Automated Identification of Porphyry Systems

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SUMMARY
Porphyry-style mineralisation often appears as near circular anomalies within magnetic data. This article presents an automatic grid analysis system to detect such responses. Our approach follows three steps: (1) Find circular features using the radial symmetry transform; (2) Validate the detected features by the presence of high magnetic contrast at the feature location; and (3) Highlight the alteration zone boundary using deformable splines. The outcome of this system is two-fold. First, provide estimates of the location of potential porphyry systems, and second, accentuate the appearance of potential exploration targets to aid manual data inspection.

Experiments were conducted on survey data from Reko Diq, Pakistan, a region known to contain numerous occurrences of porphyry-style mineralisation. The prediction results of our system closely matched the location of the known deposits in this region thus rendering confidence in the effectiveness of our approach. It is suggested that this system be used as an initial screening tool for large datasets, therefore reducing the time and cost imposed by manual data inspection in the exploration targeting process.

Key words: porphyry systems, magnetic survey, image processing, radial symmetry.

INTRODUCTION
Utilisation of aeromagnetic data is standard practice during mineral exploration, with such data approaching the importance of seismic data in petroleum exploration. Aeromagnetic data are comparatively cheap, and significantly so when compared with gravity and electromagnetic surveys. This has allowed many national and local governments to acquire, and make available at nominal cost, extensive reconnaissance-style datasets as a means of promoting exploration within their jurisdictions. Mining and exploration companies routinely supplement these data with higher resolution datasets acquired within the areas they are exploring. The result of these activities is an ever increasing volume of data and an emerging need to develop methodologies to automatically analyse the data with the intention of identifying areas of exploration significance for further manual analysis.

Aeromagnetic data map variations in rock magnetism in the upper part of the Earth’s crust. The principal source of rock magnetism is the iron oxide magnetite, with the iron sulphide pyrrhotite important in some geological environments. Spatial variations in total magnetic intensity, and products derived from transformations of this primary source, are presented in raster form and hence are suitable for image processing and analysis methods.

Currently the normal approach to the interpretation of magnetic data is manual. When exploring, a magnetic data interpreter may seek patterns of variation consistent with responses from mineralisation itself, alteration associated with the mineralised environment and/or some specific geological environment in which mineralisation occurs. Massive nickel sulphide mineralisation is an example of a deposit type where responses from the mineralisation itself may be detected, whilst a good example of responses from a particular geological setting is magnetic responses from potentially diamondiferous kimberlites. Perhaps the best examples of responses associated with alteration are those from porphyry-style mineralisation where extensive areas of hydrothermal alteration usually have different magnetism to the areas of unaltered geology.

Hydrothermal alteration may be either magnetite creating or magnetite destructive, giving rise to positive or negative anomalies, respectively. In porphyry-style mineralisation the alteration comprises near-concentric alteration zones surrounding a roughly circular central intrusion. These annular magnetic responses may be positive or negative with respect to the surrounding host rock depending on whether magnetite has been destroyed or created and the magnetic properties of the unaltered geology.

Image analysis provides an objective and efficient means to automatically enhance and identify responses associated with mineralised environments within large magnetic datasets. For example, magnetic anomalies, caused by alteration, with specific shape characteristics can be sought within the data using a shape-based feature detection technique. In this article, we present an image analysis system based on circular feature detection for rapidly locating magnetic signatures typical of porphyry copper-gold systems. Our system efficiently and accurately identifies circular features with strong magnetic contrasts with their surroundings and estimates the location of the boundaries of these zones. This latter capability is useful for screening and prioritising targets in large datasets. Furthermore, this system provides visual enhancements that aid any manual inspection or searches for circular features of a specific size.
**Idealised Porphyry System Model**

According to Clark et al. (1992), the magnetic anomalies caused by copper porphyry systems have specific characteristics. A magnetic porphyry, and in the case of gold-rich copper mineralization the presence of a magnetite-bearing potassic alteration zone, typically features a circular central elevation in its magnetic profile (Figure 1). This circular elevation is further surrounded by a magnetic trough characteristic of propylitic and phyllic alteration zones, and further surrounded by the incoherent magnetic noise frequently attributed to volcanic host rocks.

![Figure 1: Magnetic anomaly model of a copper porphyry system (Clark et al. 1992)](image)

We adopted the magnetic response model provided by Clark et al. (1992) as the ideal response of a porphyry system. Notice the distinctive circular magnetic peak at its centre which contrasts sharply with the surrounding zones and corresponds roughly with the central intrusion. Taking this characteristic magnetic alteration pattern we search the data looking for such signatures since they are indicative of the possible occurrence of a porphyry system.

**METHODOLOGY**

With a model established, we adapted and extended two existing image processing algorithms: the radial symmetry transform (Loy & Zelinsky, 2003) and active contours (Williams & Shah, 1990), for automating the pattern search. The former algorithm measures the degree of convergence and divergence of image gradients to find elevated and depressed circular features. This transform finds the centre of elevated or depressed circular features by identifying where image gradients converge or diverge respectively. This transform performs in real-time and permits the user to provide parameters specifying the radial size, circularity, and completeness of features of interest. This transform is described below.

**Circular Feature Detection**

The radial symmetry transform is an algorithm proposed by Loy and Zelinsky (2003) that locates the centres of circular features. This transform finds the centre of elevated or depressed circular features by identifying where image gradients converge or diverge respectively. This transform performs in real-time and permits the user to provide parameters specifying the radial size, circularity, and completeness of features of interest. This transform is described below.

Given a set of radii, \( R \), corresponding to the size of features of interest, first calculate the image gradients by convolution with the Sobel operator. Then for each pixel \( p \), the local gradient is the vector \( g(p) \) consisting of a magnitude and orientation. Given these image gradients and the feature radius \( n \in R \), for each \( p \) find the positively and negatively affected pixels, namely \( p_{+ve}(p) \) and \( p_{-ve}(p) \), that are located in the same and opposite directions of the gradient \( g(p) \) at a distance \( n \), respectively. These affected locations are used to generate the orientation projection image, \( O_n \), which stores an accumulated count of the number of gradient convergences or divergences at each location; and the magnitude projection image, \( M_n \), which accumulates the gradient magnitudes converging and diverging at each location. The orientation projection image is defined as follows:

\[
O_n(p_{+ve}(p)) = O_n(p_{+ve}(p)) + 1, \quad \text{and} \quad O_n(p_{-ve}(p)) = O_n(p_{-ve}(p)) - 1.
\]

And the magnitude projection image is defined as:

\[
M_n(p_{+ve}(p)) = M_n(p_{+ve}(p)) + \|g(p)\|, \quad \text{and} \quad M_n(p_{-ve}(p)) = M_n(p_{-ve}(p)) - \|g(p)\|.
\]

where \( \|g(p)\| \) is the magnitude of the gradient.

The symmetry image \( S_n \) for a radius \( n \) is calculated as:

\[
S_n = F_n \ast \mathcal{A}_n
\]

where \( \mathcal{A}_n \) is a Gaussian smoothing filter with the size and standard deviation as function of \( n \), and \( F_n \) is the magnitude-weighted-orientation-based feature image, that is:

\[
F_n(p) = \frac{M_n(p)}{\kappa_n} \left( \frac{O_n(p)}{\kappa_n} \right)^\alpha
\]

The parameter \( \alpha \) controls the degree of radial symmetry strictness and is typically an integer between 1 and 3. The factor \( \kappa_n \) is used scale the response since as the radius \( n \) increases, the number of potential gradient vectors converging or diverging at a point also increases. Loy and Zelinsky have empirically determined \( \kappa_n \) to be typically 9.9.

The final symmetry image is calculated by summing together all the symmetry images at each radius. Non-maximal suppression and thresholding of this final transform yields the centres of circular features.

**Target Magnetic Contrast Transform**

Given a set of locations identified by the radial symmetry transform, the validity of each of these locations is confirmed by checking for strong magnetic contrast with its surroundings. We have developed a transform that measures the magnetic contrast of circular features of specific sizes, and call it the Target Magnetic Contrast Transform (TMCT).

Similar to the radial symmetry transform, the target magnetic contrast transform is based on image gradients. For each image location, \( p \), the TMCT returns the absolute difference between the magnetic readings at two points, located at distance \( r \in R \), along and opposite the direction of the gradient \( g(p) \) as shown in Figure 3.

The magnetic contrast transform targets points of strong contrast along the periphery of circular elevations or depressions. As a result, circular feature boundaries are enhanced as broad ‘halos’ for clearer identification as shown.
in Figure 4. By comparison, a simple gradient magnitude approach would only produce a very thin edge response, along with many other irrelevant local edge features. This transform is most effective when the distance, $2r$, is similar to the feature size of interest.

Figure 2: The Target Magnetic Contrast transform (TMCT) returns the range of values at a distance $2r$.

Figure 3: The TMCT of features in the top row are shown in the bottom row. Notice the haloing effect.

To facilitate the detection of a range of feature sizes it is necessary to use a range of search radii. This produces magnetic contrast transforms at many scales. From a set of transforms, a single combined transform is found by taking the maximum of the transforms found at each location. This represents the highest contrast in the region surrounding each location. Alternatively, using the mean has proved advantageous when data is noisy.

**Snake Algorithm**

Boundary detection locates the rim of high magnetic contrast surrounding each feature and provides information about the extent and geometry of the central alteration zone. Given feature locations identified and validated by the above steps, feature boundaries are traced using deformable splines commonly known as *snakes* (Williams & Shah, 1990).

A snake is a spline contour whose overall size and shape is regulated by a series of connected but moveable control points. Starting from an initial configuration of these points, the overall shape of the snake iteratively converges into its final configuration based on an energy function. This function specifies the shifting of each of the control points to locations that minimise the overall energy of the entire spline.

In our system, spline energy is a function of the target magnetic contrast and two additional constraints of elasticity and curvature. The former precludes the spline from converging into a degenerate solution, for example, a single point or an unclosed contour; and the latter prevents the formation of sharp corners. Thus the spline energy is expressed as:

$$ E = \int (\alpha E_{\text{elas}} + \beta E_{\text{curv}} + \gamma E_{\text{cont}}) \, ds $$

where $\alpha$, $\beta$, and $\gamma$ are weights that determine the relative influence of elasticity, $E_{\text{elas}}$, curvature, $E_{\text{curv}}$, and magnetic contrast, $E_{\text{cont}}$.

The elasticity term maintains equidistance between adjacent control points in the spline by minimising the average distance between points for that iteration. The curvature term controls the smoothness by examining the directions of the line segments connecting each control point. Finally, the magnetic contrast term uses the contrast strength calculated earlier to steer the snake to converge on points of greatest contrast.

In our approach, snakes are initialised as circles whose radii correspond with the radius that returned the strongest TCMT response. The snake is then allowed to evolve into its final configuration according to the above equation.

**RESULTS**

Experiments were conducted on aeromagnetic survey data from Reko Diq in Baluchistan Province, Pakistan. The geology and distribution of porphyry deposits in this region is well known (Fletcher et al., 2009) and provided a good test bed for our system. A section of the original dataset is depicted in Figure 4 where black lines mark out porphyry systems confirmed by exploratory drilling. Notice that the systems have an approximate radial size of between 100 and 500 metres.

Figure 4: Reduced-to-pole aeromagnetic data gridded at 25 metre intervals. Known porphyry systems are outlined in black (Courtesy of Barrick Gold).

The output of the radial symmetry transform is shown in Figure 5. The colourmap encodes the radial symmetry strength at each particular location. The significant peaks are selected through applying non-maximal suppression and thresholding, and denoted by the yellow markers.

Once radially symmetrical centres have been identified, confirmation of their likelihood of being anomalies of interest is achieved by screening their magnetic contrast transforms. The presence of annular ‘halos’ confirms that these points
satisfy the appearance requirements of our porphyry system model and the estimated boundary of the potassic intrusion is traced out using spline snakes as shown in Figure 6.

Figure 5: The radial symmetry transform with search radii between 100m and 500m and $\alpha = 2$. The centres of likely circular features are marked by yellow dots.

Figure 6: The estimated intrusion boundaries overlaid onto the TCMT output. $a = 1, \beta = 4$, and $\gamma = 1$.

A comparison between the predicted potassic intrusion boundaries and the known porphyry systems is shown in Figure 7. The known systems are outlined in dashed white lines and our prediction results outlined in solid black lines.

Inspection of Figure 7 shows our system possesses quite good capture efficiency with most of the known deposits being identified. However, a number of known prospects have been missed, in particular one in the lower middle of Figure 7. Closer examination reveals that this feature does not fit the circularity criterion of our search which included moderately elliptical but not linear features. Whilst the circularity constraint can be relaxed to capture linear features, this would likely return many false positives and dilute the effectiveness of our system.

CONCLUSION

We have presented an automatic image analysis method that is amenable as a tool for screening magnetic data for porphyry-indicative anomalies. It combines the use of circular feature detection based on the radial symmetry transform, the target magnetic contrast transform (TMCT), and boundary tracing using active contours. Experiments executed on datasets containing porphyry rich regions have demonstrated the high capture efficiency of this system. However, significant magnetic anomalies may be missed if they do not match our idealised porphyry model template or if the search parameters are poorly chosen. As such the false positive rate of this system remains undetermined. Further testing of this system is needed for different geological settings to evaluate its versatility and robustness.

REFERENCES


