 ($I = 5.875$ m/m^2). Rose plots show fracture orientation also varies across the bedding surface. Scanlines 4 and 5 show the presence of an ENE-WSW striking fracture set (green fractures), which is rare in the bottom half of the outcrop (scanlines 1 & 2). Relative intensities of fracture sets changes across the bedding surface. Generally, the black fracture set striking NW–SE has the highest intensity throughout the sampled areas ($I = 1.25$–2.625 m/m^2), however in the areas of scanlines 3 and 4 the blue fracture set has elevated intensities ($I = 2.125$–2.375 m/m^2), making this the dominant set. The variation in orientation modes across the sample site begins with scanline 5 where three distinct fracture orientations with very little data scatter are

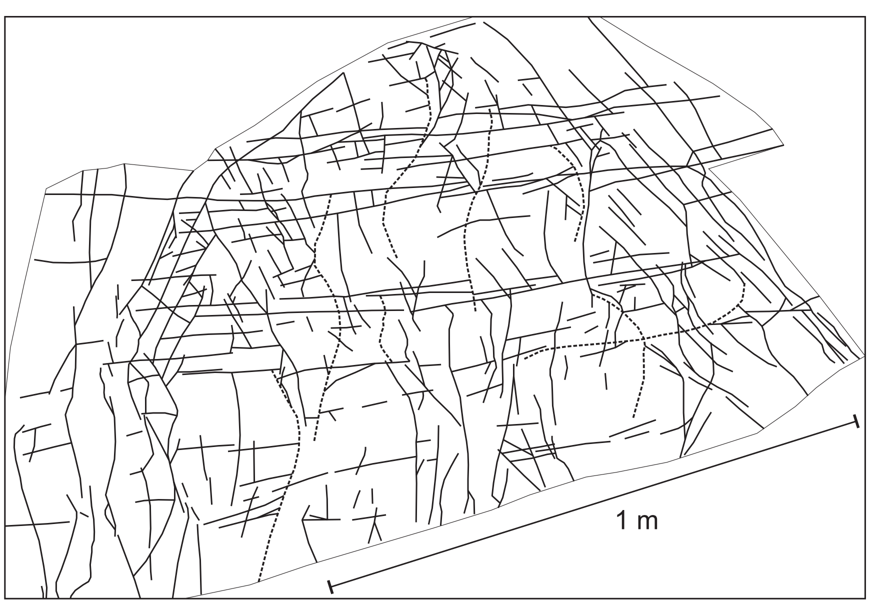


Fig. 9. Line diagram at site B (see Fig. 3b for site location) of a fractured bedding plane, curved fracture traces (dashed lines) make orientation measurements problematic.

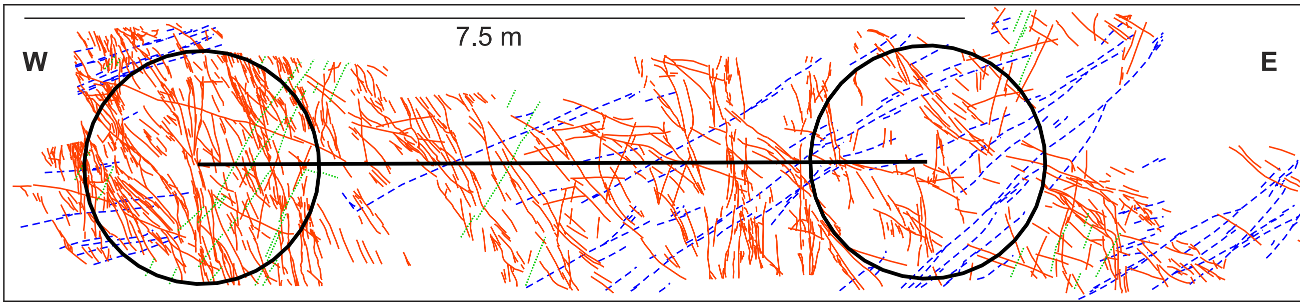
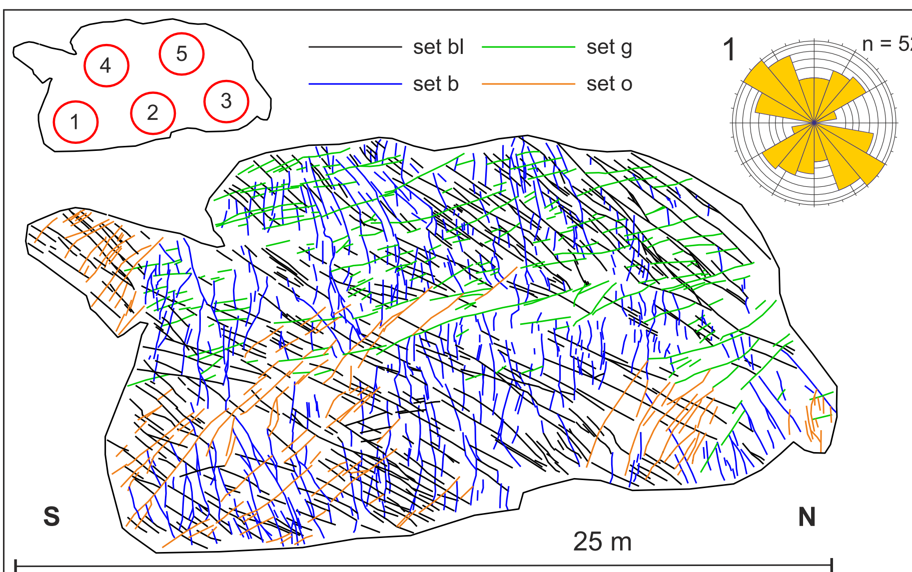
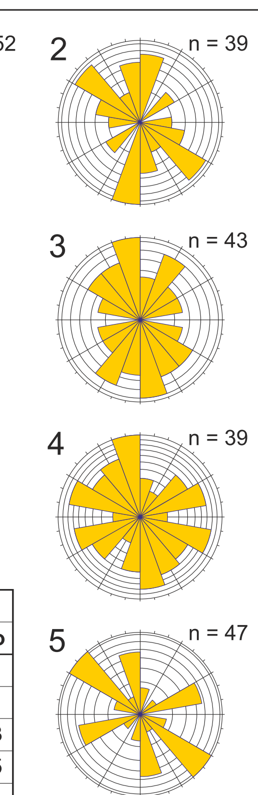


Fig. 10. Fracture trace map at site C (see Fig. 3b for site location) showing three fracture sets (solid, dotted & dashed lines). A circular scan line does not record variations in fracture distribution over large areas. A linear scan line, of equal length to the circumference of each circle, is better for capturing changes in fracture intensity in regions of heterogeneous strain because the position of each fracture is recorded along the line, whereas only a single value of intensity is given for each circle. Intensity along linear scanline: 12.87 per m uncorrected, 15.70 per m after Terzaghi correction (Terzaghi, 1965). Circular scanline data: circle radii: 0.92 m, western circle: $n = 105$, $m = 700$, intensity = 28.53 m/m^2. Eastern circle: $n = 41$, $m = 313$, intensity = 11.14 m/m^2. Areal fracture intensity within western circle: 28.51 m/m^2, eastern circle: 13.73 m/m^2, areal intensity of whole outcrop: 16.66 m/m^2.

present, whereas the other scanlines show a greater variation in orientation distributions. This difference indicates fractures have consistent orientations in the top northern corner of the outcrop, whereas fracture orientations can vary significantly throughout the rest of the bedding surface. By using the augmented circular scanline method, fracture sets were quickly characterised and variations in fracture orientations across the bedding surfaces could be interpreted. The process would have taken much longer if linear scan lines had been used as many more surveys would have been needed, given one scanline for each fracture set at each sampling site. Rectangular windows would also be very time consuming as all fractures within the window would be measured, rather than only fractures intersecting the circle.

These data collected using the augmented circular scanline method identify fracture heterogeneity within an exposure, but may still not offer as much detail as areal sampling where a fracture trace map is generated from an outcrop photograph and spatial distribution can be interpreted by clustering analysis, at any scale required. The coefficient of variation (Cv) is calculated for clustering analysis by dividing standard deviation of fracture spacing by mean fracture spacing of each set (Odling et al., 1999). A Cv less than 1 suggests regular spaced fractures, Cv = 1 suggests random spacing





	Augmented circular scanline										Areal sampling			
circle	n	m	n bl	n b	n g	n o	Cv bl	Cv b	Cv g	Cv o	Cv bl	Cv b	Cv g	Cv o
1	52	116	21	19	0	12	0.72	0.79	-	0.71	0.66	0.63	-	0.41
2	39	100	18	19	0	3	0.83	0.40	-	0.10	0.60	0.72	-	0.51
3	43	106	10	19	7	8	0.72	0.66	0.58	0.54	0.63	1.71	0.55	0.63
4	39	141	10	17	8	3	0.52	0.68	0.44	0	0.84	0.74	0.67	0.55
5	47	194	21	14	11	1	0.93	0.88	0.82	-	0.60	0.77	0.74	-

Fig. 11. Testing how effective the augmented circular scan line method is at recording small scale fracture pattern changes on a bedding plane at site D (see Fig. 3 for site location). Heterogeneity is identified by multiple circular scan lines (radii: 2 m, locations on schematic) but more detail can be gained by using an areal sampling approach. Circular scanline intensities: circle 1: 6.5 m/m^2; circle 2: 4.875 m/m^2; circle 3: 5.375 m/m^2; circle 4: 4.875 m/m^2; circle 5: 5.875 m/m^2. Rose diagrams apply area scaling. Areal sampling intensities: circle 1: 5.49 m/m^2; circle 2: 4.77 m/m^2; circle 3: 4.49 m/m^2; circle 4: 4.99 m/m^2; circle 5: 6.48 m/m^2, whole outcrop: 5.24 m/m^2. n counts for fracture intensity calculations and coefficients of variation (Cv) for cluster analysis are shown in the table.

and a Cv value greater than 1 indicates clustered fractures (Odling et al., 1999). We compare clustering analysis results for areal sampling and augmented circular scanline sampling for the five circles on Fig. 11, where fracture distributions vary at a scale smaller than the sampling circle size. The results for areal sampling are considered to represent the actual fracture distribution at the site because the areal map (Fig. 11) is the largest and most complete sample. Cv values for the augmented circular scanline method are calculated for each individual fracture set by measuring the distance (perpendicular to the fracture trace) to the nearest fracture of the same set, using only the fractures that intersect the circle. Cv values for areal sampling are calculated by measuring the distance (perpendicular to the fracture trace) to the nearest fracture of the same set, using all fractures inside the circle. Correlation between augmented circular scanline and areal sampling data is poor ($R^2 = 0.0194$), suggesting that the augmented circular scanlines do not offer high enough resolution data to represent fracture clustering trends. To improve augmented circular scanline resolution, the user could reduce the circle radius and distance between circles, however the minimum circle size is restricted as this method requires at least 30 n and m counts to ensure reliable fracture estimations. Although the augmented circular scanline data do not offer as high resolution data as the areal sampling results, this method is up to 4 times quicker than areal sampling as fewer fractures are measured.

Figs. 10 and 11 have shown that in regions with heterogeneous networks, we see the spatial distribution of fracture sets can change significantly within very small areas. Fig. 12 shows a circular scanline on an outcrop at site A (see Fig. 3b for site location). Fracture traces at the top of the image are closely spaced in a tight cluster, whereas at the bottom fractures are much further apart and appear to have more random orientation and spatial distributions. This change in distribution occurs over only a few cm, highlighting the difficulty that may be encountered in characterising fracture patterns using any one of the linear, circular, rectangular window, areal or augmented circular scanline sampling surveys.

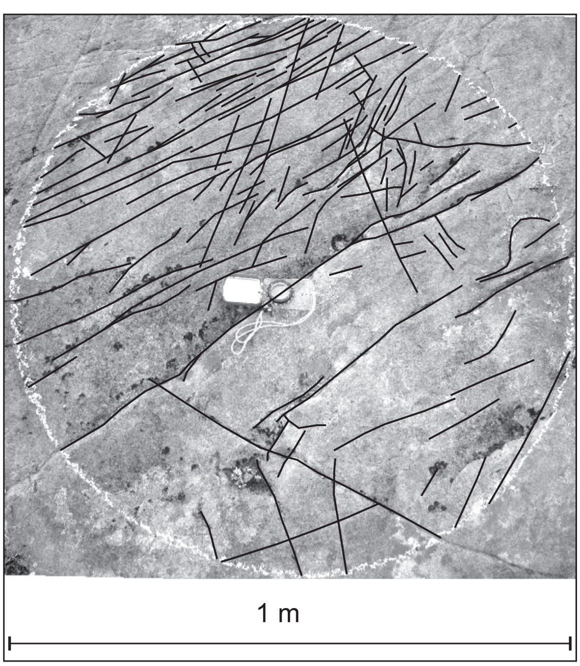


Fig. 12. Site A (see Fig. 3b for site location): the spatial distribution of fractures can change significantly over short distances in regions of heterogeneous strain; fractures at the top of the sampling circle are dense and clustered whereas at the bottom intensity is much lower and distribution is random.

4.3. Length

When measuring fracture lengths, censoring can be encountered for linear scanlines, rectangular window sampling, areal sampling and our augmented circular scanline methods. If the scanline or sampling area intersects or contains part of a fracture that extends beyond the outcrop the true length of that fracture cannot be recorded. Fig. 13 shows a bedding surface outcrop at site A (see Fig. 3b for site location) with the four different sampling strategies (bold line, circle & rectangle, grey line for areal sampling outcrop outline). Fractures that continue beyond the outcrop are shown as dashed lines. All four sampling lines/areas contain fractures, for which the true length is unknown. The circular scanline strategy by Mauldon et al. (2001) does offer a method for estimating average trace length within the circle area without having to measure individual fractures. This estimator can be applied to outcrops that contain a large number of fractures that are longer than the size of the outcrop itself. Rohrbaugh et al. (2002) considered how to determine if one has a sufficient count for determining mean tracelength in context of circles being small with respect to the actual tracelengths. Using synthetic fracture patterns, they concluded that almost all samples yield reliable results for average tracelength if 30 or more m points (fracture terminations) are counted. The method does not give information about individual fracture lengths, but rather counts n (intersections with the circle) and m (fracture terminations) points to yield a mean fracture tracelength using the following equation (Mauldon et al., 2001):

$$\mu = (\pi r/2)(n/m)$$

where μ = mean trace length (m), r = circle radius (m), n = number of intersections with the circle, m = number of terminations within the circle. The method does not distinguish between different fracture sets that may have different length distributions unless individual fracture sets are defined before data collection. If individual fracture sets are defined an average fracture length for each set can be calculated by only counting n and m points for the fracture set in question. However the method does not distinguish between a fracture set with medium and consistent fracture lengths versus one with a combination of very long and very short fractures because both sets may have the same average fracture length (Fig. 14). For these reasons, we find the circular scanline method alone is not adequate in characterising fracture length variations. Our augmented circular scanline workflow incorporates collection of individual fracture length data, from which it is possible to divide into sets by orientation and determine whether length distribution varies between sets and within individual sets.

4.4. Aperture

Fracture aperture is difficult to accurately measure at outcrop as bedding surface exposures are likely to have been subjected to erosion, meaning fractures may appear wider at the surface than at depth. This error will be encountered for all sampling strategies. Data collection on recently exhumed outcrops such as strip-mined bedding surfaces or glaciated pavements that have seen recent ice retreat may allow for reliable fracture aperture measurements. Linear scanline, rectangular window sampling and our augmented circular scanline methods allow for direct measurements of apertures at outcrop. Since the circular scanline method of Mauldon et al. (2001) does not involve collecting data that characterises apertures, it cannot be defining and analysing the apertures of a fracture population. The areal sampling method may also be insufficient for estimating fracture apertures, depending on what scale of fractures are of interest. Fracture aperture results would be

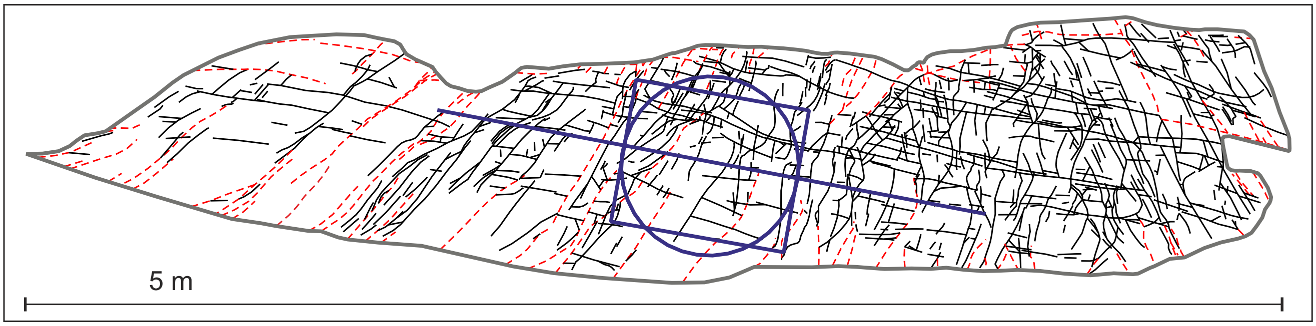


Fig. 13. Line diagram of a fractured bedding plane at site A (see Fig. 3b for site location). Linear scan line (bold line), areal (grey line), window (bold box) & circular scan line (bold circle) sampling are all affected by length censoring; each sampling area contains fractures which are only partially preserved on the outcrop (dashed lines).

significantly affected by photo quality. Fractures with narrow apertures may not be seen on the photographs, therefore areal sampling is only useful if fracture apertures are within the photograph resolution. LIDAR or low level georeferenced aerial photography may be used to generate fracture trace maps. These methods have been used by many authors, such as Odling et al. (1999), and Casini et al. (2011), and show high resolution trace maps can be generated, from which aperture data could be extracted. Light levels at the time of photographing are also likely to affect apparent apertures for areal sampling; fracture sets oriented normal to the direction to the sun will have much darker shadows than those at 90°, and therefore may appear much wider than they actually are.

4.5. Fracture intensity

Fracture intensity estimation using the augmented circular scanline method adopts Mauldon's circular scanline technique (Mauldon et al., 2001). Fracture intensity data collected using the circular scanline estimator are compared to other sampling techniques at sites A–D (see Fig. 3b for site locations). Linear scanline sampling can incur orientation bias if fractures are oriented oblique to scanlines, which is corrected for by using the Terzaghi correction technique (Terzaghi, 1965) for individual fracture sets. However, where fracture orientations are dispersed it may be difficult to define individual fracture sets, for example at site A (Fig. 8a), meaning the correction cannot be applied. At site C (Fig. 10), three fracture sets can be defined, meaning Terzaghi correction can be applied. Before correction, fracture intensity along the linear scanline was calculated as 12.87 per m, and after correction the value increased to 15.70 per m. This corrected value may still be subject to error since fracture orientation dispersion is seen within individual fracture sets. By using multiple linear scanlines normal to individual fracture sets, orientation bias is significantly reduced, meaning orientation correction is not required. This technique is used at site B (Fig. 8b), where three fracture sets with little orientation dispersion are seen. Fracture intensity results yielded by the three linear scanlines give an overall fracture intensity of 6.63 per m. Circular scanline sampling is also used at sites A–C to estimate fracture intensity (site A: $I = 9.55$ m/m^2; site B: $I = 6.03$ m/m^2; site C west: $I = 28.53$ m/m^2; site C east: $I = 11.14$ m/m^2). Data collected using this technique is not subject to orientation bias within the 2D data collection surface, as the scanline does not have a single orientation. This geometry means no orientation correction is required, and only a single scanline is needed to calculate fracture intensity. Thus, the circular scanline method takes less than half the time for intensity calculation when compared with linear scanline sampling.

We compare how efficient the circular scanline and areal sampling techniques are for estimating fracture intensity at site D (Fig. 11). Neither the circular scanline nor areal sampling data required any correction as neither was subject to orientation bias, however the areal sampling method is significantly more time consuming as it requires creation of fracture trace maps, and measurement of trace lengths within certain areas of interest. Although fracture intensity was not calculated using rectangular window sampling, this method would also be very time consuming as the total fracture trace length within the rectangle would be measured manually at outcrop.

By comparing the sampling techniques, we have determined that Mauldon's circular scanline method (Mauldon et al., 2001) is the most efficient for estimating fracture intensity. However, since this method provides an estimate rather than a value based on

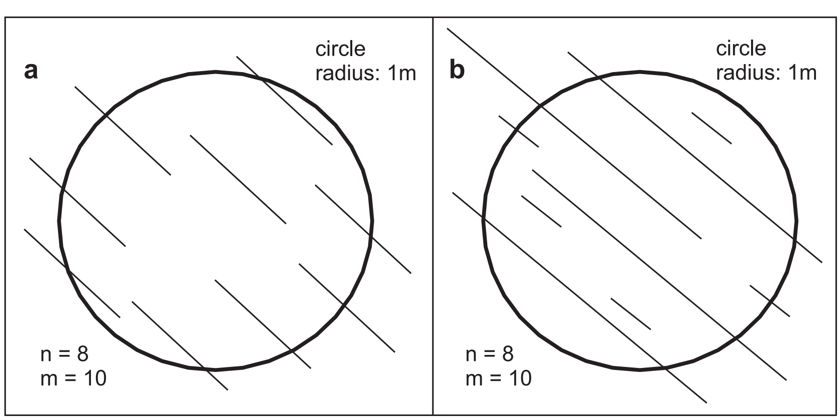


Fig. 14. a) Circular scanline sampling medium length fractures (0.9 m). b) Circular scanline sampling long (2.2 m) and short (0.3 m) fractures. Mean trace length for both circles is 1.26 m.

actual fracture intensity measurements, the accuracy of the estimator is unknown. We now focus on the circular scanline method and the augmented circular scanline method for fracture intensity estimation and assess how accurate results are. Fracture intensity, estimated using the Mauldon circular scanline method (Mauldon et al., 2001), is compared to fracture intensity measured from field photographs (areal sampling), for each circle at sites A-D. Since areal sampling involves measuring the actual length of fractures within a known area, this method is considered to give an accurate value for fracture intensity within the area sampled. Fig. 15a shows a good correlation between fracture intensity estimated using the circular scanline method, and fracture intensity measured within each circle, using areal sampling ($R^2 = 0.9837$). The line of best fit for these data is also very close to the 1:1 line. This correlation shows that the circular scanline method of Mauldon et al. (2001) accurately estimates fracture intensity values.

Fracture intensity calculated for the whole outcrop, using areal sampling, is compared to fracture intensity estimated at circular sampling sites. If more than one circle is present at each site, the average values are plotted. Fig. 15b shows good correlation between the fracture intensity of the whole outcrop to circle intensity calculated using the circular scanline estimator (dark grey, $R^2 = 0.9900$) and measured data from areal sampling (light grey, $R^2 = 0.9833$). However circular scanline and areal sampling of individual circles both give overestimates of fracture intensity, when compared with areal sampling data for the whole outcrop. These overestimates are due to intensity heterogeneity within each sampling site, suggesting circles have been placed at positions where intensity is elevated compared to the rest of the outcrop. To overcome this effect using the circular scanline method, multiple circles distributed across the bedding surface should reduce error. Fracture intensity data from site D lies on the 1:1 line on Fig. 15b, meaning intensity estimated using circles gives a good estimate of whole outcrop intensity. At site D, five circles were used to calculate average fracture intensity, whereas at sites A–C only one or two circle were used. This approach shows that increasing the number of sampling circles on an outcrop improves the intensity estimate for the whole outcrop, in regions of heterogeneous fracture networks.

5. Discussion

Using the workflow described in section 3, our augmented circular scanline sampling was tested against the four other fracture data collection methods at sampling sites A–D (see Fig. 3b for locations), where fracture networks were considered to be heterogeneous. We found the augmented circular scanline method to be the most efficient for fracture data collection compared to linear scanline sampling, rectangular window sampling, areal sampling and circular scanline sampling. An advantage of the augmented circular scanline method over linear scanline sampling is that data are not subject to orientation bias within the 2D surface on which data are collected. For linear scanline sampling fracture orientation data may be biased if scanlines are not oriented normal to fracture traces. Data can be corrected using the Terzaghi method (Terzaghi, 1965), however this procedure provides additional source for error. The augmented circular scanline method can be less time consuming than the linear scanline method, especially if multiple linear scanlines are used perpendicular to the orientation of each fracture set, as suggested by Priest (1993). This outcome is illustrated in Fig. 16 (site D) where four linear scanlines are used to record attributes of four fracture sets (black, blue, green and orange). Data collection takes four times longer than if the augmented circular scanline method was used because only one scanline is needed (red circle) to record roughly the same amount of data.

Although the rectangular window sampling method does not incur any orientation bias and can be implemented on small outcrops, the method is very time consuming because required attribute data have to be collected from all fractures within the rectangle. The time taken for data collection, especially where fractures are heterogeneous, is impractical as large numbers of fractures may have to be measured. This difficulty is illustrated in Fig. 16 (site D), where a rectangular window (red rectangle) is small relative to the outcrop size. To characterise heterogeneity on the bedding surface a much larger window would be required, which would enclose hundreds of fractures. Areal sampling can be much more time consuming than augmented circular scanline sampling because fracture trace maps must be created and analysed. Accuracy of areal sampling data is dependent on source image resolution, meaning smaller fractures may not be represented in the dataset, and often apertures cannot be measured. By using the augmented circular scanline method, data are collected in the field so these resolution issues are not encountered. Areal sampling does have the advantage of providing a much larger dataset that represents fracture networks on a larger scale than other sampling techniques. For example, the areal sampling rose-plot on Fig. 16 shows the fracture orientation distribution for the whole outcrop,

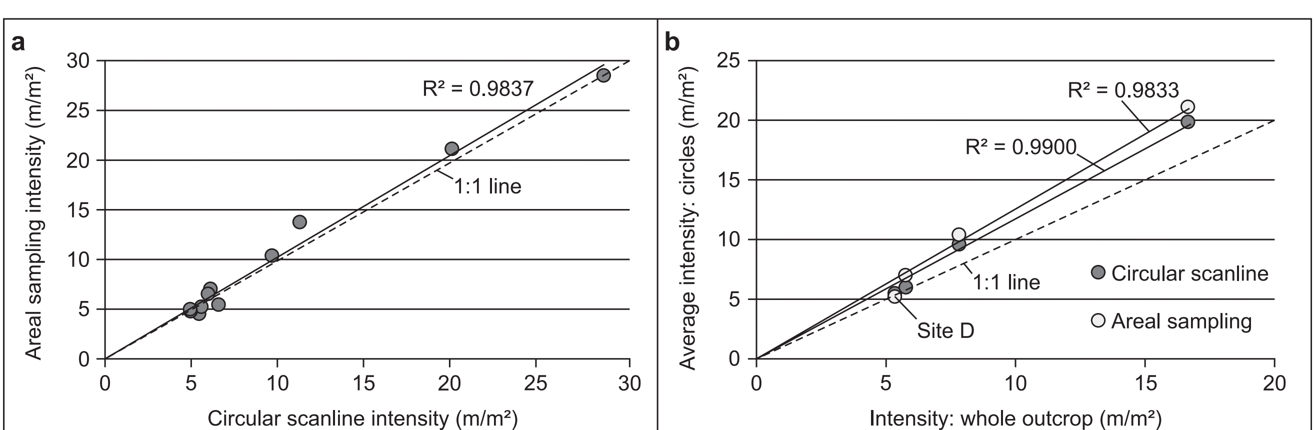


Fig. 15. a) Correlation between estimated fracture intensity (Mauldon et al., 2001) and fracture intensity measured using areal sampling within sampling circles at sites A–D (see Fig. 3b for site locations). b) Correlation between fracture intensity of whole outcrops and fracture intensity calculated from circles using Mauldon's circular scanline estimator (dark grey) and fracture intensity measured within the circular area using areal sampling (light grey).

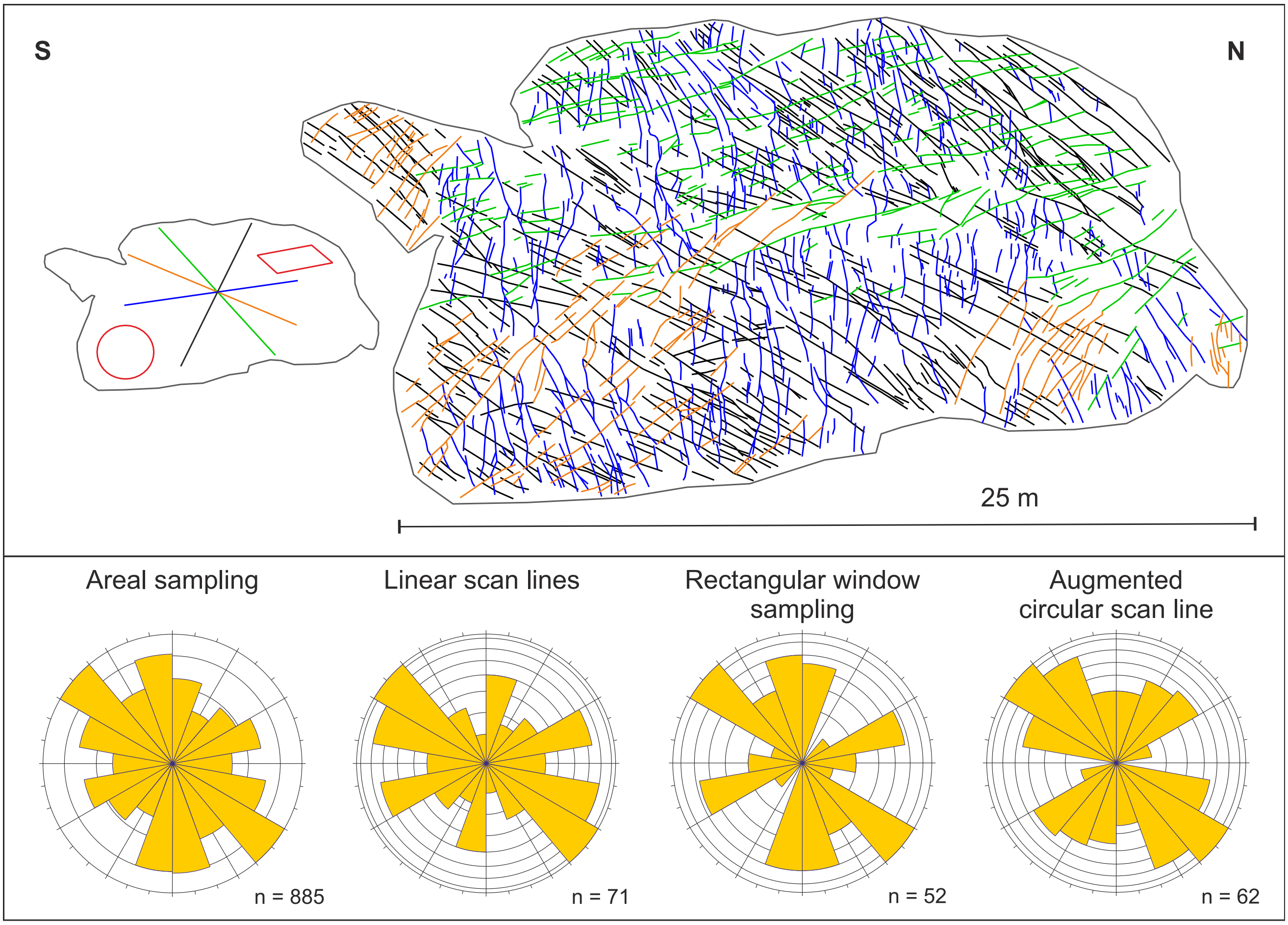


Fig. 16. Line diagram of a fractured bedding plane at site D (see Fig. 3b for site location) showing orientation data from areal sampling (whole outcrop), four linear scan lines (black, blue, green & orange lines, 14.35 m length) oriented perpendicular to each fracture set, a circular scan line (red circle, 2.3 m radius) & a rectangular window sampling area (red box, 11.4 m^2 area). Positions of each survey are shown on the schematic. Rose diagrams apply area scaling.

whereas results from other sampling techniques represent much smaller areas. Although very similar, the augmented circular scanline workflow is preferred over Mauldon's circular scanline method (Mauldon et al., 2001) because it involves collecting a wider range of fracture attribute data, including individual fracture lengths, apertures and spacing.

Our augmented circular scanline sampling method has several disadvantages. As discussed earlier, data are subject to length censoring, as are all other sampling methods. We also found that recording variations in fracture characteristics over distances larger than the area of the sampling circle was difficult, so we could not sufficiently record spatial distributions. This issue is illustrated in Fig. 16 (Site D), where four fracture sets are heterogeneously distributed across a bedding surface. The circular scanline (red circle) is small relative to the size of the outcrop so it does not record heterogeneity of fracture spatial distribution. To overcome this problem, we used multiple circular scanlines spaced across an outcrop (Fig. 11). Although this method allows for quantitative data collection, it does not capture distribution variations (for orientation, length, spacing/clustering and intensity) to the level of detail that areal sampling can, because even with very closely spaced circles, only a sample of fracture traces are recorded. The areal sampling method might be used as an alternative to augmented circular scanline sampling where this level of detail is desired.

Alternatively, we suggest areal sampling is used alongside augmented circular scanline sampling. By implementing both fracture sampling techniques, qualitative data can be collected using the augmented circular scanline method, and areal sampling can be used to characterise fracture distribution variations for orientation, length, spacing and intensity. By using these methods, heterogeneous networks can be characterised relatively quickly to cover large areas. Although we find this method the most appropriate for characterising heterogeneous networks, often the nature of the outcrop dictates which fracture sampling method can be used, meaning that the augmented circular scanline and areal sampling methods cannot be implemented. Core data and outcrops on road cuttings are examples where data can only be collected in 1D along linear scanlines. Although we find this method less useful than our suggested workflow, it can still be used to collect good quality data, provided the user is aware of its disadvantages.

We have shown that fracture attributes can vary significantly over short distances and it can be very difficult to characterise these fracture network heterogeneities. Fracture network orientations can vary depending on the sampling site position on a bedding surface. For example, Fig. 11 shows that the green and orange fracture sets are not present across the entire outcrop, and can forms clusters. Fracture orientation can change on a very small scale, as for example Fig. 9 where fracture trace azimuths can vary along their lengths by up to 90°. Fracture intensity is also seen to vary over short distances, as for example Fig. 12 where fracture intensity decreases significantly over the space of only a few centimetres, from the top of the sampling circle to the bottom. This highlights the difficulty of sampling fracture networks as fracture attributes can vary below the resolution of the sampling technique used.

It is important to characterise fracture heterogeneity at outcrop because it may give insight into how variable fracture networks are in the subsurface. Fig. 12 shows how sensitive fracture attribute data may be to data collection position. If this outcrop was in a potential reservoir horizon in the subsurface, an exploration well drilled through the top of the sampling circle would indicate a high intensity network of well-connected fractures, indicating good quality reservoir. An exploration well drilled through the bottom of the sampling circle would indicate lower intensity, poorer connectivity fractures, which would suggest poorer quality reservoir for a tight sand that requires fracture connectivity for flow. Therefore it is important to characterise how variable fracture networks can be at outcrop, in order to understand how representative subsurface data collected from widely spaced boreholes might be. By using an appropriate fracture sampling technique, such as our augmented circular scanline method combined with areal sampling, we can begin to understand fracture heterogeneity at outcrop, and heterogeneities between sampling locations can be considered.

6. Conclusions

Many different methods exist for fracture data collection, each of which has its own advantages and disadvantages. We propose a workflow involving augmented circular scanline sampling to quantitatively record fracture set orientations, lengths, apertures and intensities for fractured reservoir quality prediction in the subsurface. We also use areal sampling to record variations in fracture spatial distributions over areas larger than the extent of sampling circles to gain insight into the potential variability of fracture patterns in the subsurface, and therefore highlight potential risk in using outcrop analogues or well log data in characterising fractured reservoirs.

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