

Introduction

Lineament detection is an important tool for evaluating the structural geology of a region. Airborne geophysical data, most commonly magnetic data, are often used for interpreting major regional structures. The SW England region is a world-class tin orefield but the current state of regional lineament mapping is inconsistent. Whilst recent geological mapping in the region is of high quality, the coverage is incomplete and newly mapped districts are interspersed with the previous generation of geological mapping. The purpose of this contribution is to demonstrate how the regional structural geology can be mapped using semi-automated lineament detection techniques to produce a consistent lineament network from airborne geophysical data.

Previous lineament detection studies have used Landsat TM data. Small-scale lineament detection for mineral exploration was conducted by Moore & Camm (1982) and James & Moore (1985). A manual regional lineament analysis was conducted by Rogers (1997). The study used multiple Landsat TM scenes which had variable image quality. Furthermore, the data were coarsened to 150 m pixels to remove anthropogenic noise. The criteria for identifying lineaments required that a lineament be longer than 4 pixels, therefore, all lineaments <600 m were rejected.

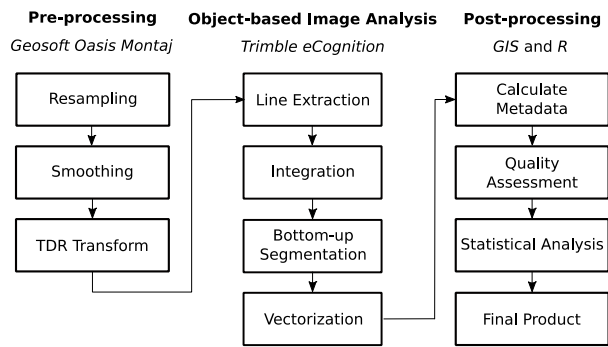
Semi-automated algorithms for lineament detection are common such as STA (Koike et al., 1995), TecLines (Rahnama and Gloaguen, 2014a, 2014b) and LINDA (Masoud and Koike, 2017). Object-based Image Analysis (OBIA) has been applied for lineament detection using satellite imagery (Mavrantza and Argialas, 2006), SAR (Marpu et al., 2008) and airborne LiDAR (Rutzinger et al., 2007). Sukumar et al. (2014) acknowledge that object-based approaches and linear filtering guarantee a high degree of accuracy.

Middleton et al. (2015) first demonstrated the use of OBIA for lineament detection using airborne magnetic data. The method was developed using eCognition software (v.9.3, Trimble, Germany) and used OBIA algorithms. The segmentation step creates image objects which provide a powerful link between the pixel-based information within an object and the geometric characteristics of the vector defining the object. Furthermore, all image objects are related through a topology which can compare objects across the dataset.

Herein, a complementary approach to the OBIA methods of Middleton et al. (2015) is presented. The approach uses a bottom-up OBIA methodology whereby the amount of user information required is minimal. Bottom-up OBIA methods segment the image into many small image objects which are then merged into larger objects. The method is computationally efficient and allows for integration of multiple datasets prior to segmentation and requires minimal user input. The method is tested over the SW England region covered by the Tellus South West project which collected high resolution airborne geophysical data including magnetic, radiometric and LiDAR datasets. SW England is an excellent test area with a complex structural geology that pervades the region with two dominant fault orientations of approximately E-W and NW-SE (Shail and Alexander, 1997). The result is a consistent regional lineament network that captures the known structural trends derived from field-based studies. The newly-derived data provide a new baseline dataset that can be used for future exploration for tin-tungsten, base metal and geothermal deposits.

OBIA Methods for Lineament Detection

The use of a bottom-up OBIA methodology is advantageous as it allows efficient integration of multiple datasets to create a composite lineament network. The workflow Figure 1 conducts pre-processing in the Oasis Montaj software package (Geosoft, Canada) and the R project software (<https://cran.r-project.org>), specifically the *raster* package (Hijmans et al., 2017). The main processing steps for OBIA operations are conducted in eCognition (Trimble, Germany) using the Cognitive Network Language (CNL). Final post-processing makes use of GIS software and R for metadata manipulation and quality assessment of the resulting lineament network.



The input datasets to the method are the Reduced-to-Pole Total Magnetic Intensity (RTP-TMI) magnetic data, Digital Terrain Model (DTM) derived from LiDAR data and the Total Count (TC) channel from the radiometric data.

Figure 1 (left) Flowchart illustrating the workflow for a bottom-up Object-based Image Analysis methodology.

Pre-processing

The data are pre-processed to the same extent and resolution (40 m pixels) using a bidirectional operator before being clipped to the coast. Note that the initial airborne magnetic and radiometric data have a rectangular inset of missing data due to flight restrictions over a naval base at Plymouth. The LiDAR data includes data in this area which was not removed as the method does not require complete data coincidence. Pre-processing steps in Oasis Montaj used an upward continuation filter and 9 x 9 convolution filter on the magnetic data to minimise cultural noise and artefacts from N-S oriented flight lines. The radiometric data and LiDAR data were also smoothed using a 9 x 9 convolution filter. The smoothing particularly improved areas in the LiDAR Digital Terrain Model (DTM) where thick vegetation and dense urban areas were poorly removed, and road cuttings were also smoothed out. The final pre-processing step applied the Tilt-Derivative (TDR) transform to all three datasets. The TDR transform is useful as it normalises the magnetic field image and discriminates between signal and noise, whilst also normalising the data range to -1.57 to +1.57 and acting as an automatic gain control (Verduzco et al., 2004). The resultant TDR-filtered data are taken forward into eCognition for lineament detection using OBIA methods.

Bottom-up OBIA methods

The initial operation using in the CNL within eCognition is to use the line extraction algorithm to identify linear features. The algorithm targets the minima in the TDR-filtered data to identify lineaments rather than the 0 contour which would identify the edge of bodies. The minima are used on the assumption that fault expressions in SW England are less magnetic, have a negative geomorphological profile and have leached radiogenic elements such as potassium and uranium for the magnetic, LiDAR and radiometric data, respectively. The line extraction algorithm derived a new raster layer defining the 'lineness' in a 0-255 range. The lineness raster is a measure of the likelihood a lineament exists and its significance. Once a lineness raster has been derived for each dataset these are integrated through a summation and normalisation back to a 0-255 range.

The integrated lineness raster is the single input into the segmentation step. The lineness raster is segmented using the multiresolution segmentation algorithm to create image objects across the whole image. These image objects are then merged using the spectral difference algorithm. A classification step is added to define 'major' and 'minor' objects based on a user-defined threshold. The image objects are then refined based on the relative border with objects of the opposite class. The border assessment reclassifies minor objects to major objects where the majority of the border is in contact with a major object. Major objects are then converted to minor objects where a *significant* majority of the border is shared with a minor object. A cleaning step removes anomalous image objects prior to vectorization.

Post-processing

The output polyline file contains metadata on the class of lineament; either major or minor. It is necessary to calculate the polyline length and orientation which is completed in a combination of GIS

software and *R*. Quality assessment of the data is then undertaken in a GIS where spurious polylines can be identified and removed. The data are also compared to the original input datasets at this stage.

Results over SW England

The lineament network produced from the bottom-up OBIA methodology is presented in Figure 2. The overall network reflects the two dominant structural trends as evidenced by the rose diagram Figure 2B. The data are classified by the major and minor divisions defined during OBIA processing. The distinction appears to be intuitive based on visual assessment.

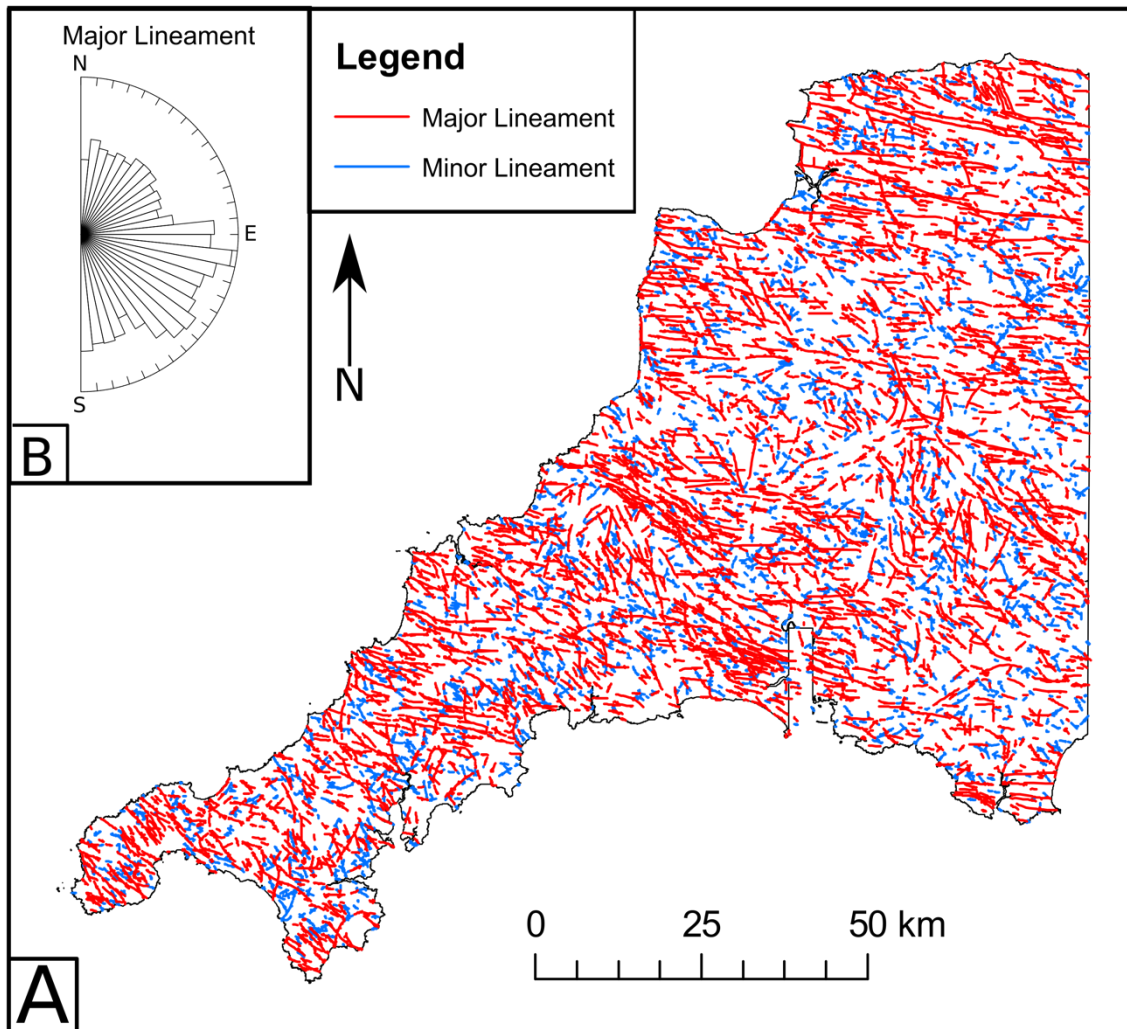


Figure 2 Results of bottom-up Object-based Image Analysis over SW England. (A) Illustrates the distribution of major and minor lineaments detected and classified in the analysis. (B) Demonstrates that the known structural trends in the region are captured.

Conclusions

The bottom-up OBIA methodology presented here provides a new semi-automated lineament detection method that efficiently integrates multiple datasets and requires minimal user input. The OBIA algorithms within the CNL provide a robust workflow for identifying lineaments and ensure consistency across a large dataset through the use of topological relationships. The classification of major and minor objects that carries through to the final lineament network is effective for visualisation and, whilst not geologically selective, can provide a useful parameter for mineral exploration.

Acknowledgements

CMY would like to thank Jim White (BGS) for his assistance and guidance in pre-processing the magnetic data. CMY would like to thank Eija Hyvönen (GTK) for her advice on geophysical processing and use of computer facilities during his time in Rovaniemi. CMY would like to acknowledge the British Geological Survey and the GW4+ NERC DTP for co-funding his doctoral research.

References

- Hijmans, R.J., van Etten, J., Cheng, J., Mattiuzzi, M., Sumner, M., Greenberg, J.A., Perpinan Lamigueiro, O., Bevan, A., Racine, E.B., Shortridge, A. and Ghosh, A., [2017] Raster: geographic analysis and modeling with raster data. R package, version 2.6-7.
- James, J.M. and Moore, J.M., [1985]. Multi-seasonal imagery studies for geological mapping and prospecting in cultivated terrain of S.W. England, in: Fourth Thematic Conference: “Remote Sensing for Exploration Geology”, San Francisco, California, April 1-4, 1985. April 1 - 4, 1985. San Francisco, California, pp. 475–484.
- Koike, K., Nagano, S. and Ohmi, M., [1995] Lineament analysis of satellite images using a Segment Tracing Algorithm (STA). *Computers & Geosciences*, **21**, 1091–1104.
- Marpu, P.R., Niemeyer, I., Nussbaum, S. and Gloaguen, R., [2008] A procedure for automatic object-based classification, in: Blaschke, T., Lang, S. and Hay, G.J. (Eds.), *Object-Based Image Analysis. Spatial Concepts for Knowledge-Driven Remote Sensing Applications*. pp. 169–184.
- Masoud, A., Koike, K., [2017] Applicability of computer-aided comprehensive tool (LINDA: LINEament Detection and Analysis) and shaded digital elevation model for characterizing and interpreting morphotectonic features from lineaments. *Computers & Geosciences*, **106**, 89–100.
- Mavrantza, O.D. and Argialas, D.P., [2006] Object-oriented image analysis for the identification of geologic lineaments. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, **36**, 1–6.
- Middleton, M., Schnur, T., Sorjonen-ward, P. and Hyvönen, E., [2015] Geological lineament interpretation using the Object-Based Image Analysis Approach: results of semi-automated analyses versus visual interpretation. *Geological Survey of Finland, Special Paper*, **57**, 135–154.
- Moore, J.M. and Camm, S., [1982] Interactive enhancement of Landsat Imagery for structural mapping in tin-tungsten prospecting: a case history of the S.W. England Orefield (U.K.), in: *International Symposium on Remote Sensing of Environment, Second Thematic Conference, Remote Sensing for Exploration Geology*. Fort Worth, Texas, December 6 - 10, 1982, pp. 727–740.
- Rahnama, M. and Gloaguen, R., [2014a] TecLines: A MATLAB-based toolbox for tectonic lineament analysis from satellite images and DEMs, Part 1: Line Segment Detection and Extraction. *Remote Sensing*, **6**, 5938–5958.
- Rahnama, M. and Gloaguen, R., [2014b] TecLines: A MATLAB-based toolbox for tectonic lineament analysis from satellite images and DEMs, Part 2: Line Segments Linking and Merging. *Remote Sensing*, **6**, 11468–11493.
- Rogers, J.D., [1997] The interpretation and characterisation of lineaments identified from Landsat TM imagery of SW England. Unpublished PhD Thesis, Department of Geological Sciences, University of Plymouth.
- Rutzinger, M., Maukisch, M. and Petrini-monteferrri, F., [2007] Development of Algorithms for the Extraction of Linear Patterns (Lineaments) from Airborne Laser Scanning Data. *Proceedings of the Conference 'Geomorphology for the Future'*, Obergurgl, 2007, 1–8.
- Shail, R.K. and Alexander, A.C., [1997] Late Carboniferous to Triassic reactivation of Variscan basement in the western English Channel: evidence from onshore exposures in south Cornwall. *Journal of the Geological Society, London*, **154**, 163–168.
- Sukumar, M., Venkatesan, N. and Babu, C.N.K., [2014] A review of various lineament detection techniques for high resolution satellite images. *International Journal of Advanced Research in Computer Science and Software Engineering*, **4**, 72–78.
- Verduzco, B., Fairhead, D., Green, C.M. and MacKenzie, C., [2004] New insights into magnetic derivatives for structural mapping. *The Meter Reader*, 116–119.