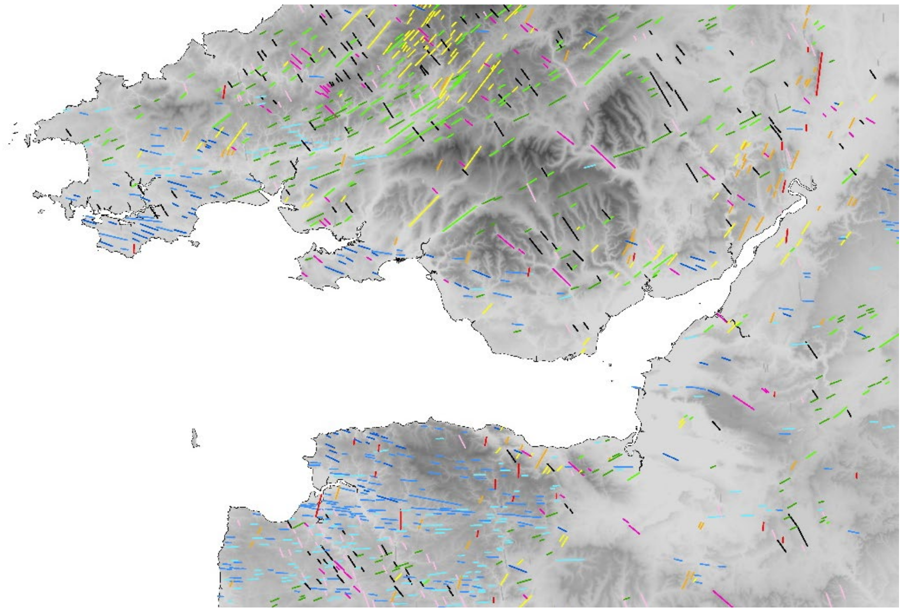
Methodology for Manual Lineament Analysis

National Geoscience Programme

Open Report OR/24/007



BRITISH GEOLOGICAL SURVEY

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Front cover

1:250,000 Lineament populations in South Wales and Southwest England. Map contains Ordnance Survey Data © Crown copyright and database rights 2023.

Methodology for Manual Lineament Analysis

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BRITISH GEOLOGICAL SURVEY

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Summary

This report describes the work on lineament analysis methods undertaken as part of the National Geological Model Project during 2018 – 2020. It describes a method for manual lineament identification and analysis from DEM data.

Introduction

It is well known that major geological structures, such as the Great Glen Fault in Scotland, and the San Andreas Fault in California, form prominent topographic features, but smaller faults also have visible surface expressions (Figure 1). For over a century, linear and sub-linear patterns in topography, vegetation and drainage have been interpreted as the results of weaknesses in the crust which influence the development of surface features (Hobbs 1912; Wise et al., 1985; Clark & Wilson, 1994). These features, known as '*lineaments*', can vary in length from tens of metres to hundreds of kilometres (Ekneligoda & Henkel, 2010). They can be identified using a number of techniques. Historically, they were identified from the field and then from maps. However, with the availability of remote sensing data, the most efficient way to identify lineaments is using Digital Elevation Models (DEMs) and satellite images.

Figure 1; OS OpenData Terrain 50 DEM of England, Scotland and Wales – the Great Glen Fault in Scotland is the most obvious lineament (*Contains OS data © Crown copyright and database rights 2023*).

Lineaments can also be identified using geophysical data, such as gravity and magnetics, which reflect the properties of the crust (Sander, 2006). A variety of features, from clearly-identifiable to purely speculative, can be interpreted from this data, as the resolution of the data is much lower than remote sensing data of the Earth's surface. Consequently, these methods identify predominantly large-scale structures which represent major discontinuities in the sub-surface but miss the smaller-scale detail which might be visible at the surface. However, these methods have huge value in identifying tectonic terrains and highlighting regions where the structures at depth do not match up to structures at the surface.

Analysis of lineaments has sometimes been criticised in the geological community (Richards, 2000; Sander, 2006). Unambiguous data on ages, tectonic settings and the stress fields responsible for their origins are commonly lacking and the relationship of lineaments to geomorphological features is sometimes difficult to understand. However, spatial analysis of lineaments and identification of lineament sets and domains may help in reconstructing tectonic histories and in testing or formulating hypotheses (Gabrielsen, 1984; Clark & Wilson, 1994). An advantage of lineament analysis is that it can be undertaken at a range of scales and can be applied consistently in small areas or across large regions, depending on the application.

The drive to decarbonise energy, develop infrastructure to support growing populations, sustainably manage our water supplies and protect communities from natural hazards requires a greater knowledge of the physical properties, strength and permeability of rock mass in the sub-surface (Gabrielsen et al., 2002, Sander, 2006; Amicarelli, Ireland & Davie, 2023). Understanding the structure (i.e. the faults, fractures, joints and weaknesses) within sub-surface volumes is key to making progress with this. In areas where bedrock is at or near the surface, and superficial deposits are minimal or thin, structures affecting the bedrock are commonly reflected in surface topography.

Lineament studies allow surface structures to be captured remotely through desk-based work, utilising remotely sensed datasets, and thus saving both time and expense compared to field or drilling studies (Sander, 2006). The orientations and spatial extents of lineaments and lineament populations can be analysed to understand local or regional weaknesses in the subsurface, inform further investigative studies, or pin-point potentially suitable areas that can be targeted by specific industries (Richards, 2000).

As part of the National Geological Model Programme (2019 – 2022) we undertook a trial lineament study, using manual digitisation of surface lineaments, to test the potential value of lineament analysis in assessing the national quality and coverage of BGS fault mapping, as well as in identifying the spatial distribution of lineament populations across the UK mainland. This study was undertaken specifically to test methodologies of lineament capture and analysis which could be scaled-up to for a national-scale study. However, the methodologies outlined are not scale-dependant and can be applied to national, regional or site-specific lineament studies. Many of the methods described can also be applied to studies of faults, fractures or joints.

1 Background

1.1 WHAT IS A LINEAMENT?

A lineament is a linear or sub-linear feature on the Earth's surface which is inferred to represent a zone of weakness in the sub-surface (Hobbs, 1912; O'Leary et al., 1976; Wise et al., 1985; Clark & Wilson, 1994). The assumption is that these lineaments represent fracture zones. This may exclude curvilinear features, such as sinuous faults, however it is often possible to break-down curvilinear features into a number of sub-linear features. The term lineament should be specifically used to refer to a linear or sub-linear feature on the Earth's surface which has been identified by remote sensing methods (O'Leary et al., 1976; Gabrielsen, 2002).

Lineaments can be defined manually from DEMs and satellite images and are commonly linear valleys, linear ridges or linear breaks-of-slope which represent crustal weaknesses (faults, fractures, shear zones, joints, veins, etc.), inclined strata, river valleys, geomorphological features (drumlins, eskers, striations, etc.) or anthropogenic features (embankments, roads, railway lines, etc.). At the point of initial identification, the parentage of the lineament may not be immediately apparent, and it is important to note that some lineaments may be the result of surface processes acting on the bedrock, such asthe movement of glaciers.

Lineaments can be commonly grouped, according to characteristics like orientation or style, and are referred to as *lineament populations*. Lineaments which are parallel or sub-parallel may be referred to as *lineament sets*. Lineament sets may have cross-cutting relationships and, in these instances, it is important to look for offsets or steps in lineaments which may assist in identifying the relative age of the different lineament sets.

Much British Isles was glaciated during the Holocene, with some parts of the UK seeing the advancement and retreat of multiple ice sheets during this period. This has left a strong signature in the landscape in affecting both the superficial deposits and exposed bedrock in areas. It is important that these geomorphological lineaments are separated from the tectonic lineaments as they do not commonly represent weaknesses in the subsurface, but rather the effect of processes on the landscape. It is proposed that these lineaments are identified, along with the tectonic lineaments, but are separated into different datasets.

1.2 LINEAMENTS IN THE LANDSCAPE

Lineaments related to weaknesses in the crust can be identified by a number of topographic features in the landscape. These include linear, or occasionally curvilinear, ridges, valleys, breaks in slope and stream deviations. Lineaments can be short-length features, only tens of meters long, or features of significant length, tens or hundreds of kilometres long, such as the Great Glen Fault which runs for around 90 km along a line of lochs, including Loch Ness, in Scotland between Inverness and Fort Willian (Figure 1). Some lineaments may appear as one long lineament when viewed at a small-scale, but as multiple lineaments on the same linear trend at a larger-scale.

1.3 TRIAL AREA

In this study we selected a trial area to test methodologies of lineament capture and analysis. This enabled us to understand the feasibility of undertaking a UK-wide manual lineament analysis. To reflect this, we chose two scales to test the methodology; 1:500,000 and 1:250,000. These were selected as they were considered to be suitable to a nation-scale analysis.

An area measuring 240 km by 160 km was selected for this study, which covered South Wales, Devon and the western Cotswolds (Figure 2). This area was selected as it includes a variety of landscapes, environments and bedrock types. It includes areas where the Palaeozoic basement rocks and Mesozoic cover rocks are at the surface, as well as areas which are covered by significant superficial deposits. Figure 3 shows the variety of landscapes within the field area, from the elevated Black Mountains and Brecon Beacons in South Wales, to the rolling hills of the western Cotswolds and the flat alluvial plain of the River Severn.

Figure 2; Left – Location of the study area outlined in the blue box. Right – Map of the extent of the area selected for this study. (*Contains OS data © Crown copyright and database rights 2023*).

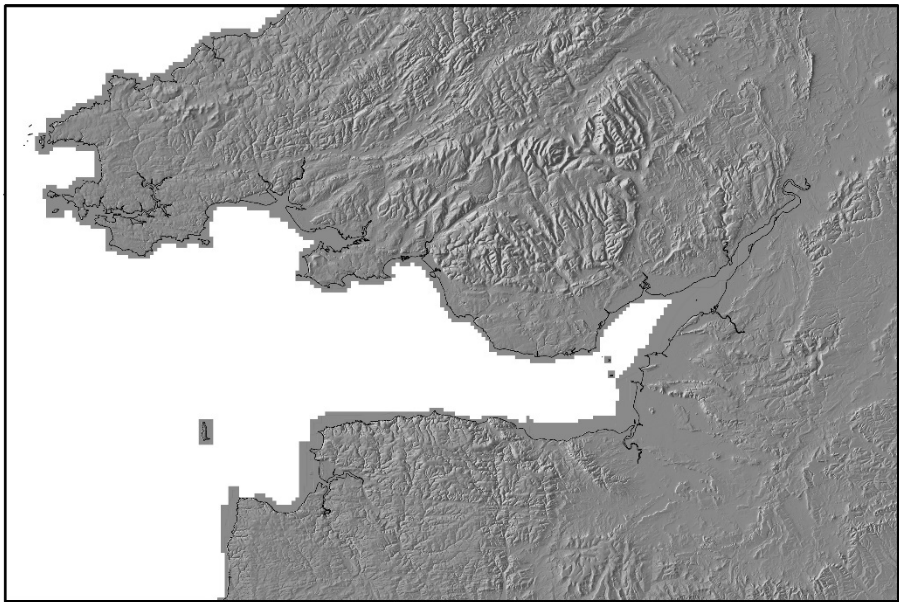


Figure 3; Bluesky DTM of the study area showing the variation in topography across the area (*Derived in part from DTM of Great Britain at 5m resolution © Bluesky International Limited; Contains OS data © Crown copyright and database rights 2023*).

2 Datasets

Digital Elevation Models (DEMs) are ideal for lineament analysis as they enable the visualisation of Earth's landscape and capture the natural and man-made features on the Earth's surface, such as ridges and valleys, or trees and buildings. DEMs are raster grids of the Earth's surface referenced to a vertical datum, most commonly the surface of zero elevation (i.e. sea level). They are generated from remotely sensed data, such as laser scanning, radar and photogrammetry, captured by satellites, drones and planes. DEMs can also be captured via ground surveying using a device called a theodolite, but this is not normally the best type of survey for lineament analysis as it is designed to capture a relatively small area in high resolution. The quality of DEM-derived products can be influenced by; vertical resolution, terrain roughness, sampling density and terrain analysis and interpolation algorithms.

DEMs can be separated into Digital Surface Models (DSM) and Digital Terrain Models (DTM). DSMs capture the Earth's surface including natural and man-made structures, such as buildings and trees. They can increase the understanding of complex urban scenarios, especially as build-up areas develop through time. However, as they capture all the features on the Earth's surface, geological features can be obscured by woodlands and buildings, making them unsuitable for lineament analysis in areas where these are present.

DTMs are bare Earth elevation models from which above-surface structures, such as trees and buildings, have been filtered out. Consequently, DTMs are more useful for lineament analysis as they capture features on the ground surface on the Earth. However, in urban or woodland areas, DTMs may be of a lower resolution as they have been reprocessed to remove above ground features, e.g. trees or buildings. Filtering processes may also decrease the resolution. DSMs capture both natural and man-made features of the Earth's surface, whereas DTMs only retain features of the bare-Earth terrain, such as rivers and ridges. A DTM can be derived from a DSM, but not vice-versa.

BGS maintains licences for a number of elevation products, which are described in section 2.1. Other elevation products are available to download or purchase should they be required.

A number of processing, filtering and stretching methods can be applied to DTMs and DSMs to enhance topographic features. These are briefly described in Table 1.

Bilinear interpolation is a resampling method that determines the new value of a cell based on a weighted distance average of the four nearest input cell centres. It is useful for continuous data and will cause some smoothing of the data.
The ***HillShade*** function uses light and shadow to create a 3D image of the terrain. It does this by setting a position for a hypothetical light source and calculating the illumination values of each cell in relation to neighbouring cells. It can greatly enhance the visualization of the topography of a surface for analysis or graphical display, especially when using transparency.
The ***Aspect*** function highlights the slope direction through identifying the direction of the maximum rate of elevation change from each cell to its neighbours. The values of each cell in the output raster indicate the compass direction that the surface faces at that location. It is measured clockwise in degrees from 0 (due north) to 360 (again due north), coming full circle. Flat areas having no downslope direction are given a value of -1.
The ***Slope*** function identifies the steepness of the raster surface in each cell. Low slope values equal flatter terrain and high slope values equal steeper terrain.

The ***Curvature*** function displays the shape, or curvature, of the slope by calculating the second derivative of the surface. Three different types of curvature can be computed to accentuate different aspects of the slope; Profile, Planform and Standard; The *Profile curvature* is parallel to the slope and indicates the direction of maximum slope. A negative value indicates that the surface is upwardly convex at that cell, a positive profile indicates that the surface is upwardly concave at that cell, and a value of zero indicates that the surface is linear. The *Planform curvature* is perpendicular to the direction of the maximum slope. A positive value indicates the surface is sidewardly convex at that cell, a negative plan indicates the surface is sidewardly concave at that cell, and a value of zero indicates the surface is linear. The *Standard curvature* combines both the profile and planform curvatures.
The ***Stretch*** function enhances a raster by changing its properties, such as brightness, contrast and gamma, through multiple stretch types. The stretch types use statistics from the rasters within the dataset to enhance their appearance by spreading the pixel values along a histogram from the minimum and maximum values defined by their bit depth.

Table 1: The stretches and filters which can be applied to DEM's to enhance topographic features.

2.1 BGS DATASETS

BGS holds licences for a number of elevation datasets which can be accessed on the S Drive. These are briefly outlined in this section. Additional non-BGS datasets are also described below. These are not exhaustive lists and there may be other local or global datasets available. Appropriate licence should always be checked for the location and type of work.

2.1.1 OS Terrain50

OS Terrain50 offers a digital terrain model at 50m resolution, provided as ASCII grid data. It is available under the terms of the Open Government License.

2.1.2 EA LiDAR

The EA LiDAR is an airborne technique which uses a scanning laser to measure the distance between the aircraft and the ground. It provides good coverage of The British Isles at 1m resolution. A number of products are available for use, including; the LiDAR point cloud, Digital Surface Models (DSM), Digital Terrain Models (DTM), First Return Digital Surface Models (FZ DSM) and Intensity Surface Models (Int DSM).

2.1.3 APGB

The APGB DSM (Digital Surface Model) is a photogrammetrically derived digital surface model of Great Britain. It provides full coverage of Great Britain at 2 m resolution. It is an accurate representation of the Earth's surface including all ground features, such as vegetation, buildings and other anthropogenic structures.

2.1.4 BlueSky

The BlueSky DTM (Digital Terrain Model) is processed at 5 m resolution and has been developed using a combination of airborne photogrammetric imagery and airborne LiDAR. Unlike other DEM's available, the BlueSky DTM has been processed to that trees and buildings have been removed from the surface. In this study we resampled the DTM to 50 m resolution.

2.2 NON-BGS DATASETS

2.2.1 SRTM

The Shuttle Radar Topography Mission (SRTM) was flown aboard the shuttle Endeavour in 2000 in an international project to acquire radar data which was used to create the first near-global set and land elevations. The data is available at 30 m and 90 m resolution. In this project we used the 30 m SRTM data.

2.2.2 ASTER GDEM

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a joint operation by NASA and the Ministry of Economy, Trader and Industry (METI) of Japan. The Global Digital Elevation Model (GDEM) uses stereoscopic pairs and photogrammetry to measure elevation. The GDEM has a global resolution of 90 m and 30 m in the United States.

2.2.3 Other Datasets

A number of other global elevation datasets are available, including; Intermap's NEXTmap & Airbus' WorldDEM, JAXA's Global ALOS World 3D and Global LiDAR.

3 Methodology

In this study we digitised and analysed lineaments at 1:250,000 and 1;500,000 scale across the study area. We undertook the lineament digitisation in ArcGIS, although QGIS could also be used. Lineament analysis was carried out using toolboxes in both ArcGIS and QGIS, as well as rose plotting software, in this instance GeoRose. Other opensource and licensed software is also available for this purpose, including GEOrient (opensource) and RocScience (Licensed). Some analyses can be carried out in either ArcGIS or QGIS, at the user's preference, while some are only available in QGIS.

3.1 LINEAMENT DIGITISATION

A 50m resampled BlueSky DEM, NextMap DEM, SRTM and LiDAR DEMs, were clipped to the region of interest (ROI) in ArcGIS. Aerial photographs were also used to ensure lineaments digitised were not anthropogenic. A number of stretches, interpolations and filters were applied to the DEM's to enhance a range of characteristics. The bilinear, hillshade, aspect, slope and profile-curve processing of the BlueSky DEM were particularly good for lineament analysis in the trial area.

The trial was designed to test the methodology for a National-scale lineament analysis and this reflected the scale at which the analysis was undertaken. Initially a scale of 1:500,000 was selected, although later large-scale (1:250,000) was also trialled. Once a scale was selected it was defined in ArcGIS and fixed for the duration of lineament digitisation at the selected scale. In order to maintain consistency of lineament digitisation across the trial area, a decision was made to refrain from zooming either in or out during digitisation. In other studies, depending on the detail required, it may not be necessary to set a fixed scale.

To collect lineament traces new polyline shapefiles were created in ArcGIS. Lineaments digitised at 1:250,000 and 1:500,000 were collected in separate shapefiles. Landscape features digitised as lineaments included linear ridges, valleys and breaks in slope, as well as curvilinear ridges and valleys. Straight-line topographic features were digitised as straight polylines within the shapefiles. Curvilinear topographic features were digitised as a number of individual straight lines between inflexion points on a curvilinear topographic feature.

The lineaments captured were not divided into tectonic or geomorphic in origin but it was clarified where any of them were anthropogenic. Aerial imagery can be used to check for anthropogenic features. Once lineaments had been digitised across the entirety of the trial area, the data frame was rotated 90° clockwise to remove any bias of the human brain towards features of a particular azimuth. This also helped in removing any location bias.

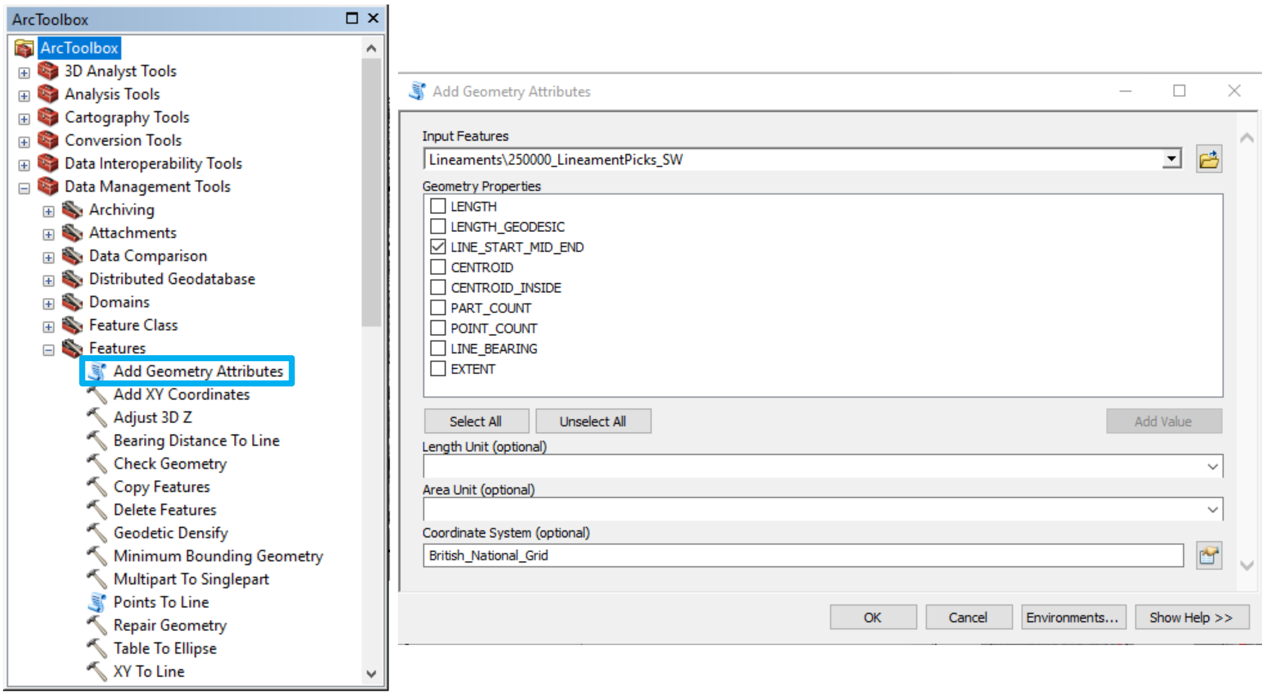
Once lineament digitisation is complete, the lineament datasets can be filtered into inferred tectonic and inferred geomorphic (i.e. glacial) datasets. To do this the BGS superficial polygons and linear landforms layers can be used. Other methods include looking at the DEMs in more detail and to also comparing to aerial photography. Superficial lineaments could include drumlines or scours for example, which may be identifiable on smaller scale DEMs or aerial photographs. At this point it is also important to check that none of the digitised lineaments correspond to linear anthropogenic features, such as roads or railways. The lineament datasets can also be filtered at a later stage following analysis. It can become and iterative process. In this trial we did not filter the dataset before or after analysis.

3.2 LINEAMENT ANALYSIS

A range of methods can be used to analyse the lineament datasets. These include; rose plots to establish dominant and sub trends in the azimuths of the lineaments, gridded rose analysis to identify local trends in the azimuths of lineaments and lineament set analysis to separate the lineaments into sets, or populations, depending on their azimuth. The methodologies for these three analyses are described below.

3.2.1 Rose Analysis

Following completion of lineament digitisation, the start-point, mid-point and end-point co-ordinates of each lineament were added to the shapefile attributes tables in ArcGIS 10.7 (the same methodology can also be used in ArcGIS 10.8) using *Add Geometry Attributes* within *Features* of the *Data Management* toolbox (Figure 4). The Azimuth of each lineament was calculated using the *EasyCalculate 10* plug-in for ArcGIS 10 (Ian-ko, accessed 2019) and added to the attribute table (Figure 5). The start-point, mid-point and end-point coordinates, as well as the lineament azimuth, can also be calculated using the *Field Calculator* within the attributes table in QGIS.



Input Features: Lineaments\250000_LineamentPicks_SW

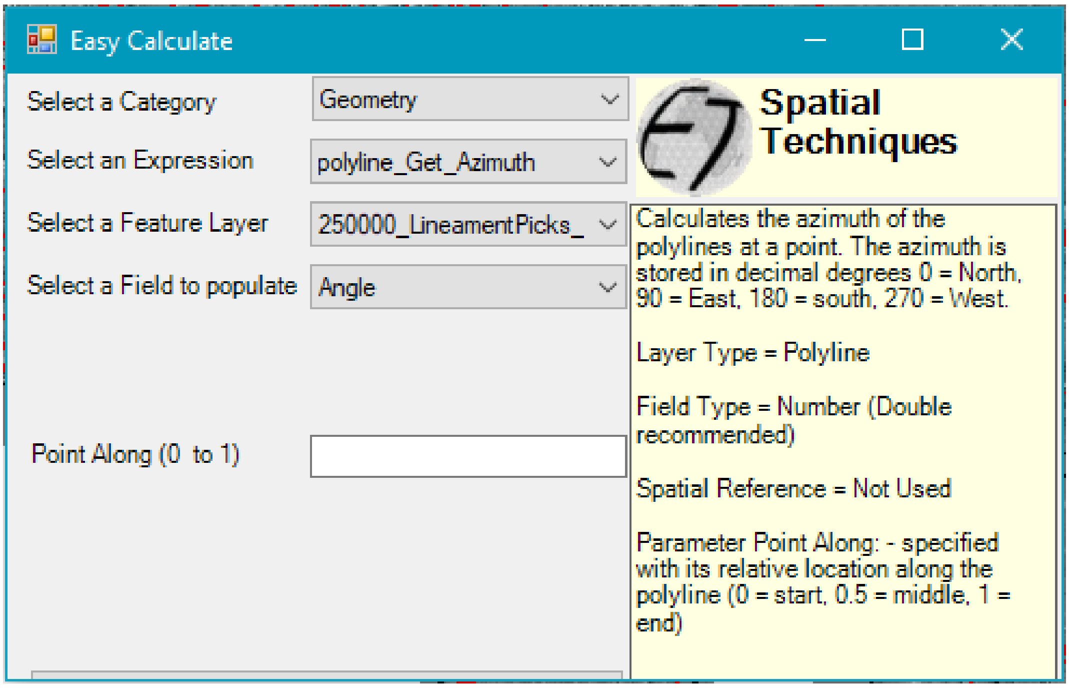
Geometry Properties
- ☐ LENGTH
- ☐ LENGTH_GEODESIC
- ☑ LINE_START_MID_END
- ☐ CENTROID
- ☐ CENTROID_INSIDE
- ☐ PART_COUNT
- ☐ POINT_COUNT
- ☐ LINE_BEARING
- ☐ EXTENT

Length Unit (optional):

Area Unit (optional):

Coordinate System (optional): British_National_Grid

Figure 4; Left – Location of *Add Geometry Features* (highlighted in blue box) in the *ArcToolbox*. Right – the ‘Add Geometry Attributes’ toolbox.



Select a Category: Geometry

Select an Expression: polyline_Get_Azimuth

Select a Feature Layer: 250000_LineamentPicks_

Select a Field to populate: Angle

Point Along (0 to 1):

Calculates the azimuth of the polylines at a point. The azimuth is stored in decimal degrees 0 = North, 90 = East, 180 = south, 270 = West.

Layer Type = Polyline

Field Type = Number (Double recommended)

Spatial Reference = Not Used

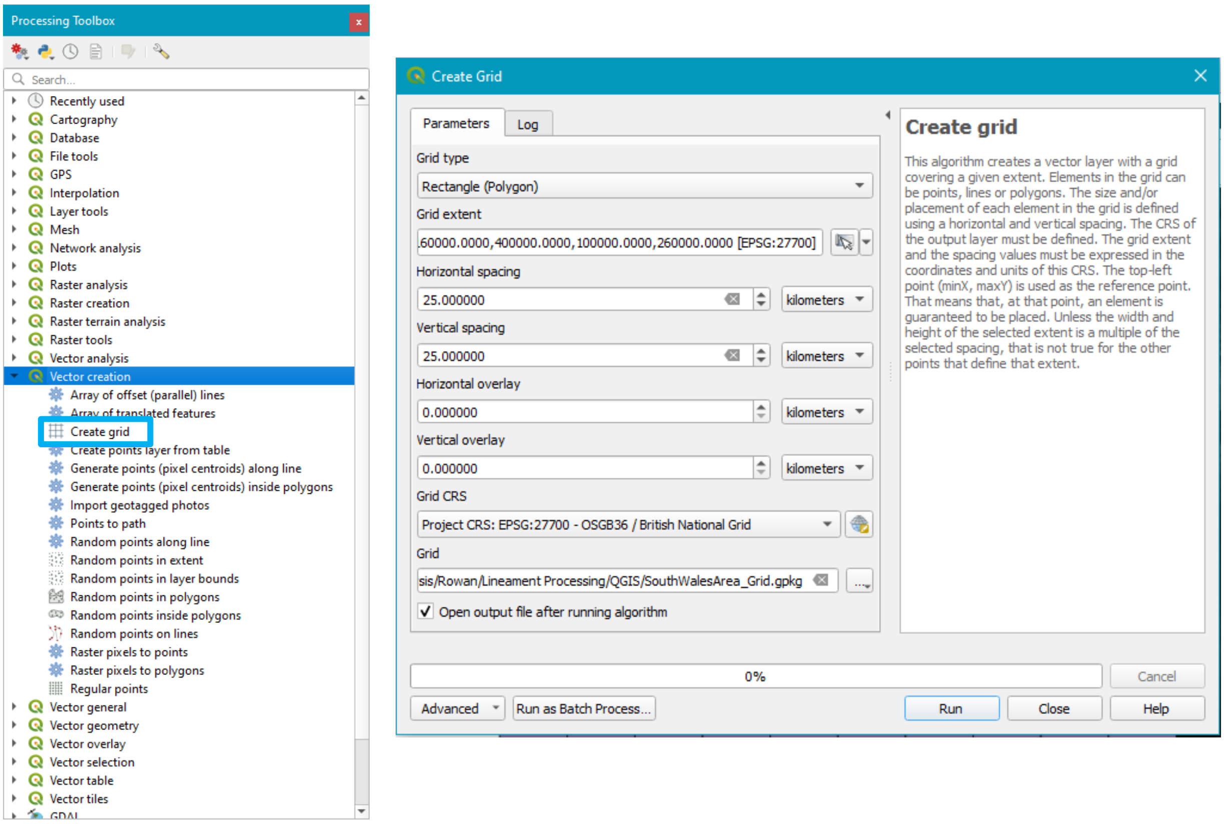
Parameter Point Along: - specified with its relative location along the polyline (0 = start, 0.5 = middle, 1 = end)

Figure 5; Using the EasyCalculate 10 Plug-in to calculate the azimuth of the lineaments that have been digitised.

The attribute tables of each shapefile were exported as a text file for use with structural analysis software. In this study we kept lineaments digitised at different scales in separate datasets. We used *GeoRose* to create 360° rose plots showing the azimuths of the lineaments, but many other Rose Diagram programmes are available (such as Dips (Rocscience, accessed 2023), or Stereonet 11 (Allmendinger, accessed 2023). The Rose Diagrams enable the identification of dominant and sub trends within the digitised lineament datasets. The bin size, in this instance the number of degrees in each category, can be changed in most rose plotting software and it can be valuable to view the rose plots with a variety of bin sizes to fully understand the trends shown in the digitised lineaments.

3.2.2 Gridded Rose Analysis

This analysis creates a grid over the ROI and rose plots for each grid square, identifying local trends in the lineament datasets. The ROI can be gridded in QGIS using the *Create Grid* tool within the *Vector Creation Toolbox* to create tiles (Figure 6). The size and style of the tile can be specified. Rose plots for each grid square can be created using the *Line Direction Histogram* Plugin also in QGIS (Tveite, H., 2015) (Figure 7). In this trial, gridded rose analysis was undertaken on the 1:250,000 and 1:500,000 scale lineament datasets and the 1:50,000 and 1:625,000 scale BGS fault datasets. A grid size of 25k grid for tiling, on rose plots with 12 bins in 180°, with each bin representing 15° of rotation.



Grid type
Rectangle (Polygon)

Grid extent
60000.0000,400000.0000,100000.0000,260000.0000 [EPSG:27700]

Horizontal spacing
25.000000 kilometers

Vertical spacing
25.000000 kilometers

Horizontal overlay
0.000000 kilometers

Vertical overlay
0.000000 kilometers

Grid CRS
Project CRS: EPSG:27700 - OSGB36 / British National Grid

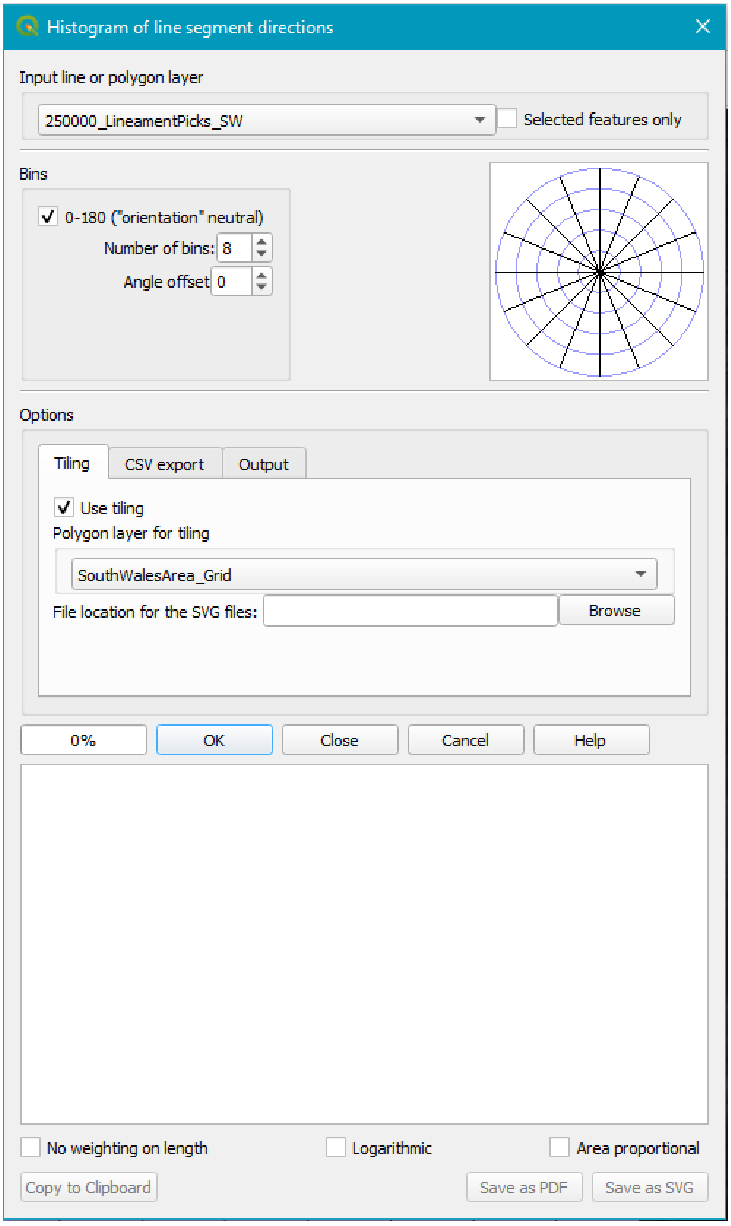
Grid
sis/Rowan/Lineament Processing/QGIS/SouthWalesArea_Grid.gpkg

☑ Open output file after running algorithm

Create grid

This algorithm creates a vector layer with a grid covering a given extent. Elements in the grid can be points, lines or polygons. The size and/or placement of each element in the grid is defined using a horizontal and vertical spacing. The CRS of the output layer must be defined. The grid extent and the spacing values must be expressed in the coordinates and units of this CRS. The top-left point (minX, maxY) is used as the reference point. That means that, at that point, an element is guaranteed to be placed. Unless the width and height of the selected extent is a multiple of the selected spacing, that is not true for the other points that define that extent.

Figure 4; Left – Location of the *Create Grid* tool within the *Vector Creation Toolbox.* Right – *Create Grid* example parameters.



Histogram of line segment directions

Input line or polygon layer

250000_LineamentPicks_SW

☐ Selected features only

Bins

☑ 0-180 ("orientation" neutral)

Number of bins: 8

Angle offset 0

Options

☑ Use tiling

Polygon layer for tiling

SouthWalesArea_Grid

File location for the SVG files:

☐ No weighting on length

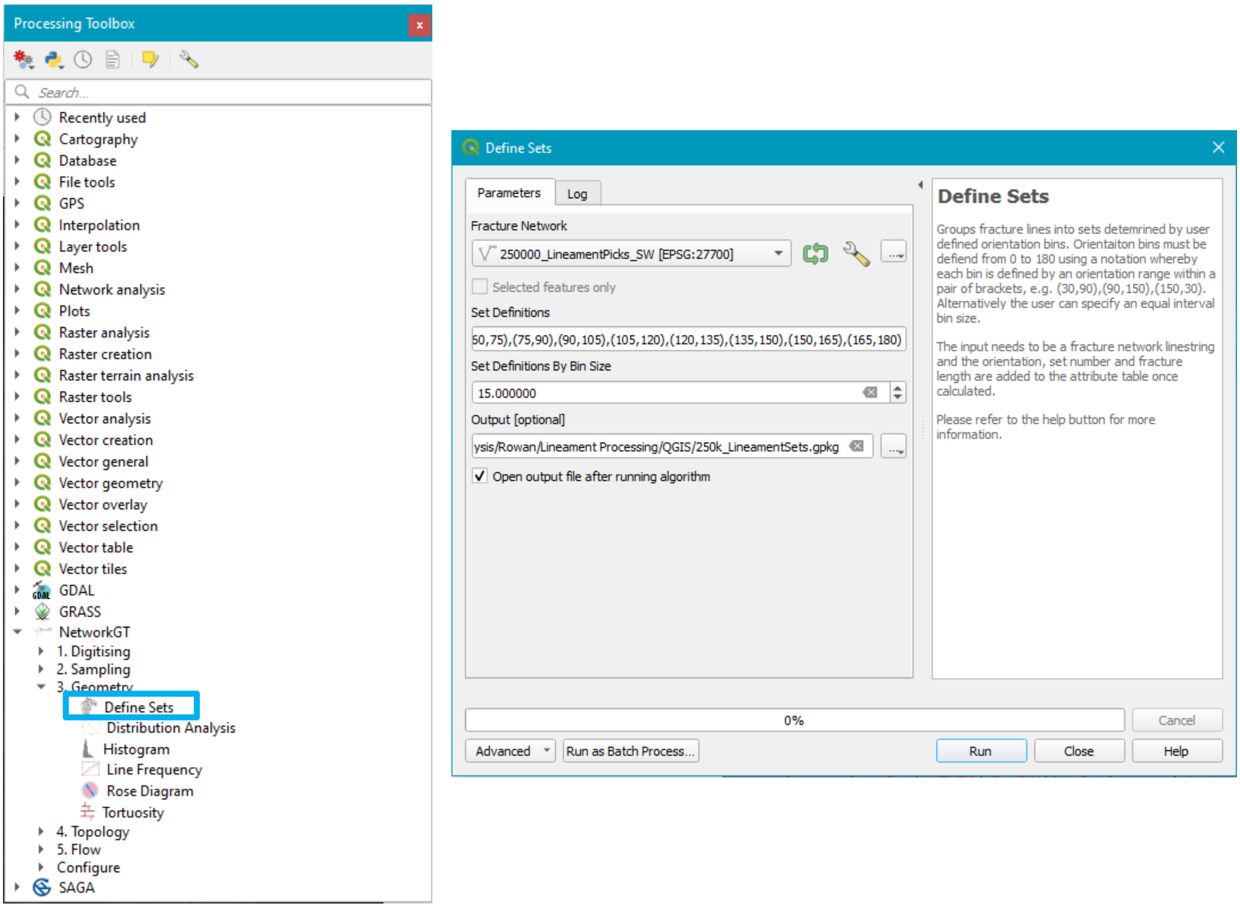
☐ Logarithmic

☐ Area proportional

Figure 5; The rose plot interface of the *Line Direction Histogram* Plugin (Tveite, H., 2015). Note that *Tiling* is selected. This will create a Rose Plot for each tile in the grid.

3.2.3 Defining Lineament Sets

A lineament dataset can be split into sets based on lineament azimuth. This can be done using the *Define Sets* function within the *Geometry Toolbox* of the *NetworkGT* experimental plugin within QGIS (Nyberg et al., 2018) (Figure 8). The azimuth bin size can be changed within this function. In this trial an azimuth bin of 15° was specified for each lineament and fault dataset. This is consistent with the azimuth bins sizes specified in the Gridded Rose Analysis for these datasets. For long or sinuous lineaments or faults, slicing the lineaments or faults into shorter lengths is advised. This function will add a column to the attribute tables of the datasets and each row will be attributed with a set number. The shapefiles of each dataset can then be given a different colour symbology in either GQIS or ArcGIS to visualise the extents of each lineament set.



Fracture Network: 250000_LineamentPicks_SW [EPSG:27700]

☐ Selected features only

Set Definitions: 0,75),(75,90),(90,105),(105,120),(120,135),(135,150),(150,165),(165,180)

Set Definitions By Bin Size: 15.000000

Output [optional]: ysis/Rowan/Lineament Processing/QGIS/250k_LineamentSets.gpkg

☑ Open output file after running algorithm

Define Sets

Groups fracture lines into sets detemrined by user defined orientation bins. Orientaiton bins must be defiend from 0 to 180 using a notation whereby each bin is defined by an orientation range within a pair of brackets, e.g. (30,90),(90,150),(150,30). Alternatively the user can specify an equal interval bin size.

The input needs to be a fracture network linestring and the orientation, set number and fracture length are added to the attribute table once calculated.

Please refer to the help button for more information.

Figure 6; Left – Location of the *Define Sets* function of the *NetworkGT* plug-in. Right – The interface of the *Define Sets* function. Here bins of 15° have been specified. The function will create a new column within the attributes table of the output file, which will contain the Set number for each lineament. The digitised lineaments can then be given a different colour symbology by set number or exported for further analysis.

4 Limitations

4.1 SUPERFICIAL COVER

Lineament analysis using DEMs is most effective where the bedrock is exposed at the surface or where the topography is not heavily eroded (Figure 9). It is challenging to identify lineaments, particularly tectonic lineaments, within basins or in areas of thick superficial cover. For the UK, this will mean that in certain areas of the country, such as the London Basin, few lineaments will be apparent, and the density and length of any lineaments defined is unlikely to reflect the true structural complexity of the region.

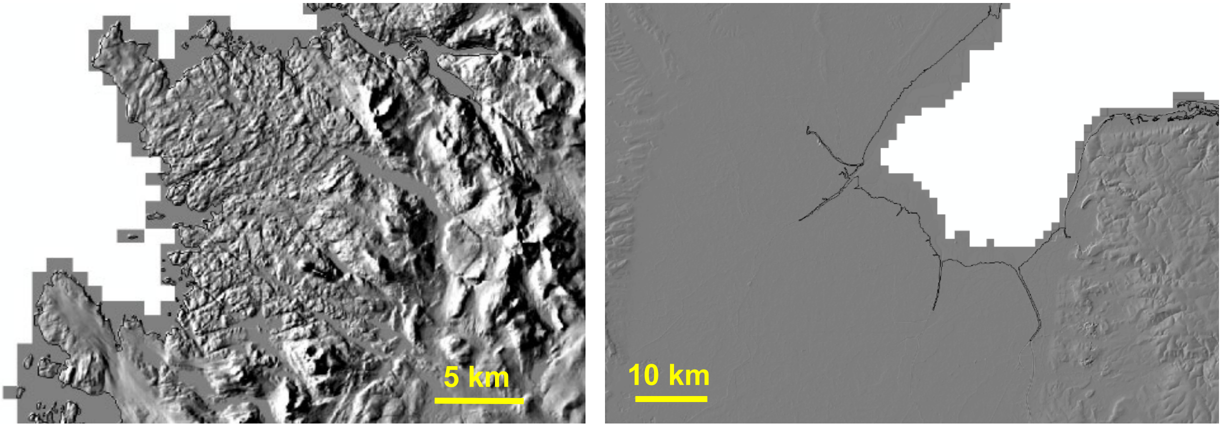


Figure 7; Left – highly lineated topography of the Assynt Terrain, NW Scotland, where bedrock is exposed or very close to the surface. Right – flat-lying terrane around the Wash on the East Coast of England where bedrock is obscured by superficial cover. (*Derived in part from DTM of Great Britain at 5m resolution © Bluesky International Limited; Contains OS data © Crown copyright and database rights 2023*).

4.2 CURVED LINEAMENTS

Not all lineaments are straight, many are curved or have steps. Whilst these lineaments are not challenging to define and can be easily observed, methods of analysing defined lineaments require these to be either a straight line defined by two end-points or to be a mid-point with the length and azimuth of the line defined. Therefore, the best way to accommodate curved or stepped lineaments within a lineament analysis is to define them as a series of shorter straight lineaments (Figure 10). This allows the local azimuth to be accurately analysed, but creates problems when analysing lineament length and could underestimate the significance of curved lineaments.

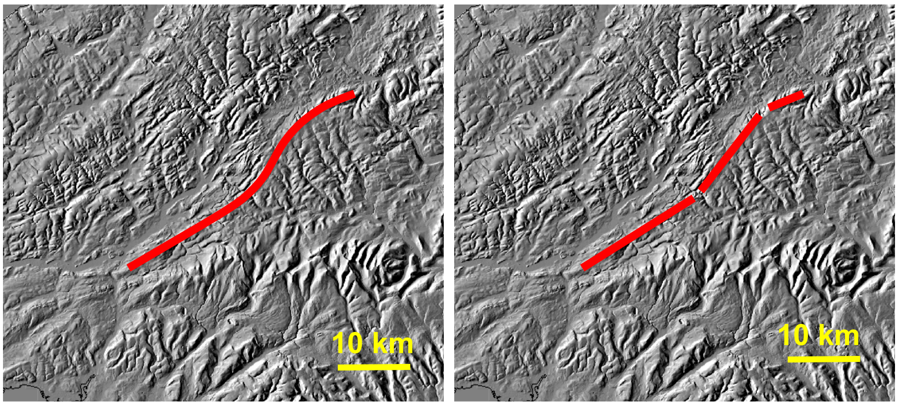


Figure 8; Left – curved lineament as it would ideally be digitised. Right – curved lineament digitised as three straight lineament segments. (*Derived in part from DTM of Great Britain at 5m resolution © Bluesky International Limited*).

4.3 SCALE

Lineaments can be digitised at any scale and increasing the zoom will increase the number of identifiable lineaments. Thus, in order to produce a consistent dataset, it is important to think carefully about the scale at which lineaments will be defined. In some studies, a scale for digitising lineaments will be needed, while in others digitising at a range of scales may be more suitable.

The aim of this study is to produce a national dataset, which will condition the definition of lineaments. The scale which needed to be applied consistently over the entire country be time-effective. As such, two scales were trialled: 1:250,000 and 1:500,000. Working at these scales enabled the definition of regionally significant lineament populations, whilst not being too time-consuming. It also enabled to the use of this trial to analyse the differences in lineament capture between to two scales and provide a recommendation going forward for lineament studies at a national scale.

It is important also to consider the resolution of the DEM and the scale at which lineaments will be defined. Using a 1 or 2 m resolution DEM to work at this scale would be too detailed, so a lower resolution DEM should be selected, or the DEM should be resampled.

4.4 NON-TECTONIC LINEAMENTS

Finally, as mentioned above, not all lineaments are tectonically induced. Contrasting erosive strengths of adjoining rock types can produce breaks in slope, ridges and valleys which may be linear. Human activities and infrastructure can produce artificial topography with linear breaks, such as embankments, roads and railway lines, and geomorphological process can produce linear features in the landscape. Whilst there is an argument about whether linear valleys should be defined as lineaments, other linear features, usually related to glacial processes, are typically unrelated to weaknesses in the bedrock. These include drumlins, eskers and striations. Two approaches can be taken to dealing with these lineaments; a decision can be taken not to define them or they can be defined and later filtered out. This study favoured the latter approach as these lineament populations are of interest to inform about more recent geological history.

5 Results

The trial area was analysed manually for lineaments at 1:250,000 scale and at 1:500,000 scale. 1291 lineaments were digitised at 1:250,000 scale and 374 lineaments were digitised at 1:500,000 scale. This significant difference shows that the larger the scale, the more lineaments defined. Comparisons of the lineaments digitised at 1:250,000 scale against those digitised at 1:500,00 scale reveal that there are few areas where lineaments were identified at the larger scale and not the smaller (Figure 11). This comparison illustrates that the larger digitisation scale allows for more detail to be visible in the DEMs, therefore resulting in higher numbers of lineaments digitised across the whole area. This is an important observation and suggests there may be a scale-relationship, with increasingly larger scales allowing digitisation of a larger number of lineaments. Therefore, lineament analysis at different scales may assist in understanding how to represent faults at different scales of map or model production. It also further highlights the need to suit the scale of lineament definition to the needs of the study. As this is a trial area for a method which may be applied nationally, it was decided that a smaller scale than 1:250,000 would be impractical.

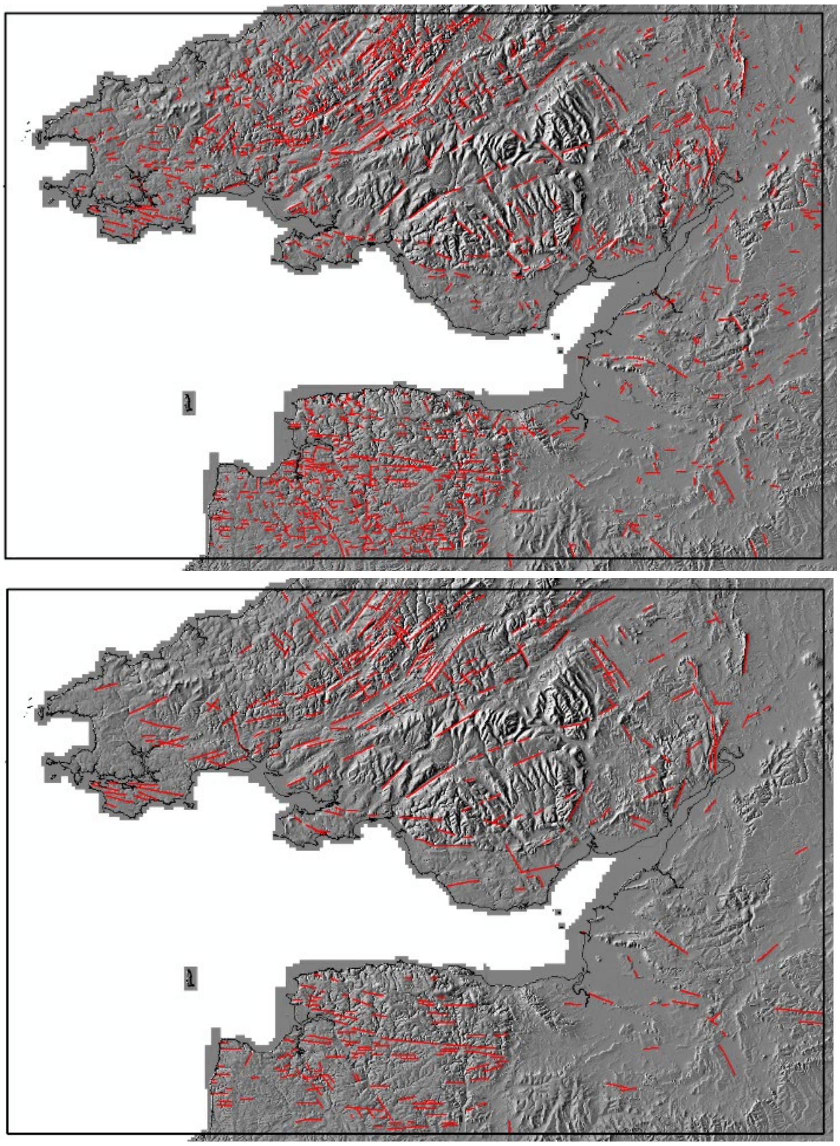


Figure 9; Top – Lineaments digitised at 1:250,000 scale. Bottom – Lineaments digitised at 1:500,000 scale. (*Derived in part from DTM of Great Britain at 5m resolution © Bluesky International Limited*; *Contains OS data © Crown copyright and database rights 2023*).

Rose plots created for both the 1:250,00 and 1:500,000 scale lineaments represent the azimuths of all the lineaments digitised at each scale and plot the orientation of the lineaments against the number of lineaments in each orientation. This highlights trends in the azimuth of the lineaments, without any skew or bias for the relative lengths of the lineaments. The most significant lineament population trends east – west, with azimuths ranging between 90° and 95° (Figure 12). Two other significant lineament populations trend southwest – northeast and northwest – southeast. The NW–SE trending populations is better defined than the SW–NE trending population and has a much narrower azimuth range, between 310° and 340°. The SW–NE trending population ranges in azimuth between 35° and 75°. At 1:500,000 scale this population includes another minor lineament population trending 35° to 45°. The 30° spread of the NW–SE lineament population is also likely to be caused by one or more minor populations. This suggests that, despite the difference in the number of lineaments digitised between the two scales trialled, the rose plots show that the same three dominant populations of lineament orientation are apparent at both scales.

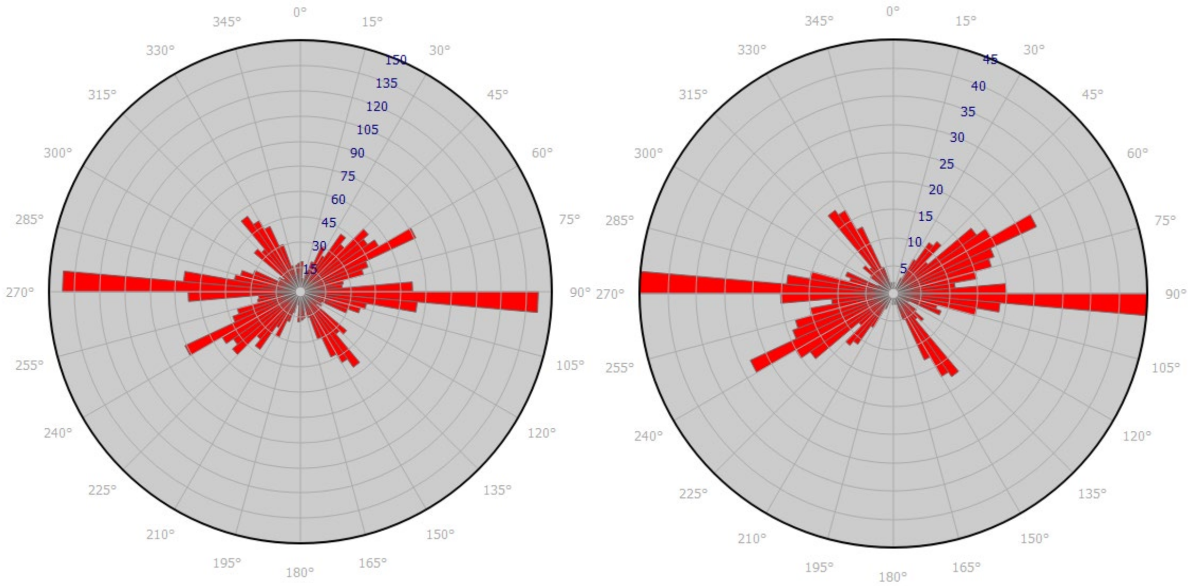


Figure 10; Left – Rose diagram showing the orientation of the lineaments digitised at 1:250k scale. Right – Rose diagram showing the orientation of lineaments digitised at 1:500k scale.

The gridded rose plots enable a more localised comparison between the two scales of lineament picks. On the whole the gridded rose plots show significant similarity between the 1:250,000 and 1:500,000 scale lineament picks (Figure 13). These similarities are particularly strong in the south of the area, within North Devon, and in the centre-north of the area, around Llandovery. These areas are slightly elevated, but are not as high as the South Wales coalfield area, and display a topography incised by rivers and streams, which has not been heavily overprinted by glaciers during the Holocene. In the south Wales coal fields, the main approximately WSW-ENE trend can be seen in the lineament azimuths at both scales however. At the 1:500,000 scale the secondary NW-SE trend which can be seen in the 1:250,000 scale lineaments is either absent, or significantly reduced. This is possibly due to the higher topography of the coalfield areas which would have led to localised, more upland style glaciation during the Holocene, creating a landscaped shaped more by glacial erosion. There are also significant differences in the lineament populations identified at each scale in the north-west of the area, around Lampeter. The lineaments digitised here, are mostly short and therefore have were more obvious at a larger scale. Across the whole trial area shorted lineaments are identified more at 1:250,000 scale than 1:500,000 scale.

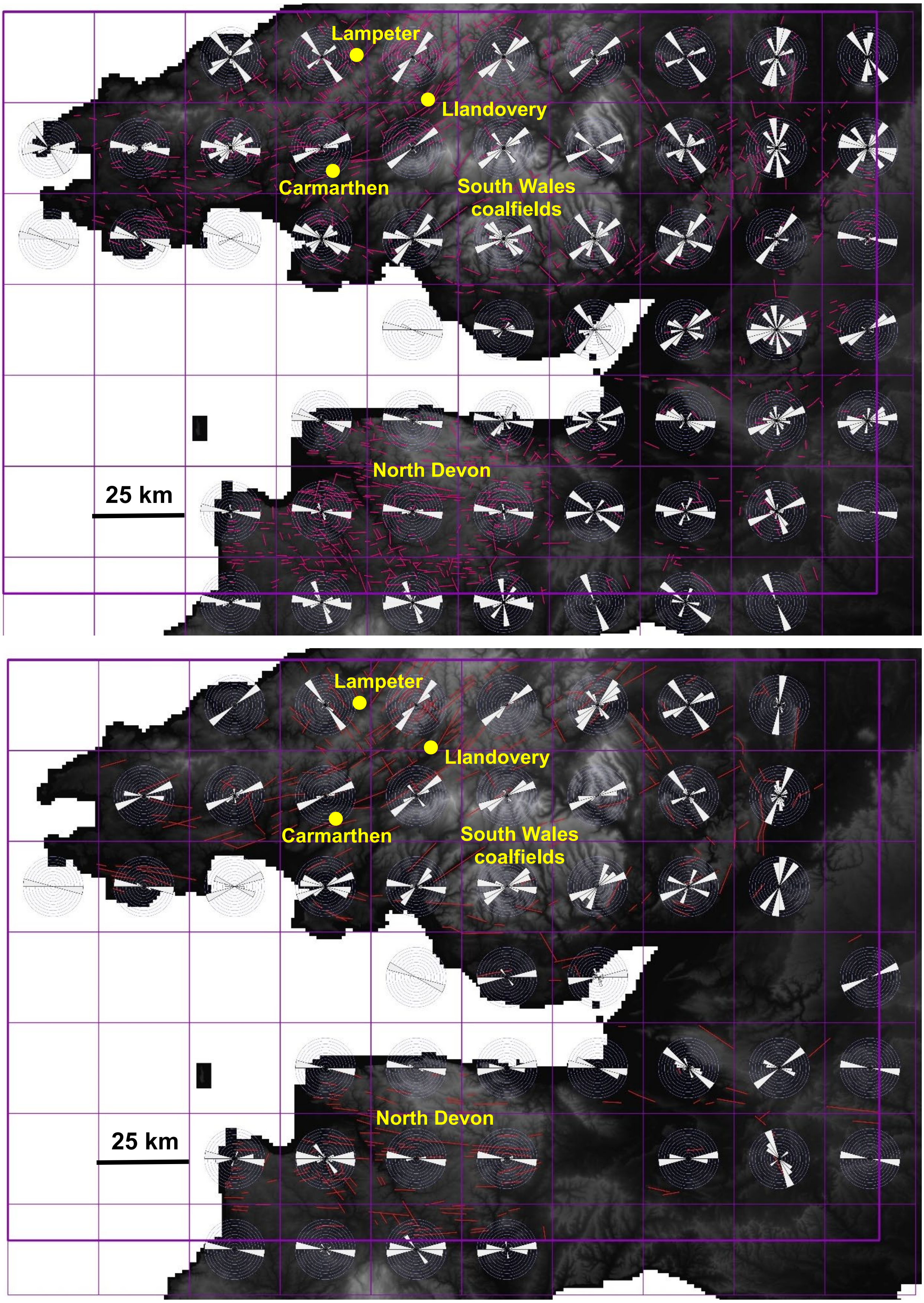


Figure 11; Top – 25 km gridded rose plots of the lineaments digitised at 1:250k scale. Bottom – 25 km gridded rose plots of the lineaments digitised at 1:500k scale. (*Derived in part from DTM of Great Britain at 5m resolution © Bluesky International Limited*; *Contains OS data © Crown copyright and database rights 2023*).

The lineaments defined can be compared to the existing BGS fault datasets. These are available at 1:50,000, 1:250,000 and 1:625,000 scales. The 1:250,000 dataset is recognised to be incomplete so this study has excluded this dataset and has compared the digitised lineaments against the 1:50,000 and 1:625000 fault datasets (Figure 14).

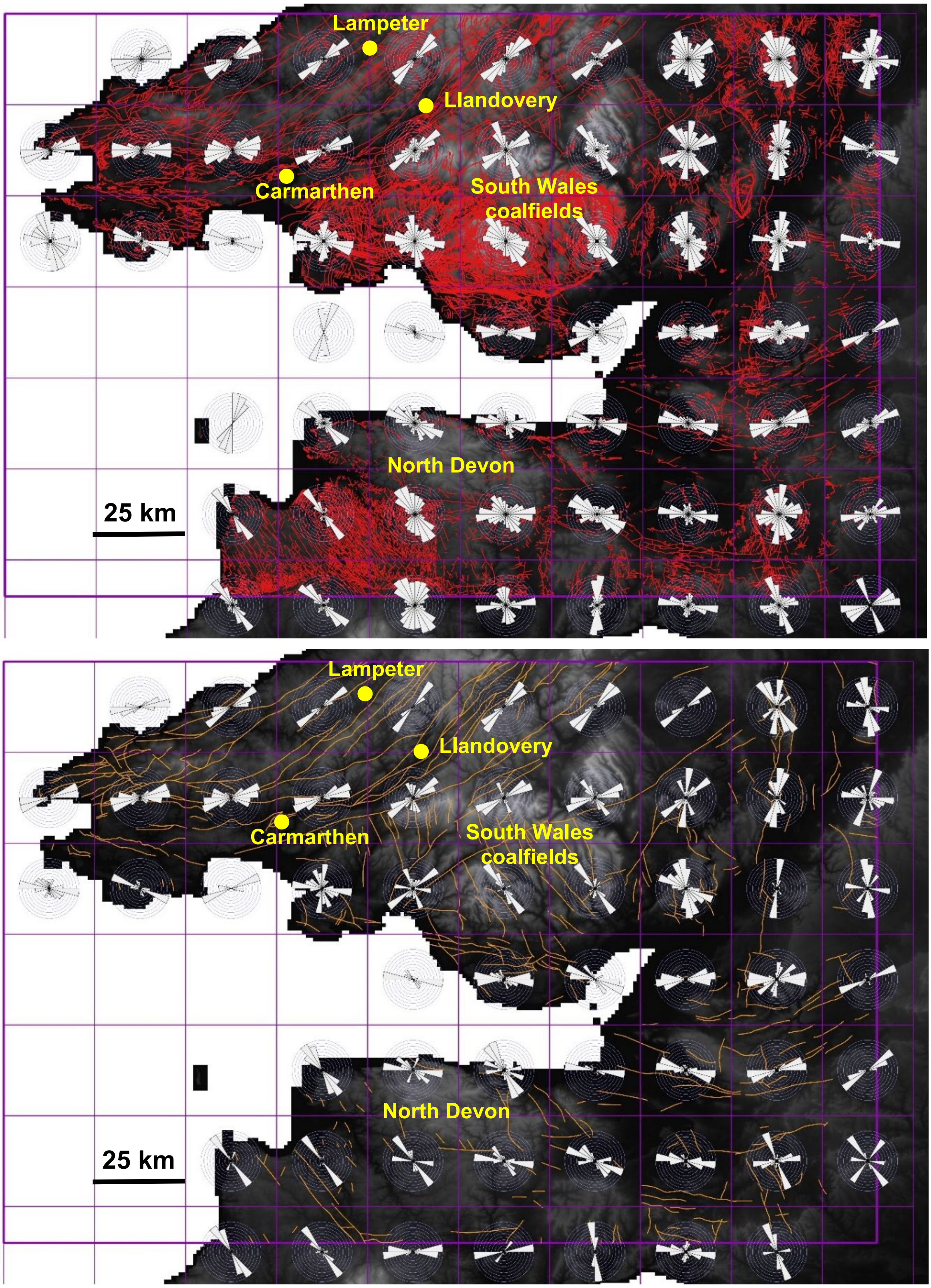


Figure 12; Top – 25 km gridded rose plots of the 1:50k BGS faults. Bottom – 25 km gridded rose plots of the 1:625k BGS faults. (*Derived in part from DTM of Great Britain at 5m resolution © Bluesky International Limited; Contains OS data © Crown copyright and database rights 2023*).

There are a few notable differences between the defined lineaments and both the 1:50,000 and 1:625,000 fault datasets. The digitised lineaments tend to be consistently shorter in length than the mapped faults. This is not unexpected as lineaments are only digitised where there is topographic evidence, whereas other observations and geological interpretation will have been used to join up sections of observed faulting into longer, continuous faults. This will particularly be the case in the 1:625,000 fault dataset, where the faults have been generalised from the 1:50,000 data to be more suitable for viewing at a smaller scale. A connectivity analysis on the lineament data could address this issue and make the lineament data more comparable with the fault data over greater distances.

In many parts of the trial area, lineament digitisation has identified significantly fewer lineaments than mapped faults in the 1:50,000 fault dataset. There are a number of reasons for this. It is likely that only the more significant faults with larger offsets will maintain a topographic expression in the landscape once they are no longer active. The digitised lineaments and mapped faults clearly display similar orientations across the trial area, suggesting that the digitised lineament populations are reflecting the trends of the mapped faults.

There are a few areas where the digitised lineaments are inconsistent with the mapped faults at both 1:50,000 and 1:625,000 scale. In the northwest of the trial area, the faults in both the 1:50,000 and 1:625,000 scale datasets trend NW-SW. Whilst there are a number of lineaments digitised in this orientation in the area, there is also a significant population of lineaments which trend northwest – southeast. This trend is absent in the mapped faults in the area and is orientated orthogonal to the mapped faults.

In the Southern Welsh Coal Field there are noticeable differences between the digitised lineaments and the mapped faults. A number of faults trend NW-SE on both the 1:50,000 and 1:625,000 scale mapping. However, these are not reflected in the digitised lineaments, probably because the faults run down wide valleys. This highlights one of the issues with lineament analysis, the relationship between valley location and faults. Faults are normally zones of weakness and thus river valleys often preferentially form along them, as the rock that is gouged, brecciated or fractured is more easily erodible than the surrounding rock. Lineaments are often digitised along straight narrow valleys, but are not commonly digitised along wide valleys, such as those in the south Wales Coal Field area, as they do not form such sharp inflections in the topography. In this region, this is likely because the valleys were widened during glaciation in the Holocene.

Lineament analysis in the north Devon area has identified a much higher density of lineaments compared to faults in the 1:625,000 scale dataset, and highlights significant inconsistencies in the 1:50,000 scale fault dataset. The lineament analysis has identified two key populations of lineaments in this area which trend E–W and NNW–SSE and are present throughout the broad north Devon area. In the 1:625,000 scale fault dataset there few faults within this area, although those present do reflect the same broad trends as the digitised lineaments. Comparison of the digitised lineaments with the 1:50,000 scale faults is challenging. A look at the 1:50,000 scale fault dataset shows that there are inconsistencies within the dataset. In some parts of North Devon, the density of mapped faults is very high and in some places, they are almost entirely absent, with faults frequently stopping abruptly at sheet boundaries. This is so obvious that the extent of some map sheets can be seen from just the fault dataset. In areas where the 1:50,000 scale mapped faults are abundant, two dominant trends are observed; a NNW–SSE trend and a SW–NE trend. The NNW–SSE trend is clearly visible in the digitised lineaments however, the SW-NE trend forms only a minor sub-trend in the digitised lineaments. Interestingly the E–W trend, which is strong in the lineaments, is almost entirely absent in the 1:50,000 scale fault dataset. These discrepancies highlight the need for revision of the mapped fault dataset in this region, something which the lineament analysis can help inform.

Defining sets of lineaments (based on 15° bins) highlights the dominant trends across the trial area and enables the visualisation of the extent of the certain lineament trend (Figure 15). This further allows interpretation of the events which the lineament populations may be attributed to.

At both 1:250,000 and 1:500,000 scales a clear SW–NE trend is dominant across central southern Wales, north and west of the coal fields. This trend is occasionally visible in the east of

Bristol, in the east of the trial area. However, along the south coast of Wales and in north Devon a clear WNW–ESE trend is visible. Across the whole trial area, a third NW-SE trend is visible cross-cutting both the previously mentioned lineament populations. This trend is prevalent in both the north Devon region and across South Wales, although it is better picked out in the 1:250,000 lineaments.

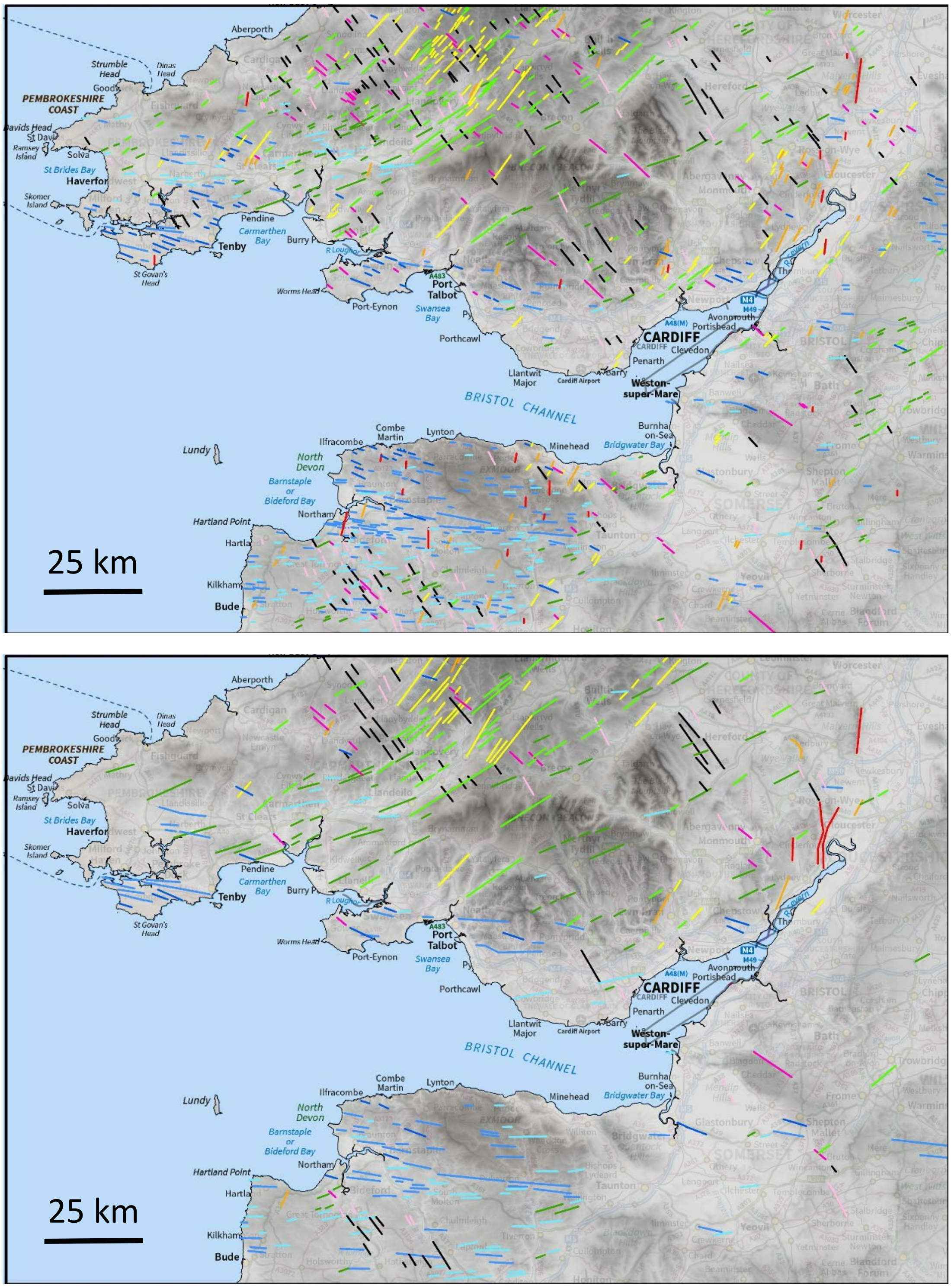


Figure 13; Top – Lineament sets identified at 250:000 scale. Bottom – Lineament sets identified at 500:000 scale. The colours of the lineaments represent different lineament sets defined by orientation in 15° categories. (*Contains OS data © Crown copyright and database rights 2023*; *Derived in part from DTM of Great Britain at 5m resolution © Bluesky International Limited*).

These populations can also be observed in the 1:50,000 mapped faults and the 1:625,000 generalised faults (Figures 16 & 17). In both instances the SW–NE population is strong throughout central southern Wales, and is weakly picked out in the Cotswolds in the east of the Trial area. The WNW–ESE population is mapped in South Wales, and is also relatively prevalent along the east side of the River Severn and into the edge of the Cotswolds, where it is absent in the lineament data. However, it is largely absent from Devon, where it is strongest in the lineament dataset. The NW–SE trending population is strong throughout the south Wales coalfields, where it is relatively weak in the lineament data, and is dominant in Devon, where the lineament dataset suggest it is a secondary population. It is nearly entirely absent from the northeast of the trial area, where it is quite strong in the lineament dataset. A weak NNE–SSW trending fault population is visible through Bristol, the Forest of Dean, the Welsh Borders and north of the South Wales coalfield. This population is very weakly visibly in the lineament data in the Forest of Dean area, but is absent from the rest of the trial area.

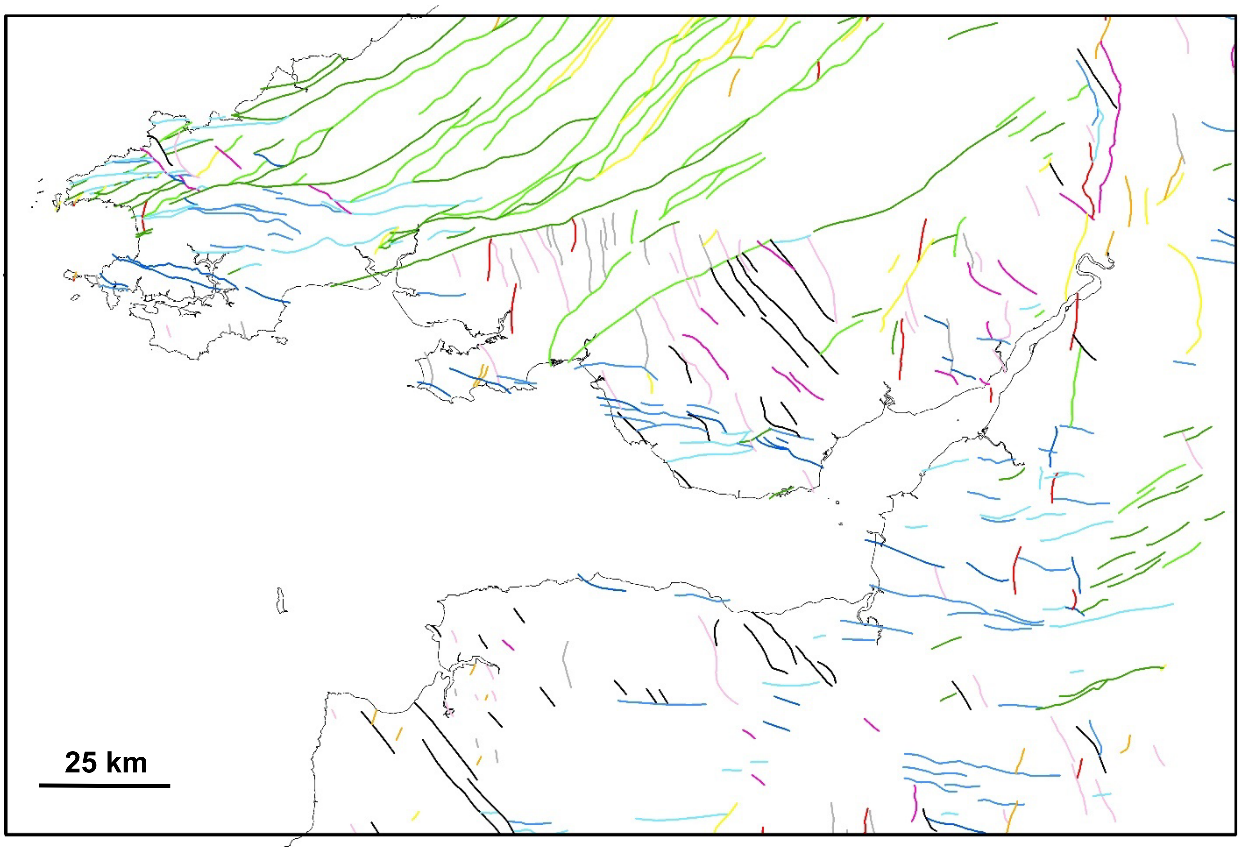


Figure 14; 625k BGS fault sets, each colour represents a 15° bin. (*Contains OS data © Crown copyright and database rights 2023*).

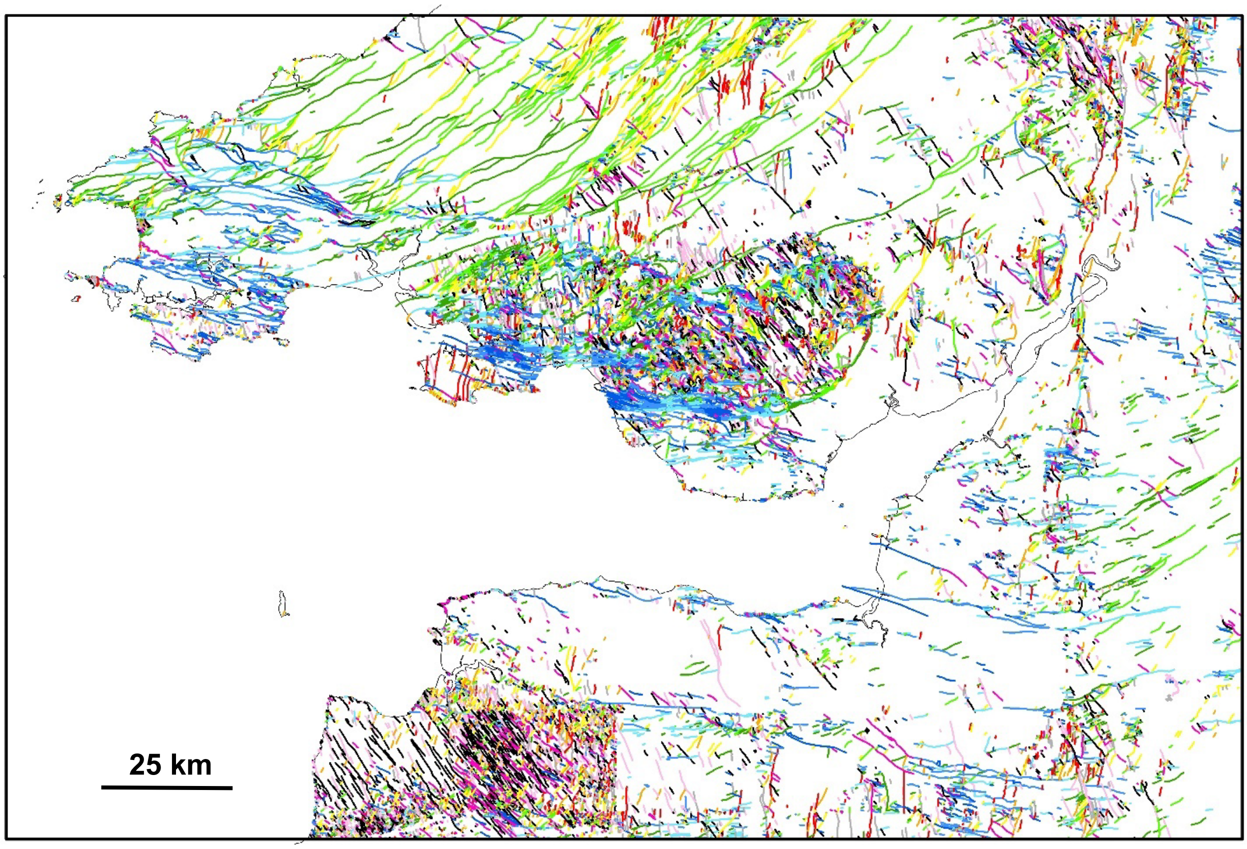


Figure 15; 50k BGS fault sets, each colour represents a 15° bin. (*Contains OS data © Crown copyright and database rights 2023*).

6 Discussion

This study was specifically undertaken in the context of assessing the BGS fault mapping for national-scale geological modelling purposes. BGS Digmap contains a UK-wide dataset of the faults mapped during the land surveying programmes. These are available at 1:10,000, 1:50,000, 1:250,000 and 1:625,000 scale and are held as cartographic lines with symbology to represent fault type. As the BGS fault dataset has been acquired over more than a hundred years and at a variety of scales, there are many inconsistencies and gaps in the data. These inconsistencies arise within map sheets, between map sheets and between scales of mapping (Figure 18). They result from a number of factors including; different mapping styles of geologists, poor edge-matching with neighbouring sheets and an inconsistent approach to digitisation of our corporate datasets. They also result from a tradition of mapping by rectangle rather than taking a broader-scale approach.

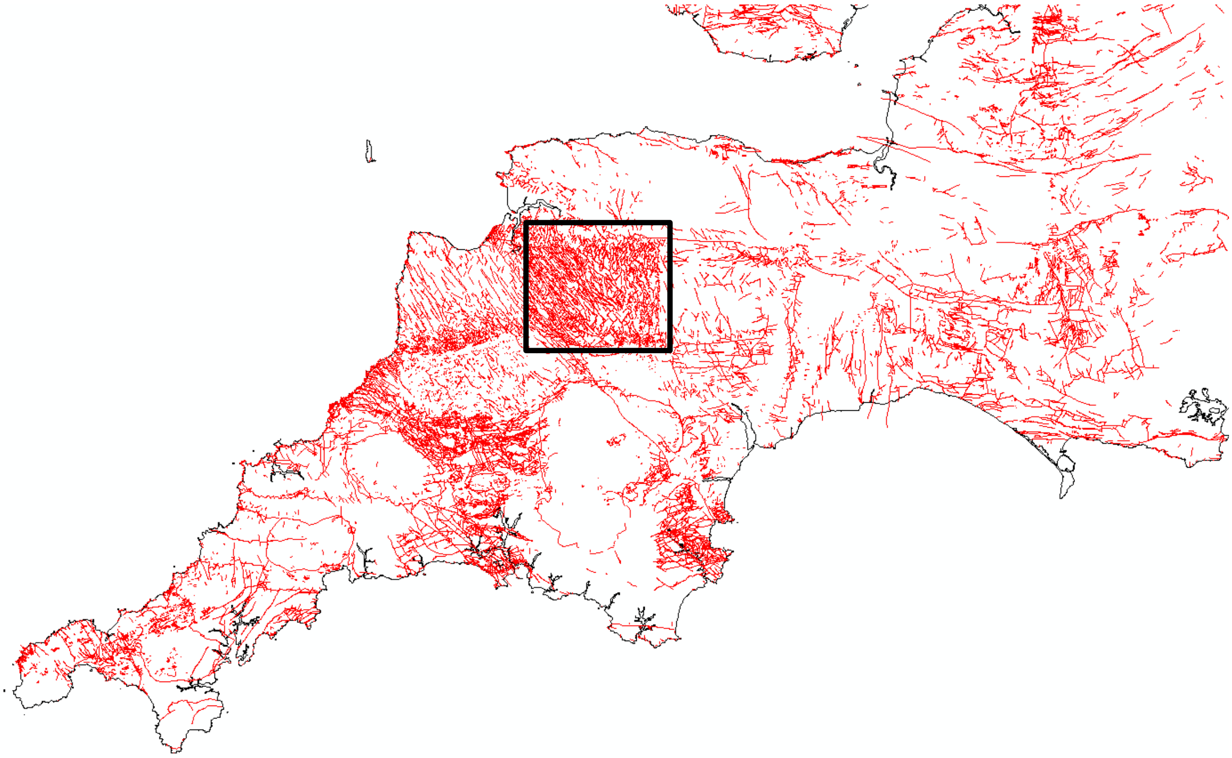


Figure 16; Inconsistencies in 50k fault mapping between map sheets in SW England. The sheet extents are often evident based on fault density, for example the Chulmleigh 50k Sheet (Sheet no. 309 in the 50k England and Wales Series) (*Contains OS data © Crown copyright and database rights 2023*).

Many map sheets have not been resurveyed since the 1950's or earlier, and many of those that have been resurveyed were done so either remotely or with minimal fieldwork. As a consequence, the geological interpretations made in many map sheets pre-date the theory of plate-tectonics and the development of modern structural geology concepts. In addition, they have been subjected to attempts to rationalise new stratigraphic units and configurations without detailed fieldwork. Recent resurveying has taken place in some areas of the UK to bring the mapping up-to-date with stratigraphic advancements. However, much of this surveying is driven by commercial contracts related to groundwater management, and are focused in defined areas, leading to further piece-meal updating which needs to be rationalised with the surrounding mapping.

One of the key issues with the fault dataset is that there is a lack of recording of the thought processes behind the data. Distinct line-styling within DigMap allows for a range of fault types and for the designation of “observed faults”, “inferred faults” and “conjectured faults” within the dataset. However, no location specific information is recorded and it is often also absent from the original fieldslips, which are available internally to BGS staff as scans. Kinematic information is even less well recorded. Ticks on fault lines within DigMap indicate the down-throw or up-throw sides of the fault, but there is no information on where or how this inference was made.

These inconsistencies and lack of detailed information make the transition from two-dimensional sheet maps to three-dimensional geological models of the sub-surface very challenging. Understanding faults and structures is the key to being able to create realistic models of the sub-surface. The improvement on the stratigraphical knowledge needs to be paired with an understanding of the structures affecting the stratigraphy. Otherwise, the models producedwill soon show themselves to be inaccurate on relatively light interrogation.

7 Future work

7.1 AUTOMATED LINEAMENT IDENTIFICATION

Automation of lineament mapping from remote sensed data has been a key research topic in structural geology for several decades (Vassilas, 2002; Yeomans et al., 2019). Manual digitisation can be viewed as time-consuming, subjective and challenging to replicate. Thus, a number of automated and semi-automated approaches have been developed and trialled since remotely sensed data became available, which aim to save time and improve objectivity.

Automated lineament detection algorithms vary in approach and have evolved over time as higher resolution remotely sensed data has become available. The earliest algorithms including the Hough Translation and the Segment Tracing Algorithm (STA), which were developed to use with Landsat TM satellite imagery (Wang & Howarth, 1990). Later algorithms employing curvature and hillshade enhancements used potential field data and remote sensing datasets including digital elevation models and magnetic surface grid and (Lee et al., 2012; Silhavy et al., 2016). Recently the LINDA software has been developed to work with spectral and potential field data, incorporating the STA algorithm (Masoud & Koike, 2017) and Yeomans et al. 2019, have developed an object-based image analysis method utilising image segmentation algorithms to group contiguous pixels.

There are still currently a number of major disadvantages to using automated methods of lineament detection. Most automated methods are very computer intensive and extremely parameter sensitive. It can take a long time to refine all the parameters to achieve a result which looks good to the human eye. Automated methods also commonly over-identify lineaments and frequently identify none geological features. Unfortunately, these disadvantages do not yet outweigh the advantages of automated methods (quick, reproducible and un-biased), hence why this trial study used the manual digitisation methodology.

As part of this study we undertook several trials of a range of automatic methods for identifying lineaments over a four-week period. At the end of this period we were still refining the automated methods and algorithms. In comparison, manual lineament identification undertaken in this study took only three days to digitise lineaments a further two days to investigate lineament analysis approaches.

7.2 LINEAMENTS IN THE DEEP SUB-SURFACE

Lineament analysis of the sub-surface is also possible using geophysical data, such as magnetic and gravity surveys. A major advantage is that it is possible to take depth-slices of the datasets and thus to analyse lineaments at different levels within the crust. Currently, the resolution of these datasets is much lower than the sub 1-meter surface datasets which are now available, but, there is still value in analysing lineaments in these datasets. It would enable the identification of deep seated regional-scale structures which will help define tectonic ‘terrains’ and key major structures. It will also help the identification of regions where the deep-seated structure is at odds with the surface structures. Using surface and sub-surface lineament datasets together would enable a better understanding and visualisation of the structure of the crust in three-dimensions.

8 Conclusions

This study finds that lineament analysis is a valuable tool which has a number of applications. It has highlighted some of the weaknesses and biases in the BGS mapped faults layer, and enabled to the review and assessment of mapped faults, as well as highlighting areas which need further geological study.

This study shows that manual lineament digitisation is a viable methodology and is valuable at a range of scales. It results in data which can be compared with existing structural datasets, e.g. faults, fractures, joints, dykes, etc. The outcomes of lineament studies can be stand-alone datasets which address a specific problem or pre-cursory datasets which guide and inform further investigations.

This study demonstrates that there are a number of analyses which can be applied to lineament datasets to establish and compare lineament trends, populations, length, connectivity and spatial extent. The lineament populations, established from the analyses, enable regional comparisons in dominant and sub-dominant linear trends which can be utilised to assess the extent of deformation associated with known tectonic events.

To scale this trial study up to a national-scale lineaments study, digitisation of lineaments at 1:250,000 km scale is recommended. This produces a higher level of detail whilst not being much more time-intensive than working digitising at 1:500,000 km scale.

The methodologies developed in this study can be applied to site-specific, local, regional, national or even global scales. They can also be applied to sub-surface lineament analysis using geophysical data, such as magnetic or gravity surveys, which can provide depth-slices through the crust and thus enable studies into structures at different depths within the crust.

Over the last decade there has been significant research into automated lineament analysis and many of the techniques investigated show promise, but require more work before they can be reliably deployed.

Lineament analysis has implications not just for assessing, extending or revising mapped faults, but can also be applied to aid understanding of the physical properties, strength and permeability of rock mass in the sub-surface. This is vital for identifying locations for new energy technologies, siting infrastructure projects, modelling groundwater systems and predicting coastal retreat.

Finally, this study highlights the inconsistencies and lack of detailed information within the BGS mapped fault datasets, which challenges the process of going from two-dimensional maps to three-dimensional geological models of the subsurface. However, stratigraphical knowledge, needs to be accompanied by knowledge and understanding of fault, fracture and joint networks to deliver high-resolution sub-surface models to address multiple challenges. Lineament analysis is a tool which can be deployed to start addressing some of these issues.

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The British Geological Survey Library holds most of the references listed below and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at https://of-ukrinerc.olib.oclc.org/folio/. Full guidelines for reference lists are available in *Notes for Authors* (BGS house style guide).

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