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Application of Fractal and Multifractal Analysis to Mineralized Systems with Special Reference to the Mount Isa Inlier

Thesis submitted by

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In October, 2007

For the degree of Doctor of Philosophy

In the School of Earth and Environmental Sciences

James Cook University
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A. Ford, PhD 2007
STATEMENT OF CONTRIBUTIONS

Financial contributions towards this PhD have included:

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“IF WE KNEW WHAT WE WERE DOING, IT WOULD NOT BE CALLED RESEARCH, WOULD IT?” - EINSTEIN
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ABSTRACT

Previous studies have suggested that controls on mineralization can be inferred from fractal analysis of mineral deposit distributions. However, many of these potential controls have been suggested on a qualitative rather than a quantitative basis. Whereas fractal analysis of mineral deposit distributions simply considers the location of the deposits, multifractal analysis can examine variation in values of attributes assigned to each deposit location such as deposit size. Yet no comprehensive study of the multifractal properties of mineral production data has been presented.

Coupled deformation and fluid flow modelling has been used to verify sites of importance for mineralization in both two- and three-dimensional modelling space. Numerical modelling in three-dimensions of strike-slip faulting has yet to fully examine the effect of variation in fault geometry. Quantitative analysis of model outputs can provide criteria for ranking of different fault geometry parameters in terms of their relative prospectivity.

The Proterozoic Mount Isa Inlier is a rich base metal province in northwest Queensland, Australia. As a well studied and well mineralized terrain, with comprehensive literature, and detailed geological and mineral deposit databases available, the Mount Isa Inlier is an ideal study area for investigating and verifying new techniques for brownfields exploration targeting. A quantitative examination of the controls on base metal deposition in the Mount Isa Inlier has substantial implications for future exploration in the region, with the techniques being readily applicable to other study areas and commodities.

A new method is presented which evaluates mineral occurrence distributions by combining fractal analysis of clustering with Weights of Evidence (WofE). Variation in clustering of copper occurrences from the Mount Isa Inlier has a strong positive correlation with variation in clustering of fault bends ($R=0.823$), fault intersections ($R=0.862$), and mafic intrusions ($R=0.885$). WofE analysis as quantified by contrast values indicates that the copper occurrences have a strong spatial association with fault intersections, and fault bends. Correlation of the variation of clustering of copper
occurrences and geological features shows a linear relationship with the contrast values indicating that the geological features controlling the clustering of the copper occurrences may be the same features controlling their localization.

A fractal dimension can be used to quantify geological complexity, which characterises the distribution of faults and lithological boundaries. Two-dimensional analysis of geological complexity in the Mount Isa Inlier suggests that there exists a strong spatial relationship between geological complexity and copper endowment ($R=0.914$). A weak inverse relationship exists between complexity gradients and copper endowment. The results indicate that geological complexity could be used as an exploration targeting tool for copper in the Mount Isa Inlier.

The de Wijs model was developed to describe the distribution of element enrichment and depletion in the crust. An expansion of the de Wijs model is presented to investigate the distribution of ore tonnage as well as grade. The expanded model produces a log-normal relationship between ore tonnage and grade. Multifractal analysis suggests that ore tonnage values from the expanded model are not multifractal. Analysis of production data from the Zimbabwe craton displays a log-normal relationship between ore tonnage and grade, and indicates that ore tonnage is not multifractal, as suggested by the expanded de Wijs model.

Variation of fault bend and fault jog system geometry parameters during coupled deformation and fluid flow modelling of strike-slip faulting reveals that having a low dipping fault, a contrast in lithology and a wide fault width generates the highest dilation and integrated fluid flux values which can be considered proxies for prospectivity. It is demonstrated that little difference is seen between the results obtained for restraining and releasing fault bend and fault jog geometries. The fault geometries observed in the modelling to be the most prospective could be incorporated into exploration targeting strategies.
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INTRODUCTION AND AIMS

Fractal geometry was first used to describe various natural phenomena by Mandelbrot (1983). Fractal analysis can be used to investigate self-similarity within a system, which can be measured by a fractal dimension. Understanding the fractal dimension of an object or system provides insight into how the fractal it is measuring occupies the space in which it resides (Barnsley, 1988).

Originally used to describe “formless” shapes such as clouds and coastlines, the theory of fractals was further expanded to examine more disconnected phenomena such as the clustering of galaxies using spatial Lévy dusts (Mandelbrot, 1983). One characteristic of fractal dusts is the degree of clustering of points, which can be measured by a fractal dimension. A fractal dust with a fractal dimension of 2 describes a random spatial distribution and a fractal dimension of 0 describes a fractal dust with only one point (Mandelbrot, 1983).

Application of fractal analysis to mineral deposits was first used to describe the spatial distribution of mineral deposits (Carlson, 1991). Further research using fractal analysis to describe mineral deposit distributions was carried out (Blenkinsop, 1994, 1995; Agterberg et al., 1996; Blenkinsop and Sanderson, 1999).

The use of fractal analysis to describe mineral deposit distributions beyond these studies has been largely unexplored, with the results of previous research showing that possible geological controls and exploration potential can be inferred (Carlson, 1991; Blenkinsop, 1994; Weinberg et al., 2004; Hodkiewicz et al., 2005). The economic impact of fractal analysis for exploration has been reviewed by Blenkinsop (1995), which lead to conclusions about how exploration companies could further develop...
exploration strategies. Many of these studies have examined what can be termed the “global” fractal dimension of the deposits, which is the single fractal dimension assigned to an entire population of deposits (Carlson, 1991; Blenkinsop, 1994; Agterberg et al., 1996; Blenkinsop and Sanderson, 1999; Blenkinsop and Oliver, 2003; Butera and Blenkinsop, 2004). Very few studies have examined how the fractal dimension may vary over a given study area (eg. Weinberg et al., 2004; Hodkiewicz et al., 2005).

The overall aim of this study was to investigate the application of fractal and multifractal analysis to different facets of mineralized systems. This was achieved through four independent studies, each of which has direct implications for empirical exploration targeting in brownfields terrains or resource evaluation within the study area examined. The techniques used within each study are generic, so that it is possible to apply the methodology to other commodities and/or mineralized terrains.

These techniques are applied to mineral deposit data with a primary focus on copper deposits in the Mount Isa Inlier, Northwest Queensland, Australia. The Proterozoic Mount Isa Inlier is an ideal study area for investigating potential techniques for exploration targeting. With a rich exploration history, and comprehensive, up-to-date geological and mineral deposit databases available for analysis (Queensland Department of Mines and Energy et al., 2000; Queensland Department of Natural Resources and Mines, 2005), it is possible to test new techniques which are developed.

With established studies of fractal analysis in economic geology, the application of existing and new methods of fractal analysis to different mineral systems and
commodities is becoming more prevalent. While previous studies have suggested potential controls on clustering of mineral deposits (eg. Carlson, 1991; Blenkinsop, 1994; Blenkinsop and Sanderson, 1999), these controls were proposed on a qualitative basis. By examining variation of clustering over a given study area, it is possible to analyze potential controls quantitatively (eg. Weinberg et al., 2004; Hodkiewicz et al., 2005). However these studies investigated a very limited number of potential controls. Hodkiewicz et al. (2005) present a study which evaluates geological complexity and complexity gradients as potential controls on gold endowment, and suggest that complexity gradients have a greater control on mineralization than geological complexity itself. The qualitative basis for this conclusion is sparse. The first two chapters of this thesis address these two issues. Chapter 1 explores the variation in clustering of mineral deposits over a study area and examines a series of potential geological controls on the clustering. These results are compared with weights of evidence analysis (Bonham-Carter et al., 1989; Groves et al., 2000; Mustard et al., 2004) to determine whether the geological factors controlling the clustering of the deposits are the same factors controlling their localization. Chapter 2 investigates geological complexity and complexity gradients as controls on copper mineralization using a more rigorous method of analysis than has been used in previous studies, and suggests potential exploration targeting consequences.

One common criticism of fractal analysis of mineral deposit distributions is that the analysis does not take into consideration the variation of values assigned to the deposit such as the size and grade. Multifractals can be used to investigate the self-similarity of properties which show a spatial variation in value, and as such have been used as a complementary tool for examination of the distribution of mineral deposits (eg. Cheng
et al., 1994; Agterberg et al., 1996; Sanderson and Zhang, 1999; Agterberg, 2001). Previous studies have shown that element concentrations can be modelled using multifractals (Agterberg et al., 1996; Cheng, 1999a; Agterberg, 2001; Xie and Bao, 2004). Production data has been examined using multifractal analysis for ore grade data on a mine scale (Roberts, 2005), and Cheng (1999b) has shown that categorized data for deposit size may fit a discrete multifractal model. However there has been no comprehensive multifractal study which investigates both non-categorized ore tonnage and grade distributions on a regional scale. Various studies have shown that results from a theoretical model for describing the distribution of elements within the crust developed by de Wijs (1951), can be described using a multifractal model (eg. Xie and Bao, 2004; Agterberg, 2005). Yet no model exists to accurately describe the distribution of ore tonnage. Chapter 3 presents an expanded version of the de Wijs model for describing the distribution of ore tonnage, examines the multifractal characteristics of this model, and compares the ore tonnage-grade relationship to that derived in previous studies. These theoretical models for describing ore tonnage and grade are then compared to actual production data to determine whether the models can predict the characteristic multifractal and ore-tonnage grade relationships seen for the production data.

Numerical modelling of coupled deformation and fluid flow has been used to verify sites of importance for mineralization in both two-dimensional (eg. Matthäi et al., 2004; McLellan et al., 2004) and three-dimensional modelling space (eg. Gow et al., 2002; Sorjonen-Ward et al., 2002). Previous numerical modelling studies of strike-slip faulting have examined the variation of input geometry in two dimensions (Chester and Fletcher, 1997), or have investigated the effect of varying modeling parameters on...
three-dimensional fault geometries (Brankman and Aydin, 2004). However there has been no comprehensive study to examine the effect of varying fault geometry parameters of three-dimensional strike-slip fault models. Chapter 4 examines a series of fault geometries to determine how variation of a set of parameters affects specified outputs, which can be used as proxies for the prospectivity of the models.

Though preliminary research shows that the results of numerical modelling may be investigated using multifractal analysis (Sanderson and Zhang, 1999), this is not well established, and consequently various outputs from the numerical models in this study were examined to determine if they could be described using multifractals. Discrete multifractal analysis of the dilation and integrated fluid flux outputs from several FLAC3D © (Itasca Consulting Group, 2002) models indicates that these data can not be described by a discrete multifractal model as no distinct break between populations was observed. It is suggested that this is due to the lack of critical state phenomena which would produce a fractal scaling of features. As FLAC3D is a continuum code rather than a discrete element code such as UDEC © (Itasca Consulting Group, 2000), it may not be possible to define a critical state for the models, so these results cannot be described by multifractal models. Discussion of this point was originally intended for inclusion in Chapter 4, but the multifractal analysis was excluded from the chapter due to the negative results obtained. Future research could potentially examine outputs from a three dimensional discrete element code such as 3DEC © (Itasca Consulting Group, 1998), in which critical point phenomena might be observed.
As this thesis is presented as a series of manuscripts for publication, it was not appropriate to include detailed reviews of the techniques for fractal and multifractal analysis used for this project in each paper. A brief review of the techniques is presented below which details the algorithms used for analyzing the data. The relevance, application and modification of these algorithms is discussed within each manuscript presented in the thesis.

Fractal Analysis

The idea of fractal dimension was rigorously developed by Mandelbrot (1983). Unlike standard Euclidean geometry where all dimensions have integer values and which is used commonly in everyday life, fractal geometry allows for non-integer dimensions to describe the “fractional dimensions”. The fractal dimension, $D$, is defined by Mandelbrot as

$$D = -\frac{\log N}{\log r(N)}$$

where $N$ is the number of self-similar shapes that cover an object and $r(N)$ is the effective length of each of the self-similar shapes being used.

Knowledge of the fractal dimension of an object provides some insight into how the fractal that it describes occupies the space in which it resides (Barnsley, 1988). Given this information about several objects or datasets, it is possible to compare the results to see how they correlate.

The most common method for evaluating the fractal dimension for a given dataset is known as the box counting method. The aim of this method is to calculate the
minimum number of boxes with a specified side length required to cover all points in
the dataset. Results can then be plotted to obtain the fractal dimension for the given
dataset using the relationship

\[ N(r) \propto r^{-D} \]

where \( N(r) \) is the minimum number of boxes with side length \( r \) needed to cover all the
data.

Though brute force methods for finding the minimum number of boxes required to
cover the data require more computing power, they provide a simple and effective way
of generating results. One method is described by Carlson (1991) for calculating the
fractal dimension for a set of hydrothermal precious metal deposits. For a given set of
deposit locations, the algorithm can be specified:

- Divide the study area into a grid of many square cells with every cell having the
  same dimension
- Count the number of cells containing at least one deposit
- Replace the current grid with a scaled version
- Repeat the second and third steps for a range of scaled grid sizes

The size of each of the cells used in this algorithm needs an upper and lower bound. An
upper bound may be considered to be the size of a geological province and the lower
bound the size of a single ore deposit. By repeating the scaling step for cell sizes from
the upper bound to the lower bound, a good approximation of the fractal dimension for
the dataset can be made. Given the size of the cell \( r \) (the side length of the square) at
each step, the number of cells \( N \) that contain at least one ore deposit for that cell size is
counted, and from a log-log plot of \( N(r) \) vs. \( r \), the fractal dimension can be evaluated as
the absolute value of the slope for the line-of-best-fit over the straightest part of the plot.
More computationally efficient box counting algorithms have also been developed (Liebovitch and Toth, 1989; Block et al., 1990). In a similar method to box counting, the fractal dimension of a dataset can be evaluated using a number-in-circle method (Carlson, 1991; Blenkinsop, 1994). Both the box counting and the number-in-circle methods have their respective advantages. However it has been shown that the box counting method generates results with higher correlation coefficients and lower regression errors than the number-in-circle method when deriving the value of $D$ from the log-log graphs (Blenkinsop, 1994).

Multifractal Analysis

As previously described, fractal analysis is able to describe the spatial distribution of a given set of data points by assigning a fractal dimension. However many geological phenomena are characterized by a variation in the value of an attribute at each data point. Multifractal analysis is able to investigate such datasets which have a value assigned to each point. An example of a multifractal is a topographic map where each contour line connecting similar altitudes defines a different fractal with a specific fractal dimension (Gagnon et al., 2003).

Two different types of multifractals have been discussed; continuous, and discrete (Cheng, 1997). The method of moments technique for analyzing a continuous multifractal, and the concentration-area technique for analyzing a discrete multifractal, are discussed below for a two-dimensional dataset.
The method of moments technique for determining whether a two-dimensional dataset can be described by a continuous multifractal model takes a grid of equal sized boxes (side length $\varepsilon$) which are placed over the study area. The number of boxes $N(\varepsilon)$ required to cover all the data points is recorded. If a box contains a single data point, the value of the data at that point is applied to the whole box. If a box contains more than one data point, the mean value of all the data points in the box is applied to that box. A measure for the $i^{th}$ box, $\mu_i(\varepsilon)$, is set to the data value multiplied by the area of the box $\varepsilon^2$. Evertsz and Mandelbrot (1992) present the partition function $\chi_q(\varepsilon)$ for each box size and a range of real numbers $q$:

$$\chi_q(\varepsilon) = \sum_{i=1}^{N(\varepsilon)} H_i^q(\varepsilon)$$

The mass exponent function $\tau(q)$ can be estimated from a plot of $q$ vs $\varepsilon$ (Agterberg et al., 1996) by the relationship

$$\chi_q(\varepsilon) \approx \varepsilon^{\tau(q)}$$

$\tau(q)$ is plotted against $q$ and three arbitrary values of $q$ at $x$, $y$, and $z$ are chosen for substitution into

$$\tau(\text{total}) = \tau(z) + \tau(x) - 2\tau(y)$$

If the solution to equation 3 is less than zero, the measures are considered multifractal (Cheng, 1999c). The function $\alpha$ can then be obtained by differentiating the mass exponent function with respect to $q$ (Agterberg et al., 1996):

$$\alpha = \frac{\partial \{\tau(q)\}}{\partial q}$$

The multifractal spectrum $f(\alpha)$ is specified by the equation (Agterberg et al., 1996):

$$f(\alpha) = q\alpha - \tau(q)$$
If the plot \( f(\alpha) \) vs. \( \alpha \) is parabolic and satisfies the conditions outlined by Evertsz and Mandelbrot (1992), the distribution is a continuous multifractal.

Using the concentration-area technique, it is possible to determine whether the data can also be described by what has been termed a discrete multifractal (Cheng, 1999b). This technique places a grid of square boxes (with side length \( \varepsilon \)) over the study area. The value assigned to each box is determined in the same way as previously described for the continuous multifractal analysis. The area \( A(\rho) \) is the number of boxes with box values greater than \( \rho \), multiplied by the area of the box \( \varepsilon^2 \). A log-log graph of \( A(\rho) \) vs. \( \rho \) is then plotted. Threshold values for differentiating between different populations are seen where the slope of the graph changes. The fractal dimension for each population can then be evaluated using the least squares method with a fractal dimension \( \alpha_1 \) below the threshold and \( \alpha_2 \) above the threshold (Cheng et al., 1994).

**STRUCTURE OF THE THESIS**

This thesis is presented as four manuscripts which are published/in press or submitted, for peer review publication in international journals. Each manuscript is intended to be independent of the others and as such the chapters may be read in any order. The four chapters are summarized below.

Chapter 1 presents a new method for investigating the spatial distribution of mineral deposits. The aim of this study was to give a spatial context to the fractal distribution of mineral deposits using spatial variation of clustering and weights of evidence. This analysis results in the prediction of different outcomes for brownfields exploration. This new technique is applied to copper occurrences in the Mount Isa Inlier, and
discusses whether the geological factors which control the clustering of the deposits are the same factors which control their localization. This manuscript has been published in *Ore Geology Reviews* (Ford and Blenkinsop, 2007).

Chapter 2 aims to evaluate geological complexity and complexity gradients as controls on mineralization. An improved method for evaluating the geological complexity and complexity gradients is presented and applied to data from the Mount Isa Inlier. Results suggest that geological complexity could be considered a new control on copper mineralization within the study area, and may be used as a new exploration targeting tool. This manuscript has been published in a special issue on Conceptual Exploration Targeting in *Australian Journal of Earth Sciences* (Ford and Blenkinsop, 2008).

Chapter 3 examines improvements in quantitative models for predicting grade and tonnage distributions of hydrothermal mineralizing systems. An expansion of the de Wijs model (de Wijs, 1951) is presented to investigate the distribution of ore tonnage as well as grade. The tonnage-grade relationship and multifractal characteristics from the theoretical models are compared to those obtained from vein-hosted gold deposits in the Archaean Zimbabwe craton. This manuscript has been submitted to *Mineralium Deposita*.

Chapter 4 investigates coupled deformation and fluid-flow around simple strike-slip fault geometries using FLAC\(^{3D}\) (Itasca Consulting Group, 2002), with applications to mineral prospectivity. Fault bend, and fault jog geometries, as well as contrasts in lithology, are examined to determine how variation of different fault system parameters
affect the models. Outputs from the models are analyzed to evaluate which geometries are the most prospective. This manuscript has been submitted to *Geofluids*.

The conclusions chapter discusses how fractal and multifractal techniques can be used to improve exploration targeting and resource evaluation. A summary of the conclusions from each of the four manuscripts contained within this thesis including avenues for further expanding on the research conducted within this project are presented.
SECTION A

Combining fractal analysis of mineral deposit clustering with weights of evidence to evaluate patterns of mineralization: Application to copper deposits of the Mount Isa Inlier, NW Queensland, Australia
ABSTRACT

The clustering of mineral occurrences and their spatial associations with particular geological features are critical aspects of mineral distributions for exploration and understanding ore genesis. Variations in the degree of clustering of mineral occurrences or geological features can be measured by fractal dimensions, obtained from a shifting-box counting method. Spatial associations between mineral occurrences and geological features can be quantified by the weights of evidence (WofE) method using the contrast value, which increases with the strength of the spatial relationship. A new method is proposed to evaluate mineral occurrence distributions by combining the power of fractal analysis of clustering with the WofE approach. The method compares the correlation between the variation in degree of clustering of mineral occurrences and a geological feature in a study area, with the contrast value of the same feature. The possible outcomes can be simplified into four scenarios, depending on whether the correlation in variation of clustering, and the contrast, are high or low, respectively. Each outcome has specific exploration implications. If either a high correlation in variation of clustering or a high contrast value is obtained, the geological feature can be used for exploration targeting.

The integrated fractal and WofE approach is applied to copper occurrences in the Proterozoic Mount Isa Inlier, NW Queensland, Australia, which hosts large numbers of copper deposits (1,869 occurrences), including the world class Mount Isa copper deposit. Variation in clustering of copper occurrences has a positive correlation with variation in clustering of fault bends (R=0.823), fault intersections (R=0.862), and mafic rocks (R=0.885). WofE results indicate that the copper occurrences are spatially associated with fault intersections and bends, and with mafic rocks. Analyses were carried out separately for the two major lithostratigraphic sequences in the Inlier, the
Eastern and Western Successions. The Western Succession copper occurrences are apparently more clustered than those of the Eastern Succession, which may reflect a lower degree of exploration and/or geological factors. The association of copper occurrences with mafic rocks compared with fault bends and intersections is greater in the Eastern Succession, which may reflect genetic factors. Correlations in the variation of clustering of mineral occurrences and geological features have a linear relationship with the contrast values, and the spatial association between all geological features and copper occurrences constitute high correlation/high contrast cases. The linear relationship suggests that the geological features that control the clustering of the copper occurrences could be the same features that control their localization.

INTRODUCTION

Perhaps the most obvious feature of any map of mineral deposits is that they exhibit some degree of clustering. Following Mandelbrot’s (1983) suggestion that mineral deposits in the Earth’s crust have a fractal distribution, Carlson (1991) showed that the clustering of mineral deposits can be sensitively measured by fractal methods, and also proposed genetic interpretations for the fractal dimensions obtained from these analyses. Evidence for a fractal distribution of mineral deposits has been adduced for gold and precious metals (Carlson, 1991; Agterberg et al., 1996; Blenkinsop and Sanderson, 1999; Kreuzer et al., 2007) and preliminary results suggest that base metal distributions may also be fractal (Blenkinsop and Oliver, 2003; Butera, 2004).

Fractal analyses of clustering of mineral deposits have generally attributed a single, global fractal dimension to the data sets studied. This approach cannot give a spatial context to the clustering of mineral occurrences within the study area, and does not
indicate variations in clustering. Blenkinsop and Sanderson (1999) examined fractal dimensions for various subsets of data from gold deposits of the Zimbabwe Craton, and suggested that spatial variation in fractal dimension might have exploration implications. This approach is developed further here.

By contrast with fractal analysis of clustering of mineral deposits, the weights of evidence (WofE) approach emphasizes spatial context by focusing on geological features that may have localized mineral deposition, and this method has been widely applied to exploration (eg., Bonham-Carter et al., 1989; Agterberg and Bonham-Carter, 1990; Agterberg et al., 1993; Bonham-Carter, 1994; Carranza et al., 1999; Raines, 1999; Harris et al., 2000; Boleneus et al., 2002; Billa et al., 2004). Although alternative methods such as neural networks and fuzzy logic have been introduced (eg., Cheng and Agterberg, 1999; Singer and Kouda, 1999; Brown et al., 2000, 2003; Knox-Robinson, 2000), and the relative merits of these different methods have been discussed (eg., Agterberg and Bonham-Carter, 2005), the weights of evidence method remains popular, especially among practitioners who favor an empirical, data-driven approach to prospectivity. Other reasons for the popularity of the WofE approach to prospectivity include that the method is statistical, it is easily understood by non-specialists, it outputs probabilities explicitly, and there are GUI software packages available to perform the calculations.

Determination of how clustered mineral occurrences are, and their spatial association with particular geological features, are critical for exploration and ore genesis. These characteristics of mineral occurrences can be interpreted in terms of potential controls on the distribution of the occurrences, and can be used to rank these controls.
The primary aim of this study is to present and test a new method of analyzing mineral deposit distributions that combines the power of the fractal geometry to describe the clustering of mineral deposits, with the weights of evidence approach that describes their spatial associations. The method is applied to copper mineralization in the Mt Isa Inlier, NW Queensland, Australia. Ancillary aims of the study are to establish whether copper deposit distribution can be described by fractals, and to examine the spatial variation in degree of clustering of the copper occurrences. The approach of this study addresses a critical question for understanding the genesis of mineral deposits, and for exploration: are the features that controlled the degree of clustering of the copper occurrences the same features that localized them?

The Mount Isa Inlier is selected for this study as it contains a wide range of base and precious metal deposits coupled with a long exploration history, and because the geological and mineral data are appropriate for analyzing the spatial distribution of mineral occurrences. Copper is particularly suitable because of the large number of mineral occurrences.

GEOLOGY AND MINERAL DEPOSITS OF THE MOUNT ISA INLIER

The Mount Isa Inlier, in NW Queensland, Australia, is a significant Proterozoic base metal province covering an area in excess of 50,000 km², containing a variety of mineral deposit types, such as copper, copper-gold, gold, uranium and stratiform lead-zinc-silver. Significant mineral deposits include the Mount Isa copper deposit with resources prior to mining of 225 Mt ore at a grade of 3.3% Cu, the Ernest Henry Cu-Au deposit with 127 Mt at 1.1% Cu and 0.55g/t Au, the Mary Kathleen U-REE deposit
containing 9.5 Mt of ore at 0.131% U\textsubscript{3}O\textsubscript{8} and the Cannington Pb-Zn-Ag deposit containing 43.8 Mt of ore at 11.6% Pb, 4.4% Zn and 538g/t Ag (Queensland Department of Mines and Energy et al., 2000). This study focuses on the spatial distribution of copper-only deposits (excluding copper-gold and iron-oxide-copper-gold deposits). Exclusion of copper-gold and iron-oxide-copper-gold (IOCG) deposits is due to the potentially different controls on mineralization, with one example being the Osborne IOCG deposit which is considerably older than the copper-only deposits within the Mount Isa Inlier (Williams, 1998).

The Mount Isa Inlier is divided into three tectonic units (Fig. 1). From west to east these are the Western Fold Belt, the Kalkadoon-Leichhardt Belt, and the Eastern Fold Belt (Blake et al., 1990). Because some differences have been suggested between the characteristics of mineral deposits in the East and West of the Inlier, mineral occurrences are sub-divided into two groups in this study: those within the Eastern Succession, including the Eastern Fold Belt, which are mainly shear and fault controlled vein copper deposits; and those within the Western Succession, including the Kalkadoon-Leichhardt Belt and the Western Fold Belt, which are mainly brecciated, sediment-hosted copper deposits (Blake et al., 1990). The terms Eastern Succession and Western Succession are not synonymous with the Eastern Fold Belt and Western Fold Belt, respectively. The split between the Eastern and Western Successions is essentially lithostratigraphic (Blake and Stewart, 1992), and the boundary was positioned at the western margin of the Eastern Fold Belt. Additional support for this position is the interpretation of this margin as a possible terrain boundary (McDonald et al., 1997).
**Figure 1:** Simplified geological map of the Mount Isa Inlier with box showing outline of entire study area (Queensland Department of Mines and Energy et al., 2000). Inset shows the location of the tectonic belts and major deposits.
Rocks in the Mt Isa Inlier recorded two major orogenic events: the Barramundi Orogeny (ca. 1870 Ma), and the Isan Orogeny (ca. 1600 to 1500 Ma); (O'Dea et al., 1997) (Fig. 2). Relicts of the Barramundi Orogeny outcrop in the older basement sequences of the Kalkadoon-Leichhardt Belt. Deposition of sedimentary cover sequences 1, 2, and 3 postdated the Barramundi Orogeny and predated the Isan Orogeny (Blake et al., 1990). Cover sequence 1 is generally thought to have been deposited in the interval 1870 to 1850 Ma, cover sequence 2 from 1790 to 1720 Ma and cover sequence 3 from 1680 to 1600 Ma (Blake and Stewart, 1992; Williams, 1998). The D2 EW-shortening event (ca. 1590 Ma; Fig. 2) was responsible for formation or reactivation of the dominant NS-striking structures in the Mount Isa Inlier (Bell et al., 1988; Laing, 1998). Upright, D2 kilometre-scale folds with generally northerly-striking axial surfaces are prominent throughout the inlier. Major deformation zones and geophysical lineaments occur in this orientation, and also strike NE and NW. Several of these may have formed as basin-bounding faults during deposition of the cover sequences, and they may have been reactivated as reverse faults during the Isan Orogeny (Queensland Department of Mines and Energy et al., 2000). Folds and crenulations of D2 fabrics, and foliations in and around plutons intruded at ca. 1550 to 1500 Ma indicate that broadly E-W shortening continued for a substantial period after D2: these deformations are collectively referred to as D3 (cf. Rubenach, 2005; Fig. 2). Faults in the Eastern Succession commonly strike N to NW and are generally straighter than those in the Western Succession. Faults in the Western Succession are less dense and are generally longer N to NE striking structures.

The distribution of the cover sequences, and their propensity to host copper deposits, varies throughout the inlier. The copper deposits are hosted within both cover sequence 2 and 3 rocks. In the Western Succession, the Lawn Hill platform (Fig. 1), which hosts
Figure 2: Chronostratigraphic framework of the Mount Isa Inlier (modified after Figure 3 of Foster and Austin, 2005), showing cover sequence deposition, major mineralization (Baker and Laing, 1998; Chapman and Williams, 1998; Williams, 1998; Baker et al., 2001), and orogenic events.
the Lady Annie copper deposit (Fig. 1), consists predominantly of sideritic and locally carbonaceous shales, mudstones and sandstones of the McNamara Group in cover sequence 3 (Feltrin et al., 2003). In the Leichhardt River fault trough (Fig. 1), the stratigraphy of the Western Succession is more complex. The Urquhart Shale (carbonaceous, pyritic, dolomitic siltstone) of cover sequence 3 is host to the Mount Isa Cu deposit, and lies above the Eastern Creek Volcanics (metabasalts) of cover sequence 2 (Wyborn, 1987; Williams, 1998). However, the Mammoth copper deposit is hosted by the Myally Subgroup (quartzite, sandstone, and siltstone) of cover sequence 2 (Scott and Taylor, 1982). Felsic volcanic rocks of cover sequence 1 and the Kalkadoon and Ewen batholiths dominate the stratigraphy in the Kalkadoon-Leichhardt Belt, and do not contain any economic copper deposits (Blake and Stewart, 1992). The calcsilicate Corella Formation in the western part of the Eastern Succession hosts the Trekelano deposit (Williams, 1998). The Williams-Naraku batholiths, the Corella and Doherty Formations (calcsilicate rocks) and the Soldiers Cap Group (siliciclastic metasediments and metabasalts) are the dominant units in the eastern part of the Eastern Fold Belt. The latter is host to many small Cu deposits such as Young Australia (Blake et al., 1990).

Both stratigraphy and structure have been suggested as controls on copper mineralization in the Mount Isa Inlier (eg., Bell et al., 1988; Laing, 1998; Williams, 1998). Copper mineralization styles vary between the Western and Eastern Succession. In the Western Succession copper deposits are hosted by brecciated sediments adjacent to faults. Mineralization is localized on N- and NNE-striking structures such as the Mount Isa and the Mount Gordon fault zones, which contain appreciable amounts of copper (Scott and Taylor, 1982; Nijman et al., 1992). In the Eastern Succession, vein and breccia style copper deposits occur in shear zones and faults (Laing, 1998;
Marshall, 2003). Many copper deposits in the Eastern Succession are spatially associated with faults, with the larger deposits such as Eloise, Osborne and Kuridala copper-gold deposits being hosted by N- to NW-striking regional structures such as the Mt Dore fault zone (Blake et al., 1990; Laing, 1998).

Copper mineralization may have occurred late in the Isan Orogeny with timing suggested as syn-D$_3$ in both the Eastern and Western Successions (Williams, 1998; Queensland Department of Mines and Energy et al., 2000). Structures produced or reactivated during the Isan Orogeny thus have potential to host epigenetic mineral deposits. There is also potential for metals to have been remobilized due to later fault reactivation throughout the Mount Isa Inlier. Fault reactivation is known to have occurred as late as the Cambrian and Ordovician (Feltrin et al., 2003; Mark et al., 2004).

In the Western Succession, the source of the copper for the world class Mount Isa copper deposit and the significant Mammoth and Esperanza deposits in the Gunpowder area has been attributed to the Eastern Creek Volcanics (Scott and Taylor, 1982; Wyborn, 1987; Matthäi et al., 2004). Though the source of the copper for base metal deposits in the Eastern Succession is a contentious issue, recent work on IOCG deposits suggests that the mafic rocks of the Soldiers Cap Group rather than the Williams and Naraku batholiths (cf. Oliver et al., 2004; Mark et al., 2006) may be implicated (Butera and Blenkinsop, 2004).

Butera (2004) suggested that regionally extensive brines in the Mount Isa Inlier leached sulfur and possibly copper from mafic dykes prior to ore deposition and close to major extensional basement structures and D$_3$ faults. Mafic rocks can also potentially provide
the rheological contrast necessary for entrapment of mineralizing fluids. Fault bends (eg., Cox, 1999; Allibone et al., 2002a, b) and fault intersections (eg., Craw, 2000; Twomey and McGibbon, 2001; Allibone et al., 2002a, b; Nie et al., 2002; Cox, 2005) could have focused fluids and localized ore deposition. Mafic rocks and NW-, N- and NNE-striking faults or shear zones and their bends and intersections may therefore have been critical factors in localizing copper mineralization in the Mount Isa Inlier (cf. Phillips et al., 1996; Twomey and McGibbon, 2001; Butera, 2004; Mustard et al., 2004).

DATA AND METHODS

Copper occurrences and geological data

The spatial distribution of 1,869 copper occurrences was examined on the basis of the Queensland Mineral Resources Database, MINOCC, (Queensland Department of Natural Resources and Mines, 2002). The database categorizes mineral occurrences using attributes that include commodity, mineralogy, host rock type, age, tonnage, and grade. All entries containing copper as the main commodity were extracted from the database for use in this study, excluding those which also contained gold. This selection was made because the deposits containing gold potentially have different controls. The existence of the wealth of data in the Queensland Mineral Resources database makes the Inlier particularly suitable for this study. Locations of the copper occurrences used in the analysis are shown in Fig. 3.

Fault bends, fault intersections and mafic rocks were investigated as potential controls on copper mineralization as they had already been shown to be important factors for copper mineralization (Blenkinsop, 2005). The Northwest Queensland Mineral Province
Figure 3: Copper occurrences (n = 1,869) in the Mount Isa Inlier, after MINOCC database, December 2002 (Queensland Department of Natural Resources and Mines, 2002).
Report (NQMPR) (Queensland Department of Mines and Energy et al., 2000) contains a database of faults divided into segments. These segments were combined to provide a comprehensive database of continuous, individual faults suitable for analysis. All fault intersections and fault bends (bends were defined as changes in strike between 5º and 45º) were extracted to point data using the MapInfo – Spatial Data Modeller © package from Avantra Geosystems. Fault bends were located as the mid-point along a given bend within the database in both clockwise and anti-clockwise directions. Equally spaced nodes were extracted from the outlines of the mafic rocks in the study area using Encom’s Discover © software in order to perform the fractal analysis on point data of this geological feature for fair comparison with the results of fractal analysis of the point data for the fault intersections, fault bends, and mineral occurrences.

**Fractal analysis of mineral occurrence and geological clustering**

The log-log approach was used to find the box counting fractal dimension (Mandelbrot, 1985). The number of square boxes \( N \) with side length \( r \) required to cover all the mineral occurrences in the study area is counted as a function of \( r \), and the fractal dimension, \( d \), is given by the relationship:

\[
N(r) = k(1/r)^d
\]

A graph of \( \log(N(r)) \) versus \( \log(r) \) was plotted and a linear regression was performed on the straightest part of the line of best fit, with the regression limits chosen to fit the straightest part of this line. If the deposits have a fractal distribution, the plot produces a straight line with a slope \( d \). In all cases, the largest box size was ignored because its side length \( r \) was determined by the size of the study area. This is referred to as the global box counting method as it calculates a fractal dimension for the entire study area (eg., Carlson, 1991). A random distribution of occurrences would produce a \( d \) value of 2 and,
as the deposits become more clustered, the value of $d$ approaches zero. However, this method does not describe how clustering may vary within the study area.

A study area of 506.6 km x 334.6 km was used to analyze the spatial variation of clustering across the Mount Isa Inlier (cf. Hodkiewicz et al., 2005). Fractal dimensions were calculated for copper occurrences within boxes with a side length of 126.65 km ($\frac{1}{4}$ of the size of the largest box size used in the global box counting method). This box size was chosen in order to contain a large enough sample of copper occurrences to calculate a reliable value for $d$. The box was shifted in steps of 50 km across the study area so that there is some overlap between the shifting boxes, and fractal dimensions were calculated for each box containing 10 or more copper occurrences. This number was determined by examining the log-log plots of $N(r)$ versus $r$ for several locations with a small number of occurrences. For areas containing less than 10 occurrences, the results were too erratic for the linear regression to be performed accurately. Examining a sample of the remaining graphs allowed regression limits to be chosen between 7.5 km and 75 km, automatically excluding the largest box size. By choosing these regression limits, the issue of roll-off (Blenkinsop and Sanderson, 1999) was avoided. The roll-off effect occurs on the log-log plot of $N(r)$ versus $r$, where for small box sizes the data deviate from the straight line as indicated in Fig. 4. Two sample graphs obtained from the shifting box counting method applied to the spatial analysis of copper occurrences are shown in Fig. 4.

A contour map was generated to visualize the variation in the fractal dimension across the study area (Fig. 5). Values for the contouring were located at the centre of each of the shifting boxes. Null fractal dimension values arising from insufficient copper
Figure 4: Examples of graphs of number of boxes N(r) against box side length (m) on logarithmic scales using the shifting box method to count copper occurrences. The roll-off effect occurs where plot deviates from the plotted straight line for small box sizes.
Figure 5: Contour plot of the fractal dimension that measures clustering of copper occurrences determined using the shifting box counting method with a box size of 126.65 km in the Mount Isa Inlier. Apparent variation in contouring outside the area of outcrop is due to the contouring method used, nearest neighbor contouring, which has the least sensitivity to copper occurrences outside the colored area.
occurrences in the shifting box were excluded from the contour map and further analysis of the clustering.

**Weights of evidence (WofE) approach**

The degree of spatial association between features on two or more binary maps can be quantified by the contrast value in WofE analysis (Bonham-Carter, 1994). The contrast value ($C_w$) can be found from the relation

$$ C_w = \ln O(B|A) – \ln O(B|\bar{A}) $$

where $O(B|A)$ are the odds of B occurring given the presence of A, and $O(B|\bar{A})$ are the odds of B occurring given the absence of A. This value compares the spatial association of two particular features (e.g., copper occurrences and fault intersections) with that expected from a random distribution of these features, which would give a contrast value of zero. Contrast values above 0.5 are considered to be indicative of a significant spatial association between two features (Wang et al., 2002).

Weights of evidence analysis was performed on the data using the MapInfo – Spatial Data Modeller © software package (Avantra Geosystems) to determine the spatial correlation between copper occurrences and the same geological features examined in the fractal analysis. Buffers around the features were varied from 0 to 3 km to determine the buffer distance that gave the optimum contrast value, as judged by the maximum value. A confidence value was also calculated for each contrast value, calculated as the contrast value divided by its standard deviation (Bonham-Carter, 1994).
A new method for evaluating the spatial distribution of mineral deposits: integrated fractal and WofE analysis

Degrees of clustering were determined for selected geological features by their fractal dimension in each of the shifting boxes, and then compared to the clustering of mineral occurrences in the same boxes by Pearson’s correlation coefficient. The spatial association of these geological features with the copper occurrences was measured by their contrast. Fractal analysis of clustering was combined with the weights of evidence approach by plotting the correlation coefficient for the variation of clustering against the contrast value for each geological feature. Four schematic maps representing the range of possible outcomes are superimposed onto the graph for such a plot in Figure 6. In the top right of the diagram, high correlation coefficients are combined with high contrast values: since the geological feature coincides everywhere with the occurrences, they have the same variation in clustering. The top left part of the diagram shows geological features that have similar degrees of clustering as the mineral occurrences, but are not spatially associated with them. The lower right part of the diagram shows a geological feature that is spatially associated with occurrences, but has a different degree of clustering, typically where the numbers of occurrences and geological features are dissimilar. The lower left part of the diagram shows a geological feature that has different degrees of clustering and a lack of spatial association with the occurrences. The plot in Fig. 6 is a therefore a way of evaluating controls on clustering and the spatial association of mineral occurrences with geological features.

Limitations of the analysis

As this study deals with spatial data analysis, the quality of the input data is critical to generating and interpreting the results accurately. Potential limitations include
Figure 6: Schematic illustration of four possible natural outcomes from combining fractal and weights of evidence analyses. The y-axis shows the correlation between the variation in degree of clustering of a geological feature (e.g., fault bends) with mineral occurrences, and the x-axis shows the log of the contrast which is a measure of the spatial association of the feature with mineral occurrences. Each panel illustrates a map pattern that characterizes the relevant part of the graph. Open circles are geological features, closed circles are mineral occurrences. Most data in this study plots in top right of the diagram i.e., the features have both similar degrees of clustering and high spatial association with copper occurrences and this panel is schematic of the data seen in Figure 8.
variations in the quality and homogeneity of mapping, the degree of outcrop, and that the study was only done in 2D (Bardossy and Fodor, 2001).

The quality of mapping should not be a problem since only mafic intrusive and extrusive rocks have been used in the analysis, and there is no reason to doubt that the mapping identified such distinctive rocks correctly. The issue of the homogeneity of the mapping was addressed by using only geological data from the Northwest Queensland Mineral Province Report (Queensland Department of Mines and Energy et al., 2000). With a uniform scale and source of mapping, any obvious potential heterogeneities were avoided.

The Palaeozoic and younger rocks that overly the Proterozoic inlier in places could, potentially, have some bearing on the results. Any such effects of cover can not be easily quantified. This study compares copper occurrences with geological features, and there is no clear evidence to suggest that cover affects the distribution of the copper occurrences more than the geological features or vice versa. Confidence in the value of the fractal dimension would be diminished by increasing levels of cover, but it is not clear whether the value of the fractal dimension would change as a result. Although the weights of evidence method is sensitive to cover due to areas that contain neither mineral deposits nor the feature being examined (Bonham-Carter, 1994), this does not represent a problem in this study because the faults have been interpreted under cover, and the contrast values for the mafic rocks were not calculated in covered areas.
RESULTS: COPPER OCCURRENCES OF THE MOUNT ISA INLIER

Fractal analysis of clustering

The global fractal dimension box counting method for all copper occurrences in the study area (Fig. 7) yields a fractal dimension of 1.36, a correlation coefficient between $\log N(r)$ and $\log r$ of 1.000 and standard error of regression of 0.02 (Table 1). Box counting gave fractal dimensions of 1.39 and 1.29 in the Eastern and Western Successions respectively (Table 1), a difference that is outside the errors of regression, and that apparently indicates more clustering in the Western Succession. Small box sizes were excluded from the regression as they can lead to inaccuracy in the calculation due to roll-off effects with the regression limits listed in Table 1 (Blenkinsop and Sanderson, 1999).

Fractal dimensions calculated for the copper occurrences by the shifting box counting method in the ~127 km squares within the Mt Isa Inlier range from 0.59 to 1.79, indicating that there is a significant variation in the clustering of the occurrences within the study area (Fig. 5).

Correlations between the variations in clustering of the copper occurrences and the variations in clustering of the fault bends and intersections, and between variations in clustering of copper deposits and mafic rocks within the Eastern and Western Successions are listed in Table 2. Spatial variation in the clustering of the copper occurrences is observed across the study area.

Table 1: Global fractal dimensions ($d$) for copper occurrences in the study areas examined showing number of occurrences ($N$), correlation coefficient ($R$) and standard error of regression ($E$).

<table>
<thead>
<tr>
<th>Study Area</th>
<th>$N$</th>
<th>$d$</th>
<th>$R$</th>
<th>$E$</th>
<th>Regression Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt Isa Inlier</td>
<td>1869</td>
<td>1.36</td>
<td>1.000</td>
<td>0.02</td>
<td>15.83km – 253.30km</td>
</tr>
<tr>
<td>Eastern Succession</td>
<td>1412</td>
<td>1.39</td>
<td>0.999</td>
<td>0.04</td>
<td>7.92km – 63.33km</td>
</tr>
<tr>
<td>Western Succession</td>
<td>457</td>
<td>1.29</td>
<td>0.999</td>
<td>0.04</td>
<td>15.83km – 126.65km</td>
</tr>
</tbody>
</table>

*Note: The regression limits were chosen from the straightest part of the log $r$ versus log $N(r)$ graph.*
Figure 7: Graph of number of boxes N(r) against box side length (in meters) on logarithmic scales for Cu occurrences in the Mt Isa Inlier. Line of best fit is illustrated.
occurrences has a higher correlation with the variation in clustering of fault bends for
the whole Inlier than any of the other geological features analysed. Mafic extrusions in
the Eastern Succession were not analysed as there were not enough mafic extrusions
present within the study area to perform the analysis. In the Eastern Succession, the
highest correlation exists between the variation in clustering of the copper occurrences
and mafic intrusions, while in the Western Succession the highest correlation is with the
fault intersections. The correlations with fault geometry in the Western Succession
(0.823 for fault bends and 0.862 for fault intersections) are appreciably higher than with
fault bends and intersections in the Eastern Succession (0.696 and 0.658, respectively).

Weights of evidence

Results from the weights of evidence analysis are listed in Table 2. The strongest spatial
relationships, as indicated by the highest contrast values, are between fault bends and
intersections and copper occurrences for both the Eastern and Western Successions.
Fault bends in the Eastern Succession have the highest contrast value (0.798) with the
copper occurrences, whereas in the Western Succession, the fault intersections have the
highest contrast value (2.330). With one exception, all contrast values are greater than
0.5 and are therefore statistically significant (Wang et al., 2002).

<table>
<thead>
<tr>
<th>Location</th>
<th>Cu occurrences correlated with</th>
<th>Correlation</th>
<th>Contrast</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Succession</td>
<td>Fault Bends</td>
<td>0.696*</td>
<td>0.798</td>
<td>2.249</td>
</tr>
<tr>
<td></td>
<td>Fault Intersections</td>
<td>0.658*</td>
<td>0.617</td>
<td>3.332</td>
</tr>
<tr>
<td></td>
<td>Mafic Intrusions</td>
<td>0.885*</td>
<td>0.536</td>
<td>3.723</td>
</tr>
<tr>
<td></td>
<td>Mafic Intrusions+Extrusions</td>
<td>0.600</td>
<td>0.567</td>
<td>4.261</td>
</tr>
<tr>
<td>Western Succession</td>
<td>Fault Bends</td>
<td>0.823*</td>
<td>1.469</td>
<td>2.921</td>
</tr>
<tr>
<td></td>
<td>Fault Intersections</td>
<td>0.862*</td>
<td>2.330</td>
<td>4.006</td>
</tr>
<tr>
<td></td>
<td>Mafic Intrusions</td>
<td>0.670</td>
<td>0.623</td>
<td>1.208</td>
</tr>
<tr>
<td></td>
<td>Mafic Intrusions+Extrusions</td>
<td>0.620*</td>
<td>0.460</td>
<td>1.883</td>
</tr>
<tr>
<td></td>
<td>Mafic Extrusions</td>
<td>0.604*</td>
<td>0.643</td>
<td>1.989</td>
</tr>
</tbody>
</table>

Note: * indicates significance at the 95% confidence level.
**Integrated fractal and weights of evidence analysis**

Figure 8 illustrates the correlation coefficients obtained from the fractal analysis between the variation in clustering of copper occurrences and geological features listed in Table 2 plotted on a log-normal graph against the contrast values obtained from the weights of evidence analysis. Figures 6 and 8 are plotted on the same axes with Figure 8 representing the top right hand corner of Figure 6. Figure 8 shows a linear trend between the results from the fractal analysis and the results from the weights of evidence analysis. A value of 0.683 (significant at the 95% confidence level) was obtained for Spearman’s rank correlation coefficient between the correlation of variation in clustering and the log of the spatial association (i.e., contrast), indicating that the log-normal relationship between fractal analysis and weights of evidence analysis is significant. A rank correlation of 0.953 was obtained when only the data plotting in the top right of Figure 6 was examined.

**DISCUSSION**

**Fractal distribution of copper occurrences and their spatial variation**

The global fractal dimensions in Table 1 indicate that fractal analysis is a viable tool for the spatial analysis of copper occurrences in the Mt Isa Inlier. The correlation coefficient from the box counting regression for $D$ for the entire Mount Isa Inlier (R=1.000) appears to be the highest reported for fractal distributions of mineral deposits (Carlson, 1991; Blenkinsop, 1994; Blenkinsop and Sanderson, 1999; Blenkinsop and Oliver, 2003). Figure 5 displays significant variation in the fractal dimension for the copper occurrences from the global value across the Mount Isa Inlier. This variation permits analysis of geological features that may have controlled the level of clustering of copper occurrences in the study area.
**Figure 8:** Graph of the correlation in variation of clustering between geological features and copper occurrences versus logarithm of contrast for (a) fault bends in the Eastern Succession, (b) fault intersections in the Eastern Succession, (c) mafic intrusions in the Eastern Succession, (d) mafic intrusions and extrusions in the Eastern Succession, (e) fault bends in the Western Succession, (f) fault intersections in the Western Succession, (g) mafic intrusions in the Western Succession, (h) mafic intrusions and extrusions in the Western Succession, and (i) mafic extrusions in the Western Succession. A trendline is displayed for data points plotting in the top right of Figure 6 (i.e., excluding mafic intrusion in the Eastern Succession), which reveals a rank correlation of 0.953. The data indicate that fault intersections and fault bends in the Western Succession are useful features to use for exploration in that area.
Factors affecting clustering and localization of copper occurrences

Figure 5 illustrates that the copper occurrences in the Eastern Succession are less clustered than those in the Western Succession. This discrepancy could be linked to greater exploration activity in, and greater wealth of information about, the Eastern Succession (cf. Blenkinsop and Sanderson, 1999). This possibility was evaluated from the location of exploration drillhole data within the Northwest Queensland Mineral Province Report (Queensland Department of Mines and Energy et al., 2000). Over 70% of the drillhole data is from the Eastern Succession, with almost 90% being from bedrock drilling. Regions with comparatively low fractal dimensions may not have been fully explored as indicated by the roll-off effect (illustrated in Figure 4) which may occur due to undiscovered mineral occurrences (Blenkinsop and Sanderson, 1999). Another factor that could cause differences in the clustering between the Eastern and Western Successions is the style of mineralization. Sedimentary breccia-hosted copper deposits are mainly located in the Western Succession, whereas the shear- and fault-hosted vein copper deposits are mainly located in the Eastern Succession (Blake et al., 1990).

The correlations between the clustering of copper occurrences and geological features listed in Table 2 indicate that fault bends and intersections have a greater spatial association with the clustering of the copper occurrences in the Western Succession, whereas mafic intrusions (R=0.885) have a greater association, and possibly a greater control on clustering, in the Eastern Succession (cf. Butera and Blenkinsop, 2004).

The weights of evidence analysis indicates that there are strong spatial relationships between the copper occurrences, fault bends and intersections, and mafic rocks (Table
2). The strongest spatial relationships exist between copper occurrences and fault bends (contrast value 2.33), and copper occurrences and fault intersections (contrast value 1.47), in the Western Succession. Strong spatial relationships also exist between the copper occurrences and the fault geometry in the Eastern Succession (0.696 and 0.658 for fault bends and intersections respectively).

Figure 8 shows a positive correlation between the logarithms of contrast values obtained from the weights of evidence analysis, and the clustering correlations obtained from the fractal analysis. The positive relationship between the fractal analysis and weights of evidence can be interpreted to indicate that the features that controlled the clustering of the copper occurrences in the Mt Isa Inlier also controlled the localization of the copper occurrences. Almost all of the data in this study (Fig. 8) plots in the top right of the graph in Figure 6, and forms a linear trend, although the mafic intrusives in the Eastern Succession do not fall on the general trend.

Fault bends and intersections may thus have a major influence on both the spatial association and the clustering of the copper occurrences in the Mount Isa Inlier. Though the results indicate that the spatial relationship between the faults and the copper occurrences is stronger in the Western Succession than the Eastern Succession, their control on the copper occurrences in the Eastern Succession is also significant. The differences between the Eastern and Western Successions appear to be real and suggest that differences exist in the role of the faults in the hydrothermal mineralizing process (Ford and Blenkinsop, 2008).
Integrating fractal analysis and mineral prospectivity

The results of this study raise questions about the processes that controlled both the spatial association and clustering of the copper occurrences. While some of the features used in the fractal and the weights of evidence analyses show high fractal dimension correlations and contrast values (e.g., fault bends and fault intersections in the Eastern Succession), the values are not high enough to imply that any of these factors individually played an exclusive part in the clustering and localization of the copper occurrences.

The significant relationship between the results of the fractal and weights of evidence analyses has potential exploration relevance. Four possible implications from combining fractals and weights of evidence as outlined in Figure 6 can be considered for exploration.

- For geological features with high fractal dimension correlation and high contrast, (in the top right of Fig. 6): explore in areas proximal to the feature, and in areas with high clustering of the feature. Examples include fault bends and fault intersections in the Western Succession.

- For features with high fractal dimension correlation and low contrast (top left of Fig. 6): explore in areas with high clustering of mineral occurrences that are not necessarily in close proximity to the features, such as mafic intrusives in the Eastern Succession.

- For features with low fractal dimension correlation and high contrast (bottom right of Fig. 6): explore in areas proximal to the features.

- For features with low fractal dimension correlation and low contrast (bottom left of Fig. 6): the features should not be used for exploration targeting.
These outcomes are possibly most relevant to guiding brownfields mineral exploration at the regional scale, and they may be used to re-evaluate areas of previous exploration (Hronsky, 2004).

Future research should focus on subdividing mineral occurrences by style of mineralization. Consideration of the different styles of mineralization may provide further insights into what factors controlled the clustering and localization of the mineral occurrences. However, styles of mineralization are known only for the largest deposits. The conclusion that the features that controlled the clustering of the occurrences are the same that controlled the localization requires additional testing for different commodities and geological features in other study areas.

**CONCLUSIONS**

Clustering of mineral deposits and their spatial association with selected geological features are basic attributes of mineral deposit distribution that have implications for exploration and understanding ore genesis. This study suggests a method for evaluating the degree of clustering and spatial association simultaneously. In this method, the correlation between spatial variations in degree of clustering of mineral occurrences and geological features is compared with the spatial association of the occurrences with the same geological features, as measured by contrast values.

This integrated fractal analysis and weights of evidence method was tested on the copper occurrences in the Mt Isa Inlier. These copper occurrences have a better-defined fractal distribution than any previously analyzed mineral occurrence populations. However, there are important spatial variations in the degrees of clustering. Significant
spatial associations occur between the copper occurrences, fault bends and intersections, and mafic rocks, in both the major lithostratigraphic divisions of the Inlier, the Eastern and Western Successions. Variations in the degree of clustering of these geological features correlate with variations in the clustering of the copper occurrences.

The higher degree of clustering (lower fractal dimension) observed in the Western Succession may be due to either or both relative lack of exploration and geological factors. Slight differences in the spatial relationships between the Eastern and Western Successions, which are also seen in the respective styles of mineralization, suggest differences in mechanisms of copper mineralization.
SECTION B

Evaluating geological complexity and complexity gradients as controls on copper mineralization, Mount Isa Inlier
ABSTRACT

Faults and lithological boundaries are pathways for focusing the large volumes of fluid required to form hydrothermal orebodies. The distribution of faults and lithological boundaries as a function of scale can be measured by the geological complexity, quantified by a fractal dimension obtained by box counting, that increases with complexity. Copper mineralization in the Mount Isa Inlier has well documented structural and stratigraphic controls, and may therefore have a strong relationship with geological complexity. In this study, a two-dimensional approach is implemented for analyzing the relationship between complexity, complexity gradients and copper mineralization. There is a strong positive relationship between complexity and copper distribution and endowment in both the major lithostratigraphic subdivisions of the inlier, the Eastern and Western Successions. This relationship may suggest that abundant fluid pathways and physico-chemical contrasts are critical factors in copper mineralization. A weak inverse relationship exists between complexity gradients and copper endowment. At small scales, there is a departure from the fractal relationship between the number of boxes containing faults or lithological boundaries and box size, called roll-off. Roll-off is shown to be a function of the detail of mapping. This allows variation in mapping detail to be accounted for in measurements of geological complexity by due consideration of the scale at which roll-off occurs. The results imply that complexity could be used as an exploration tool.

INTRODUCTION

Faults and lithological boundaries are important factors in the genesis of hydrothermal ore deposits, as they can permit significant fluid flow, and create contrasts in physico-chemical conditions by juxtaposing different rock types. For example, these factors are
critical for the genesis of the Yilgarn gold deposits (Groves et al., 2000; Cox and Ruming, 2004). The concept of “geological complexity” (abbreviated hereafter to complexity) has been developed to describe the distribution of faults and lithological boundaries as a function of scale (Hodkiewicz, 2003), which can be quantified using the box counting technique (Weinberg et al., 2004). The variation of complexity over a region can be measured by a shifting box counting method in a similar way to the analysis of spatial variation in mineral occurrence clustering (Ford and Blenkinsop, 2007). Hodkiewicz et al. (2005) concluded that there was no direct correlation between absolute complexity and gold endowment; rather the gradients in complexity were important for orogenic gold deposits in the Eastern Goldfields Province of the Yilgarn Craton.

The Mount Isa Inlier provides an ideal study area for investigating relationships between complexity, complexity gradients, and mineralization, with an abundance of up to date mineral occurrence data (Queensland Department of Natural Resources and Mines, 2005) and geological data (Queensland Department of Mines and Energy et al., 2000) available for analysis. Lithological and fault controls on copper mineralization have been suggested for both the world class Mount Isa copper deposit (Matthäi et al., 2004), and for other deposits in the inlier such as the Mammoth Cu and Century Pb-Zn-Ag deposits (Scott and Taylor, 1982; Blake et al., 1990; Williams, 1998). Numerical modelling by Oliver et al. (2001) shows that 1) the faults and lithological boundaries in the inlier acted as pathways for fluid flow and 2) that there is a close spatial association between these pathways and copper mineralization.
This study investigates spatial variations in geological complexity and complexity gradients within the Mount Isa Inlier. Both absolute values of the geological complexity and complexity gradients can be regarded as potential controls on copper mineralization.

**GEOLOGY AND COPPER MINERALIZATION IN THE MOUNT ISA INLIER**

Mid-Proterozoic metasedimentary and metavolcanic rocks of the Mount Isa Inlier are divided into the Eastern and Western Successions based on lithostratigraphic differences (Blake and Stewart, 1992; McDonald et al., 1997). Tectonic divisions of the Inlier from east to west include the Eastern Fold belt, the Kalkadoon-Leichhardt Belt, and the Western Fold Belt (comprising the Leichhardt River Fault Trough and the Lawn Hill Platform). For the purposes of this study the Western Succession incorporates the Western Fold Belt and the Kalkadoon-Leichhardt Belt, and the Eastern Succession incorporates the Eastern Fold Belt.

The Proterozoic stratigraphy of the Mount Isa Inlier (Fig. 1) is usually described in terms of sedimentary cover sequences 1, 2, and 3 (Blake et al., 1990). Cover sequence 1 is generally thought to be deposited at 1870-1850 Ma, cover sequence 2 at 1790-1720 Ma and cover sequence 3 at 1680-1600 Ma (Blake and Stewart, 1992; Williams, 1998). The Lawn Hill platform in the Western Succession consists mostly of cover sequence 3 rocks of the McNamara Group, which are predominantly sideritic and locally carbonaceous shales, mudstones and sandstones (Feltrin et al., 2003). Cover sequence 2 rocks, comprising the Eastern Creek Volcanics (metabasalts) and the Myally Subgroup (quartzite, sandstone, and siltstone), are the predominant rocks in the Leichhardt River Fault Trough (Scott and Taylor, 1982; Wyborn, 1987). The Kalkadoon-Leichhardt Belt is dominated by cover sequence 1 rocks and the intrusive rocks of the Kalkadoon and
Figure 1: Simplified geology map of the Mount Isa Inlier (Queensland Department of Mines and Energy et al., 2000). Inset shows the location of the tectonic belts and major deposits.
Ewen Batholiths, with the former dated as coeval with cover sequence 1 and the latter dated at c. 1840 Ma (Blake and Stewart, 1992). The calcisilicate Corella and Doherty Formations (cover sequence 2), the siliciclastic metasedimentary and metabasaltic Soldiers Cap Group (cover sequence 3), and the Williams and Naraku granitic Batholiths (1540-1500 Ma) are the predominant units in the Eastern Fold Belt (Blake and Stewart, 1992; Laing, 1998; Williams, 1998).

Three major orogenies occurred in the Mount Isa Inlier. The Barramundi Orogeny at c. 1870 Ma and its remnants outcrop in the older basement sequences of the Kalkadoon-Leichhardt Belt. This was followed by a second orogeny at around 1750-1730 Ma (Holcombe et al., 1991; Pearson et al., 1992), before the major Isan orogeny from ca. 1600 – 1500 Ma, which has been subdivided into a number of deformation events (eg. Bell, 1983; Blake, 1987; O'Dea et al., 1997; Rubenach and Barker, 1998; Giles et al., 2002; Betts et al., 2006). Using a simplified three-event deformation chronology for the Isan orogeny, D\(_1\) produced early layer-parallel fabrics, but its age and kinematics are unclear on a regional scale. D\(_2\) was the major deformation event, involving E-W shortening, and coinciding with peak metamorphism between 1600 and 1570 Ma. E-W shortening continued in D\(_3\) to at least 1530 Ma. D\(_3\) is thought be associated with much of the copper mineralization in the Mount Isa Inlier (Bell and Hickey, 1998; Laing, 1998).

Metamorphic grade generally decreases from upper amphibolite facies in the eastern Mount Isa Inlier to greenschist facies in the west (Foster and Rubenach, 2006). The peak of metamorphism has been suggested to be between 1550-1530 Ma based on U-Pb SHRIMP ages in the Mount Isa area (Connors and Page, 1995), but monazite age dating
in the Eastern Fold Belt suggests a peak metamorphic event between 1600 Ma and 1570 Ma (Foster and Rubenach, 2006).

Copper deposits in the Mount Isa Inlier study area have two primary styles of mineralization: brecciated sediment hosted deposits, and shear and fault controlled vein deposits (Blake et al., 1990). The brecciated sediment hosted copper deposits are most prevalent in the Western Succession, and include the Mount Isa copper deposit (255Mt @ 3.3% Cu). Matthäi et al. (2004) suggest that the Mount Isa Cu deposit formed by mixing of fluid from overlying metasedimentary rocks (Mount Isa Group) with a fluid from underlying metabasalts (Eastern Creek Volcanics) entering a brecciated contact zone. Copper mineralization at Mount Isa lies proximal to the Mount Isa fault zone, which is a potential fluid pathway from the Eastern Creek Volcanics. Matthäi et al. (2004) propose that this sequence is the source of the copper. Wyborn (1987) and Williams (1998) suggest that the copper mineralization and the breccias at Mount Isa were emplaced during the D₃ deformation event of the Isan Orogeny.

The Eastern Creek Volcanics have also been suggested as the source of the copper for the Mammoth-Esperanza deposits near Gunpowder (Scott and Taylor, 1982). Fluids transported along the Portal Fault and Mammoth-Mammoth Extended Fault system in the Mt Gordon fault zone initially leached copper from the Eastern Creek Volcanics, leading to the formation of the Mammoth deposit in the siliclastic Myally Subgroup (Scott and Taylor, 1982; Van Dijk, 1991). Mineralization at Esperanza occurs in the dolomitic Esperanza Formation in the footwall of the Esperanza Fault and proximal to the Mammoth-Mammoth Extended Fault system (Van Dijk, 1991). A D₃ timing is proposed for both deposits (Van Dijk, 1991).
The Mount Kelly copper deposit (Van Dijk, 1991) is hosted near a contact between the siliclastic Gunpowder Creek and mainly dolomitic Paradise Creek Formations. Mineralization is localized by the intersection of a D₃ fold zone with a D₁ thrust fault. The timing of the alteration and mineralization is considered to be similar to that at the Mount Isa deposit. The Lady Annie copper deposit is hosted entirely by the Paradise Creek Formation (equivalent to the Urquhart Shale at Mount Isa) and has formed during D₃ (Van Dijk, 1991). The source of the copper in these deposits is unknown.

Smaller copper deposits in the Western Succession occur in a variety of lithological units, with many located proximal to D₃ structures and some near older D₁ structures (Van Dijk, 1991). High grade, low tonnage shear and fault controlled vein copper deposits are more numerous in the Eastern Succession, with many containing a considerable quantity of gold (Blake et al., 1990). The Great Australia copper deposit (Cannell and Davidson, 1998) is hosted in the greenschist grade Toole Creek Volcanics (part of the Soldiers Cap Group) near a faulted contact with the Corella Formation. Mineralization occurs at the intersection of a N-S striking fault with a NE-SW striking extension of the Cloncurry Fault.

In summary, copper mineralization in the Mount Isa Inlier is hosted in a variety of cover sequence rocks and has a variety of styles. The deposits show strong structural and lithological controls (Blake et al., 1990; Williams, 1998; Oliver et al., 2001) and are associated with faults and lithological boundaries, which acted as pathways for focused fluid flow. Timing of mineralization is generally consistent with D₃ in the Isan orogeny.
Deposits containing gold have been excluded in this study because Cu-Au deposits have potentially different mineralization controls.

**MEASURING COMPLEXITY**

Complexity values across the Eastern and Western Successions of the Mount Isa Inlier were determined using data from the Northwest Queensland Mineral Province Report or NQMPR (Queensland Department of Mines and Energy et al., 2000). Equally spaced nodes along rock contacts or faults with a maximum spacing of 250m were extracted from the rock type and Proterozoic fault databases to represent these features in the fractal analysis. The 250m spacing was used as it is less than the minimum box size used in the box counting.

Fractal dimensions were measured in the Eastern and Western Succession study areas by shifting a box in 10 km increments over each study area, and calculating complexity in each box. The dimensions of the boxes were ¼ the size of each study area (126.65 km x 35.2 km in the Eastern Succession and 126.65 km x 48.5 km in the Western Succession). Box counting within each shifting box was carried out from a maximum box size of 126.65 km to a minimum box size of 494.7m. The regression to calculate the fractal dimension was calculated over a 75 km-7.5 km range of box sizes. Errors for the fractal dimension are given as standard errors of regression. Figure 2 shows the variation in complexity across the Western Succession.

This shifting box method was also used to determine the spatial variation in fractal dimension of 1687 copper deposits (1299 in the Eastern Succession and 388 in the Western Succession), extracted from the Queensland mineral occurrence database
Figure 2: Variation in raw complexity across the Western Succession. Low values in SW correspond to areas outside the Proterozoic inlier.
(Queensland Department of Natural Resources and Mines, 2005). The same box sizes and counting method were used as above and the regression was preformed over a 65 km-1.5 km range of box sizes. Using the same database, the tonnage of each deposit was extracted and the total tonnage for each of the regional areas from the shifting box counting method was calculated. The same method was used to extract data on the metal content for each copper deposit.

Spline functions were generated to fit the 3-dimensional surface of geological complexity for each study area. Splines are piecewise polynomials of n\(^{th}\) order used for interpolation of one dimensional or multi-dimensional data (Bonham-Carter, 1994). The polynomial functions provide a good approximation of the actual data for analysis. As the order of the function increases (i.e. increasing the number of terms in the function), more accurate approximations to the actual data can be achieved. For each study area examined the coordinates \((x, y)\) at the centre of the shifting box and their corresponding geological complexity value \(z\) were used to generate a spline function of the form:

\[
z(x, y) = a + bx + cy + dx^2 + ey^2 + fx^3 + gy^3 + \ldots
\]

Functions of the 4\(^{th}\) (up to \(x^4 + y^4\)), 5\(^{th}\) (up to \(x^5 + y^5\)) and 6\(^{th}\) orders (up to \(x^6 + y^6\)) were generated to fit the data. Each function was then differentiated in order to calculate the gradient at a given point on the surface. A grid with 1 km\(^2\) cell sizes was placed over each study area and the value of the gradient calculated for the coordinates at the intersections of the grid lines. This gave an average measure of the gradient in a particular region of each study area (Fig. 3). In order to compare the complexity
Figure 3: Variation in average complexity gradients across the Western Succession.
gradients and the complexity in a similar way, the average complexity values from the spline functions were calculated in the same fashion as the gradients.

Pearson’s moment correlations and Spearman’s rank correlations between various map parameters were calculated to test the strength of their spatial associations. Because the nature of the relationships between the complexity, complexity gradients and copper mineralization were not known a priori, correlations between parameters (excluding the regressions for the fractal dimensions from box counting) discussed in this text are Spearman’s rank correlations (Conover, 1999).

RESULTS

The faults and lithological boundaries within the Eastern Succession were found to be more complex than in the Western Succession, with fractal dimensions of $1.572 \pm 0.053$ compared to $1.404 \pm 0.050$ respectively.

Results of correlations between raw complexity values and mineral deposit data are shown in Table 1. Though the relationships in the Eastern and Western Successions vary, all correlations using raw complexity values were found to be statistically significant at the 95% confidence interval. The results for the Eastern Succession show a correlation of 0.817 between the complexity and the clustering of the copper deposits. Results show a correlation of 0.914 between complexity and the tonnage. Substitution of the metal content for the tonnage makes no appreciable difference to the correlation. The Western Succession indicates slightly different relationships between the complexity and the copper mineralization. A correlation of 0.693 was found between the clustering of the copper deposits and the complexity. The relationship between the
Table 1: Correlations (using Spearman’s rho) between complexity and copper deposit characteristics in the Mount Isa Inlier (* indicates significance at 95% confidence). FD = Fractal Dimension

<table>
<thead>
<tr>
<th>Study area</th>
<th>Correlate with</th>
<th>Spearman’s Rho</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Succession</td>
<td>No. of deposits</td>
<td>0.903 *</td>
</tr>
<tr>
<td></td>
<td>FD(deposits)</td>
<td>0.817 *</td>
</tr>
<tr>
<td></td>
<td>Tonnage</td>
<td>0.914 *</td>
</tr>
<tr>
<td></td>
<td>Metal</td>
<td>0.913 *</td>
</tr>
<tr>
<td>Western Succession</td>
<td>No. of deposits</td>
<td>0.923 *</td>
</tr>
<tr>
<td></td>
<td>FD(deposits)</td>
<td>0.693 *</td>
</tr>
<tr>
<td></td>
<td>Tonnage</td>
<td>0.914 *</td>
</tr>
<tr>
<td></td>
<td>Metal</td>
<td>0.914 *</td>
</tr>
</tbody>
</table>

complexity and the tonnage was found to be the same as that obtained in the Eastern Succession, 0.914.

Correlations between the average complexity and complexity gradients and copper occurrence data are shown in Table 2. Correlations for the 6th order spline functions are considered the most accurate due to their goodness of fit to the data (0.854 in the Eastern Succession and 0.841 in the Western Succession) and these values are discussed further. Results for the correlations with the average geological complexity indicate that there are high, positive correlations between the average geological complexity values and the copper occurrence data (Fig. 4a and b), including numbers of occurrences, clustering, tonnage, and metal content. Conversely, there are inverse relationships between the complexity gradients and the copper occurrence data (Figures 4c and d). All these correlations with one exception (complexity gradient with deposit clustering in the Eastern Succession) are significant at the 95% level.

North-South and East-West linear profiles were examined to determine whether using a linear complexity method for comparison with the tonnage of the deposits produced differing results to the two-dimensional method used. Figure 5 shows that profiles can produce some negative correlations between the average complexity and copper...
Figure 4: Graphs showing relationships in the Western Succession between (a) average complexity and the fractal dimension of copper occurrences, (b) average complexity and the tonnage of copper occurrences, (c) average complexity gradient and the fractal dimension of copper occurrences, and (d) average complexity gradient and the tonnage of copper occurrences.
Figure 5: Correlation between average complexity and copper tonnage for incremental N-S profiles (▲) and E-W profiles (▼) across the Western Succession and correlation between complexity gradients and copper tonnage for N-S profiles (○) and E-W profiles (●). The upper horizontal line represents the two-dimensional correlation between the average complexity and tonnage (0.768) and the lower horizontal line is the corresponding correlation between the complexity gradients and tonnage (-0.172).
Table 2: Correlations (using Spearman’s rho) of average complexity and complexity gradients with copper occurrence data: number of deposits (N), fractal dimension (FD), tonnage (T), and metal content (M). Fit indicates the goodness of fit of the function to the actual data for functions of the 4th, 5th and 6th order.

<table>
<thead>
<tr>
<th>Order</th>
<th>Correlate With</th>
<th>Eastern Succession</th>
<th>Western Succession</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Complexity</td>
<td>Complexity Gradient</td>
</tr>
<tr>
<td>4</td>
<td>Fit = 0.850</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.900*</td>
<td>-0.108*</td>
<td>0.354*</td>
</tr>
<tr>
<td>FD</td>
<td>0.813*</td>
<td>0.045</td>
<td>0.423*</td>
</tr>
<tr>
<td>T</td>
<td>0.880*</td>
<td>-0.122*</td>
<td>0.373*</td>
</tr>
<tr>
<td>M</td>
<td>0.882*</td>
<td>-0.120*</td>
<td>0.373*</td>
</tr>
<tr>
<td>5</td>
<td>Fit = 0.854</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.941*</td>
<td>-0.248*</td>
<td>0.727*</td>
</tr>
<tr>
<td>FD</td>
<td>0.777*</td>
<td>-0.098</td>
<td>0.519*</td>
</tr>
<tr>
<td>T</td>
<td>0.914*</td>
<td>-0.241*</td>
<td>0.763*</td>
</tr>
<tr>
<td>M</td>
<td>0.915*</td>
<td>-0.241*</td>
<td>0.763*</td>
</tr>
<tr>
<td>6</td>
<td>Fit = 0.854</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.936*</td>
<td>-0.276*</td>
<td>0.736*</td>
</tr>
<tr>
<td>FD</td>
<td>0.790*</td>
<td>-0.078</td>
<td>0.479*</td>
</tr>
<tr>
<td>T</td>
<td>0.912*</td>
<td>-0.276*</td>
<td>0.768*</td>
</tr>
<tr>
<td>M</td>
<td>0.913*</td>
<td>-0.277*</td>
<td>0.768*</td>
</tr>
</tbody>
</table>

Note: * indicates significance at 95% confidence.

tonnage when the two-dimensional correlation is positive, and a positive correlation between the complexity gradients and tonnage when its corresponding two-dimensional correlation is negative. These are the opposite relationships to the general, two dimensional cases.

**DISCUSSION**

Results shown in Table 1 indicate that a significant relationship exists between the raw complexity values and the copper mineralization in both the Eastern and Western Succession study areas. High correlations indicate that the complexity could have a high level of control over the clustering and endowment of copper.

Vein-hosted mineral deposits, such as those found predominantly within the Eastern Succession, form as a result of fluid flow and with the faults and lithological boundaries acting as fluid flow conduits, the relationship between the number and clustering of the
deposits and the complexity of the geology is expected (Sanderson and Zhang, 1999). Though the results in Western Succession differ slightly to those in the Eastern Succession, with rank correlations varying between approximately 0.7 and 0.9, it can be inferred that the complexity is a potential control on copper mineralization in each study area.

The relationship between copper endowment and complexity in the Western Succession is strong. The high tonnage copper deposits also have a high correlation with geological complexity in each study area. The area in the Western Succession with the highest complexity is centered on the Mammoth and Esperanza copper deposits, with the area of next highest complexity focussed on the Mount Isa copper deposit. These deposits lie along a N-S trending corridor of higher complexity that stretches from south of Mount Isa to north of Gunpowder (Fig. 6). Complexity could therefore be used as a tool to explore for large tonnage copper deposits within the Mount Isa Inlier. The spatial analysis suggests that exploration should target areas of higher complexity and comparatively low fractal dimensions for the distribution of the copper deposits. The exploration target area could be further reduced by decreasing the size of the shifting box.

The results in Table 2 indicate that there is a relationship between the complexity gradient and the copper endowment in both the Eastern and Western Successions, as Hodkiewicz et al. (2005) proposed for gold deposits in the Yilgarn craton. However, the results of the present study indicate the nature of the relationship for copper in the Mount Isa Inlier is opposite to that which has been shown for gold in the Yilgarn craton. Instead of the endowment increasing with the complexity gradients, this study shows an
Figure 6: Contour maps of raw complexity (left) and average complexity values (right) in the Western Succession. Major copper deposits (1 – Lady Annie, 2 – Mt Kelly, 3/4 – Mammoth & Esperanza, 5 – Hero, 6 – Mt Isa) are shown to sit proximal to regions of higher complexity.
inverse relationship between the complexity gradients and endowment. Although the relationship in the Western Succession is weaker than that in the Eastern Succession, the correlations in each study area indicate that the relationships between the complexity gradients and copper mineralization are still significant. The results indicate that the complexity may have a greater influence on copper mineralization than the complexity gradients.

The differing conclusions reached on the role of complexity gradients by Hodkiewicz et al. (2005) and those of this study may be due to the differences in the commodities and areas studied (geological factors), and/or to the approaches taken (methodological factors). Hodkiewicz et al. (2005) suggest that complexity gradients are significant for gold mineralization because they mark locations where transitions from the presence of dangling elements of a permeability network (high complexity) to low complexity backbone structure (their Fig.7) focused fluid flow. In the Mount Isa Inlier copper deposits, the high complexity itself is associated with copper mineralization. There are several possible geological reasons for the difference in the role of complexity vs complexity gradients between the two systems. Firstly, the possibility of post-mineralization changes in the distribution of complexity may obscure the true relationship between complexity, complexity gradients, and mineralization. This is unlikely at Mount Isa since copper mineralization generally occurred with the last significant tectonic event. Secondly, there may be differences between the two systems in the relative importance of faulting compared to physico-chemical changes at lithological contrasts in localizing mineralization. Lithological contrasts contribute substantially to the complexity at Mount Isa – hence analysis of the complexity or complexity gradients exclusively in terms of a permeability network may be less applicable because lithological contrasts are important apart from their possible role as fluid pathways.
Thirdly, there are many possible differences in the basic controls of mineralization between the two systems. The copper deposits in the Mount Isa Inlier are hosted in predominantly sedimentary sequences compared to the mesothermal Archaean gold deposits hosted in greenstone belts in the Yilgarn craton. Thus, the temperature, pressure, fluid composition, etc. were all potentially different during mineralization between the two study areas, which could have influenced the relationships between mineralization and complexity or complexity gradients.

The most obvious difference between the methods of the two studies is that this study approached the problem using a two-dimensional method for examining the variation in complexity and the corresponding gradients for comparison with the deposit characteristics, while the previous research by Hodkiewicz et al. (2005) looked in detail at comparisons with complexity and gradients over linear sections of the Bardoc Tectonic Zone and the Boulder-Lefroy Shear Zone. It is possible that complexity gradients are more important in the linear analysis because the permeability network model applies better to an analysis of a single, linear structure than it does to a two dimensional area. Independently of this possibility, however, this study has shown that there are significant local differences in the correlation results when linear profiles are used to calculate geological complexity correlations compared to the two dimensional method used in this study (Fig. 5). Therefore using a single linear profile may reverse the overall nature of the relationship between the geological complexity/complexity gradients and the tonnage locally, and affect the strength of that relationship.
Because the different methodologies in the two studies may have contributed to the different conclusions, it is not possible to resolve the suggestions above. A high priority in future studies should be to compare different mineralising systems with similar methodologies.

The complex distribution of the lithology across the Mount Isa Inlier can be attributed to the complex nature of the deformation history in the terrain. Multiple terrain scale deformation events coupled with local events and intrusions have created regions of high complexity. Complexity may be a response to increased energy in the system. Ord et al. (2007), suggest that kinetic energy and second order work during deformation can cause instability in a system, which can generate fractures on a micro-structural scale under continuous loading. During deformation, $2^{nd}$ order work is the product of the stress rate tensor and the plastic strain rate tensor with instability occurring when this product is less than or equal to 0. As the instability increases more fractures are generated, thus creating more pathways for fluid flow, which is critical in the formation of hydrothermal mineral deposits. This theory can potentially be expanded to regional scale structures such that areas with a higher dissipation of energy/work into the system will produce larger and denser fault networks, thus creating a region of higher geological complexity.

Blenkinsop and Sanderson (1999) proposed that the roll-off effect observed when using box counting to calculate the fractal dimension of the distribution of Archaean gold deposits, can be due to undiscovered deposits existing in the study area. We propose that a similar situation applies to the box counting method used to calculate the fractal dimension of geological complexity in both this study and the previous work by
Hodkiewicz et al. (2005). Evidence of a roll off effect is apparent for small box sizes (consistently starting at about 1000 m) used in calculating the geological complexity. Box sizes of greater than 1500 m were used in the fractal dimension calculations in order to avoid the effect of roll-off. It is proposed that the roll off effect for the geological complexity is due to the fact that the detail of mapping of the faults and lithologies is inevitably limited at the smallest scale. Similar to the explanation of Blenkinsop and Sanderson (1999), there may be “undiscovered”, i.e. unmapped, faults and lithological boundaries within the study area. These structures and rock type boundaries could be “undiscovered” due to being under cover, as well as due to limitations on the detail on mapping at the smallest scale. In order to demonstrate this effect, an 8 km x 8 km region of the study area was selected from NQMPR that had six different rock types (Fig. 7a). Boundaries between the rock types were removed progressively (Fig. 7b), from five down to one rock type, and box counting was carried out at each stage. Figure 8 shows that the onset of the roll-off effect occurs at larger box sizes as fewer boundaries are mapped, and that the fractal dimension decreases due to the slope of the log-log graph not being as steep as the number of “undiscovered” boundaries increases.

The identification and attribution of the roll-off effect given above has a significant positive advantage for studies of complexity. Even with a simplified GIS database, it is possible that some areas will have a higher degree of map detail than others, which is a likely artefact of the amount of exploration and mining that has occurred in certain areas, as well as degree of exposure. Any such inconsistencies in the detail of mapping have been accounted for in this study by measuring the complexity from the linear part of the
Figure 7: Faults and lithologic boundaries in an 8 km x 8 km study area in the Mount Isa Inlier centred on the point 376076.01 mE; 7723146.35 mN (MGA94 zone 54). Map (a) displays all mapped faults and lithologic boundaries from the NQMPR (Queensland Department of Mines and Energy et al., 2000) and (b) shows same area with 3 rock types combined.
Figure 8: Log-log plot of box size $r$ vs. number of boxes $N(r)$ showing how roll-off varies as the number of undiscovered boundaries increases. Data taken from study area shown in Figure 7.
relationship between number of boxes containing boundaries and box size, so that the fractal dimension is not affected by variations in the detail of mapping or exposure.

CONCLUSIONS

This study highlights the importance of complexity for copper mineralization in the Mount Isa Inlier. Regions with higher complexity, as measured by a fractal dimension, have the potential to transport large volumes of fluid and to provide physico-chemical contrasts, which are both critical in the formation of large hydrothermal ore deposits. There are strong positive correlations between complexity and both clustering and tonnage of copper deposits. The highest fractal dimensions were calculated around the Mammoth, Esperanza and Mount Isa copper deposits. The correlation between the complexity gradients and copper mineralization is significant but negative, and this relationship is much weaker than with the absolute complexity. Complexity and complexity gradients need to be analysed in two dimensions to reveal their full properties and to give an accurate representation of the relationship with mineralization. Based on the results obtained in this study, complexity can be used as an exploration targeting tool for large copper deposits in under-explored areas of the Mount Isa Inlier. Variations in mapping detail can be allowed for by measuring only the linear part of the relationship given by box counting.
An expanded de Wijs model for element enrichment by hydrothermal mineralization
ABSTRACT

Hydrothermal ore deposits form by enriching elements and minerals from background values to very high concentrations in small volumes of the crust. The de Wijs model provides a simple and widely used mathematical description of this process; however, it does not account for the increase in density which generally attends the formation of high specific gravity minerals in many mineral deposits. We present an expanded version of the de Wijs model to investigate the distribution of ore tonnage as well as grade. The expanded model generates a log-normal relationship between ore tonnage and grade. Continuous multifractal analysis of results from the new model using the method of moments technique predicts that ore grades are multifractal (as in the original de Wijs model) but that ore tonnage values are not multifractal. Production data from vein-hosted gold deposits in the Archaean Zimbabwe craton display the log-normal relationship between ore tonnage and grade, the multifractal nature of ore grade, and the non-multifractal nature of ore tonnage, as generated in the expanded de Wijs model.

INTRODUCTION

The spatial distribution and several other aspects of mineral deposits are fractal (e.g. Turcotte, 1986; Carlson, 1991; Cheng et al., 1994; Sanderson et al., 1994; Agterberg et al., 1996; Johnston and McCaffrey, 1996). Studies analyzing fractal aspects of mineral deposits typically deal with only one or two variables, such as vein thicknesses, or the x and y coordinates of mineral deposits. However, many aspects of mineral deposit research require a more complex approach that can accommodate additional variables. For example, the size of mineral deposits and their grade need to be evaluated as well as their spatial distribution. Multifractals can be used to study the spatial distribution of quantitative measures. Previous research has shown that multifractals can be used to
describe ore grade distributions, to separate geochemical anomalies, and to describe the concentration of elements in the crust as revealed by geochemical surveys (Agterberg et al., 1996; Roberts, 2005; Agterberg, 2007a).

Ore production data has also been examined using multifractal analysis on a mine scale (Roberts, 2005), and Cheng (1999b) showed that categorized data for deposit size might fit a discrete multifractal model. Turcotte (1989) showed several examples of a fractal relationship between ore grade and tonnage, and proved that such a fractal relationship is predicted by a modified de Wijs model. The de Wijs model redistributes elements such that as one area is enriched, another area is depleted (de Wijs, 1951, 1953; Agterberg, 2007b). This concept captures the fundamentals of many ore genetic models, namely the progressive enrichment of elements in parts of the crust and their corresponding depletion elsewhere. However, it does not explicitly deal with changes in density accompanying mineralization, and does not describe ore tonnage distributions.

This main aim of this study is to propose a theoretical model for describing the distribution of ore tonnage as well as grade through an expansion of the de Wijs model for element concentration. The distribution of ore tonnage is investigated by allowing for an increase in density at the site of ore deposition. The properties of this model are explored and compared with production data analyzed using the same techniques. A theoretical model that could predict ore tonnage as well as grade distributions would be very significant in assessing mineral resources and exploration, and to ore genesis studies.
CONSTRUCTION OF AN EXPANDED DE WIJS MODEL

The expansion of the de Wijs model proposed here allows for an increase in tonnage within each cell due to the generally higher density of ore minerals compared to rock forming minerals. Figure 1 illustrates the proposed model for distribution of ore tonnage in two dimensions. Using the original definitions specified by de Wijs (1951), a density term is added to tonnage of the host rock.

The initial concentration \( c_0 \) of an element \( (0 \leq c_0 \leq 1) \) in the host rock, initial tonnage of the host rock \( M \), and the initial ore tonnage \( M_0 \) can be defined. An enrichment factor \( \phi \) (for \( 0 \leq \phi \leq 1 \)), represents the amount of enrichment or depletion of an element from one cell to the next for subsequent iterations of the model (Fig. 1). The de Wijs model is effectively a multiplicative cascade (iterative model) in which the ore tonnage at the \( n^{th} \) iteration \( (M_n) \) of the expanded model, can be derived in two stages. Firstly, the concentration of an element within the model at stage \( n \) \( (c_n) \) can be generalized to give the relationship:

\[
   c_n = c_0 (1 + \phi)^{n-r} (1 - \phi)^r
\]

where \( r \) is an index based on the stage number \( n \) of the model and is calculated from the binomial theorem (cf. de Wijs, 1951), which can be re-arranged to:

\[
   n = \frac{\ln \left( \frac{c_n}{c_0} \right) - r \ln \left( \frac{1 - \phi}{1 + \phi} \right)}{\ln(1 + \phi)}
\]

Secondly, the ore tonnage within a cell \( (M_n) \) can be calculated by multiplying the initial ore tonnage \( (M_0) \) of the cell as specified in the original de Wijs model by the concentration of the cell \( (c_n) \) to give the metal content and then adding this metal content to the host rock tonnage of the cell, thus giving each cell a density factor.
\[
\begin{array}{c|c|c}
\frac{M}{4} + \frac{M_2}{4} c_0 (1 + \phi)^2 & \frac{M}{4} + \frac{M_2}{4} c_0 (1 + \phi)(1 - \phi) \\
\frac{M}{4} + \frac{M_2}{4} c_0 (1 + \phi)(1 - \phi) & \frac{M}{4} + \frac{M_2}{4} c_0 (1 - \phi)^2 \\
\end{array}
\]

\[
\begin{array}{c|c|c|c|c}
\frac{M}{16} + \frac{M_8}{16} c_0 (1 + \phi)^4 & \frac{M}{16} + \frac{M_8}{16} c_0 (1 + \phi)^3 (1 - \phi) & \frac{M}{16} + \frac{M_8}{16} c_0 (1 + \phi)^2 (1 - \phi)^2 & \frac{M}{16} + \frac{M_8}{16} c_0 (1 + \phi) (1 - \phi)^3 & \frac{M}{16} + \frac{M_8}{16} c_0 (1 - \phi)^4 \\
\frac{M}{16} + \frac{M_8}{16} c_0 (1 + \phi)^3 (1 - \phi) & \frac{M}{16} + \frac{M_8}{16} c_0 (1 + \phi)^2 (1 - \phi)^2 & \frac{M}{16} + \frac{M_8}{16} c_0 (1 + \phi) (1 - \phi)^3 & \frac{M}{16} + \frac{M_8}{16} c_0 (1 - \phi)^4 \\
\frac{M}{16} + \frac{M_8}{16} c_0 (1 + \phi)^2 (1 - \phi)^2 & \frac{M}{16} + \frac{M_8}{16} c_0 (1 + \phi) (1 - \phi)^3 & \frac{M}{16} + \frac{M_8}{16} c_0 (1 - \phi)^4 \\
\frac{M}{16} + \frac{M_8}{16} c_0 (1 + \phi) (1 - \phi)^3 & \frac{M}{16} + \frac{M_8}{16} c_0 (1 - \phi)^4 \\
\end{array}
\]

**Figure 1:** Proposed two-dimensional model for distribution of ore tonnage based on expanded version of the de Wijs distribution model (de Wijs, 1951, 1953). Parameters as described in the text.
which is the last term on the right hand side of the following equation (this last term is absent from the original de Wijs model):

\[ M_n = M_0 \frac{1 - c_0 + c_n}{4^n} \]

Given that \( M \) represents the initial ore tonnage \((M_0)\) minus the initial metal content \((M_0c_0)\), this can be rearranged to show that

\[ \frac{M_n}{M_0} = \frac{1 - c_0 + c_n}{4^n} \]

Thus taking the logarithm of each side and substituting for \( n \),

\[ \ln \left( \frac{M_n}{M_0} \right) = \ln(1 - c_0 + c_n) - n \ln 4 \]

\[ \ln \left( \frac{M_n}{M_0} \right) = \ln(1 - c_0 + c_n) - \frac{\ln \left( \frac{c_n}{c_0} \right) - r \ln \left( \frac{1 - \phi}{1 + \phi} \right)}{\ln(1 + \phi)} \ln 4 \]

which can then be rearranged and simplified to give the relationship between ore grade and tonnage at a given iteration \( n \) of the model

\[ \frac{M_n}{M_0} = (1 - c_0 + c_n) 4^{\frac{\left( \frac{r}{\ln(1 + \phi)} - \frac{1}{\ln(1 - \phi)} \right)}{\ln(1 + \phi)}} \]

The relationship between ore tonnage and grade derived for the expanded model above differs by a factor of \( 1 - c_0 + c_n \) from the corresponding original two-dimensional de Wijs model. Turcotte (1989) has shown that the original de Wijs model predicts a lognormal relationship between the cumulative ore tonnage and grade as \( n \to \infty \). However, it is contentious whether the relationship between actual cumulative ore tonnage and grade is power-law (fractal) or lognormal (Turcotte, 1989). In order to examine the new relationship between ore tonnage and grade derived above, the ore tonnages for the cells at a particular iteration of the expanded de Wijs model were calculated using the two-
dimensional model. Figure 2 illustrates that the expanded de Wijs model predicts a lognormal relationship between cumulative ore tonnage and grade. This relationship is also a property of one-dimensional versions of the original de Wijs model (Turcotte, 1986, 1989).

Using a similar methodology to that outlined by Xie and Bao (2004), a 128 x 128 grid was generated after seven iterations of the expanded de Wijs model with an initial concentration of $c_0 = 2 \times 10^{-7}$ (cf. Phillips et al., 1987), and an enrichment factor of $\varphi = 0.4$ (cf. Agterberg, 2007b). Ore tonnage distributions were generated with an initial host rock tonnage $M = 4.42368 \times 10^{10}$ t (assuming each cell is 1 km x 1 km x 1 km, and has a mean crustal density of $2.7 \times 10^3$ kg/m$^3$). Partition functions $\chi_q(\varepsilon)$ and the resultant $f(\alpha)$-curves were generated for a range of real numbers $q$ from -10 to 10 in steps of 1 using the method of moments technique outlined below for continuous multifractal analysis.

DETERMINING MULTIFRACTALITY

In a multifractal, spatial variations in the value of a property are assessed by a multifractal measure. If the measure shows self-similarity, it can be described as a multifractal (Evertsz and Mandelbrot, 1992). To determine whether a multifractal is continuous in two dimensions, a grid of equal size boxes is placed over the study area with the box size $\varepsilon$, and the number of boxes $N(\varepsilon)$ noted. If a box contains a single data point, the value of the property at that point is applied to the whole box. If a box contains more than one data point, the values assigned to each data point in that box are averaged. The multifractal measure $\mu(\varepsilon)$ is calculated by multiplying the value assigned
Figure 2: Log-log plot of ore tonnage with a grade greater than a specified value vs. ore grade for the expanded de Wijs ore tonnage model (de Wijs, 1951, 1953).
to the box by the area of the box. The partition function $\chi_q(\varepsilon)$ for each box size and a range of real numbers $q$ is calculated, allowing the mass exponent function $\tau(q)$ to be estimated and the function $\alpha$ evaluated (in this study) from the derivative of a 4th order polynomial in order to determine the multifractal spectrum $f(\alpha)$. The method of moments technique for evaluating these parameters is detailed in several studies (eg. Evertsz and Mandelbrot, 1992; Agterberg et al., 1996; Roberts, 2005).

VEIN-HOSTED GOLD PRODUCTION DATA
A study area in the Zimbabwe craton was chosen for analysis, where gold mineralization is hosted primarily in Archaean greenstone sequences and is generally considered to have formed in the late Archaean (Blenkinsop, 1994). Gold production is recorded in the database of the Gold Deposits of Zimbabwe (Bartholomew, 1990), which lists location, cumulative gold production reported to the Ministry of Mines to the end of 1984, and average recovery grade based on production to 1977 (to 1964 for mines with less than 300 kg production), for all deposits that produced more than 100 kg Au, for which it is considered complete in that all known production records are captured in the database (Bartholomew, 1990; Blenkinsop and Sanderson, 1999). Brief geological descriptions of the mines are also given, which were used to filter the data to include only vein-hosted gold deposits. Since not all deposits with a listed ore tonnage (460 deposits) had a listed grade (462 deposits) and vice versa, slightly different subsets of data were used for grade and tonnage analysis. The maximum and minimum grades were 197.8 g/t and 1.2 g/t and the corresponding figures for tonnage were 3420495600 t and 208800 t. Limiting the study to a single deposit type optimizes the data set for comparison with the model, which only considers a single mechanism for deposit formation, at least in the simple formulation used here.
Each data subset was then studied using continuous multifractal analysis as outlined above. The latitude and longitudes were converted to Eastings and Northings (UTM (WGS 84), Zone 35) for the analysis. Table 1 gives the coordinates and grade and ore tonnage values for 10 sample locations extracted from the dataset used in the analysis.

### Table 1: Coordinates (in Eastings and Northings: UTM (WGS 84), Zone 35), and corresponding grade and ore tonnage values for 10 sample locations of vein-hosted gold deposits in the Zimbabwe craton (Bartholomew, 1990).

<table>
<thead>
<tr>
<th>Eastings (m)</th>
<th>Northings (m)</th>
<th>Grade (g/T)</th>
<th>Ore Tonnage</th>
</tr>
</thead>
<tbody>
<tr>
<td>491706</td>
<td>13446998</td>
<td>3.8</td>
<td>1444000</td>
</tr>
<tr>
<td>467888</td>
<td>13546137</td>
<td>12.5</td>
<td>7225000</td>
</tr>
<tr>
<td>467180</td>
<td>13545132</td>
<td>18.4</td>
<td>6329600</td>
</tr>
<tr>
<td>466822</td>
<td>13540406</td>
<td>5.3</td>
<td>969900</td>
</tr>
<tr>
<td>463027</td>
<td>13546618</td>
<td>8.5</td>
<td>4335000</td>
</tr>
<tr>
<td>462489</td>
<td>13356169</td>
<td>11.2</td>
<td>2408000</td>
</tr>
<tr>
<td>423938</td>
<td>13508356</td>
<td>7.8</td>
<td>62368800</td>
</tr>
<tr>
<td>423464</td>
<td>13549545</td>
<td>22.6</td>
<td>8904400</td>
</tr>
<tr>
<td>414178</td>
<td>13454106</td>
<td>8.6</td>
<td>5977000</td>
</tr>
<tr>
<td>407608</td>
<td>13464777</td>
<td>10.5</td>
<td>19960500</td>
</tr>
</tbody>
</table>

**RESULTS**

The plots of $\chi_q(\varepsilon)$ vs. $\varepsilon$ derived using the expanded de Wijs model for ore tonnage can be seen in Figure 3(a) which shows that the plots are straight as required for multifractals by Evertsz and Mandelbrot (1992). Figure 3(b) illustrates the corresponding plot of $f(\alpha)$ vs. $\alpha$ as derived from the method of moments continuous multifractal technique, which shows that $f(\alpha) = \alpha = 2$ for all values of $q$. This result violates the condition which states that the $f(\alpha)$-curve must be parabolic (Evertsz and Mandelbrot, 1992) for a multifractal.

Figure 4 illustrates the relationship between ore tonnage with a grade greater than a specified value and the ore grade for the Zimbabwe craton production data. The plot illustrates that the data is closer to a lognormal relationship between the ore tonnage and grade than a fractal relationship. Continuous multifractal analysis of the tonnage and
Figure 3: Relationship between (a) natural log of $\chi_q(\varepsilon)$ and natural log of $\varepsilon$, and (b) $f(\alpha)$ and $\alpha$, of the expanded de Wijs model for ore tonnage (de Wijs, 1951).
Figure 4: Log-log plot of ore tonnage with a grade greater than a specified value vs. ore grade for vein-hosted gold data in the Zimbabwe craton.
grade datasets for the Zimbabwe craton suggests that only the grade dataset could be described using a continuous multifractal model. The plots of $\chi_q(\varepsilon)$ vs. $\varepsilon$ as seen in Figure 5a and 5b can reasonably be described as linear. However, only the resultant $f(\alpha)$ vs. $\alpha$ curve for the grade data (Fig. 5a) was then found to fit a parabolic shape and thus to be multifractal. It should be noted that the estimate of $\tau(q)$ from the partition function plot of the tonnage data was taken over the smallest three values of $\ln(\varepsilon)$ in order to obtain the most accurate slope.

DISCUSSION

A major advantage of the model and methods of analysis used here is that they use only relative distributions of tonnages or grades. Therefore production data can be compared with the model outputs, even though the production data will lack undiscovered deposits, so long as relative distributions of ore tonnage and grade in the production data are comparable to the natural mineralized system. Although there is no direct way to test this, the similarity between the multifractal nature of the database and geochemical survey results discussed below suggests that it is true for grades at least.

Multifractal analysis has established that the relationship between ore tonnage and grade can be described by either lognormal or power-law distributions depending on some unspecified threshold in the size of the deposits being investigated (Agterberg, 1995). Analysis of the expanded de Wijs element distribution model described above indicates that the predicted relationship between cumulative ore tonnage and ore grade is closer to lognormal than power law (Fig. 2), as in the original de Wijs model with a constant ore tonnage (Turcotte, 1989). The Zimbabwe craton production data appears to
a.

\[
\ln(\chi_q(\varepsilon)) = 3
\]

b.

\[
\ln(\chi_q(\varepsilon)) = 3
\]
Figure 5: Multifractal relationships for Zimbabwe craton vein-hosted gold production data between (a) natural log of partition function $\chi_q(\varepsilon)$ and natural log of box size $\varepsilon$ for grade data, (b) natural log of partition function $\chi_q(\varepsilon)$ and natural log of box size $\varepsilon$ for tonnage data, (c) $f(\alpha)$ and $\alpha$ for grade data, and (d) $f(\alpha)$ and $\alpha$ for tonnage data.
have a lognormal relationship between ore tonnage and grade, but in view of the uncertainty in the nature of this relationship suggested by the Agterberg (1995) study, better comparisons between models and production data may be made by investigating the multifractal properties of tonnage and grade.

Previous studies have shown that the element concentration distributions predicted from the de Wijs model can be described by continuous multifractals (Xie and Bao, 2004; Agterberg, 2005, Agterberg, 2007a, b). The expansion of the de Wijs model may suggest a more realistic way to describe the distribution of enrichment and depletion of elements within the model, and the empirical derivation of the ore tonnages and subsequent analysis using the method of moments technique indicates that the ore tonnage is not multifractal. Figure 3b shows that $f(\alpha) = \alpha = 2$ which suggests that the expanded de Wijs model is represented by the integer Euclidean dimension. In a recent study, Cheng (2007) suggests that when $\alpha = 2$ is constant, the ore tonnage contained within given area centred on a specified point divided by the size of the area will remain constant independent of the size of the area. Due to the addition of the constant host rock tonnage, the ratio between the maximum and minimum ore tonnage for the expanded de Wijs model after 7 iterations is 1.000003, almost constant. It is possible that after running the model for thousands or millions of iterations this ratio would increase and some variability may be seen in $\alpha$ (and subsequently $f(\alpha)$). Agterberg (2001) discusses the effect of adding a constant value (which in this study is effectively the mass of the host rock) to what was originally a multifractal distribution (the concentration values in this study) and how this constant can distort the results. A further study discusses how variation of input parameters such as the enrichment factor and initial concentration can affect multifractal analysis (Agterberg, 2007a).
Turcotte formulated models for examining the distribution of ore grade and tonnage for both one dimensional (Turcotte, 1989) and three dimensional (Turcotte, 1986) scenarios based on modifications of the de Wijs concentration model (de Wijs, 1951). These studies assumed a constant density for ore tonnage. The Turcotte model does not predict multifractal grade distributions but rather Pareto distributions (Agterberg, 2005, 2007b).

Figure 5a and 5b show that the plots of $\chi_q(\varepsilon)$ vs. $\varepsilon$ for production data from the Zimbabwe craton can be considered linear as necessary for continuous multifractal analysis using the method of moments technique. However, analysis of the multifractal spectrum $f(\alpha)$ for the production data suggests that only the grade dataset can be described using a multifractal model (Fig. 5a and c), with the tonnage dataset failing the criteria outlined for the $f(\alpha)$-curve by Evertsz and Mandelbrot (1992). It has been suggested that estimates of $f(\alpha)$ can be unreliable about the point $q=1$ (Cheng, 1999a), but the curve for the Zimbabwe craton tonnage data (Fig. 5d) deviates from the parabola for a much wider range of values for $q$. The estimates of the values of $f(\alpha)$ are also unrealistic as several are shown to be greater than 2 and others are negative. An explanation for such anomalies in terms of the randomness of the values being examined and subsequent probability distributions is provided by Mandelbrot (2003).

Several studies of element concentrations from geochemical surveys (Agterberg et al., 1996; Cheng, 1999c; Xie and Bao, 2004) illustrate multifractal plots for $\chi_q(\varepsilon)$ vs. $\varepsilon$ and $f(\alpha)$ vs. $\alpha$ for which are even closer to the de Wijs model predictions than the plots for grade data in this study. The closer fits are an expected consequence of the difference between data from geochemical surveys and ore grade data. Geochemical datasets
containing stream sediment or rock chip data are sampled at essentially random locations, thus containing a fuller spectrum of data, from low concentrations bordering on the detection limit to the high end, compared to grade data that will emphasize the higher concentrations. Still, Figure 5 shows that ore grade can also be described by a multifractal model. Given that element concentrations from geochemical datasets have been shown to have multifractal distributions, it is expected that ore grade data should have multifractal properties, as the fractal nature of the data implies scale invariance, with the ore grade data simply occurring at one extreme of the scale.

The results obtained in this study are not conclusive evidence that production data or natural distributions of ore conform to any particular model distribution. However, analysis of the expanded de Wijs model and mineral production data using the same methods does reveal that similar distributions can be observed for a theoretical model (the expanded de Wijs model) and vein-hosted gold production data from the Zimbabwe craton. Neither the de Wijs model, nor the expanded version, predict the multifractal characteristics of tonnage and grade data in addition to the commonly accepted fractal tonnage-grade relationship for production data (de Wijs, 1951; Turcotte, 1989). This study expands the data sets that have been analysed by fractal and multifractal methods, hopefully leading to the selection or development of appropriate theoretical models in the future, and providing useful empirical ways of analyzing production data at present.

CONCLUSIONS

A new model for mineralization is presented that predicts the distribution of ore tonnage in addition to grades, based on expanding the de Wijs model for element redistribution by assigning a density term. This model produces a lognormal relationship between
cumulative ore tonnage and grade, and predicts that grade (concentration) is multifractal. These characteristics are observed for gold production data from the Zimbabwe craton when analyzed using the same methodology, establishing that a multifractal relationship can hold for ore grade data in addition to element concentration data. The expanded de Wijs model predicts that ore tonnage is not multifractal, a result also obtained for ore tonnage data in the Zimbabwe craton. The multifractal properties of grade and ore tonnage may be more reliable ways to compare models with production data than ore tonnage-grade relationships.
SECTION D

Factors affecting fluid flow in strike-slip fault systems: coupled
deformation and fluid flow modelling with application to the western
Mount Isa Inlier, Australia
ABSTRACT
Deformation and focussed fluid flow within a mineralized system are critical in the genesis of hydrothermal ore deposits. Dilation and integrated fluid flux due to coupled deformation and fluid flow of simple reactivated strike-slip fault geometries were examined using finite difference analysis in three-dimensions. A series of generic fault bend and fault jog geometries consistent with those seen in the western Mount Isa Inlier were modelled, in order to understand how fault geometry parameters influence the dilation and integrated fluid flux. Fault dip, fault width, bend/jog angle and length were varied, and a cross-cutting fault and contrasting rock types were included. The results demonstrate that low fault dips, the presence of contrasts in rock type, and wide faults produce highest dilation and integrated fluid flux values. Increasing fault bend lengths and angles increases dilation and integrated fluid flux, but increasing fault jog length or angle has the opposite effect. There is minimal difference between the outputs from the releasing and restraining fault bend and jog geometries. Model characteristics producing greater fluid flows can be used in a predictive capacity in order to focus exploration on regions with more favourable fault geometries.

INTRODUCTION
Deformation and fluid flow are critical factors for hydrothermal mineralization (Ord, 1990; Laing, 1998; Cox, 1999; Garven et al., 2001; Oliver et al., 2001; Tripp and Vearncombe, 2004; Cox, 2005; Bonson et al., 2007). Coupling of these factors in numerical models can lead to new insights into different mineralizing systems, with implications for ore genesis and potential identification of exploration targets (Oliver et al., 2001; Gow et al., 2002; Zhang et al., 2003; McLellan et al., 2004; Rawling et al., 2006; Schaub et al., 2006). Faults (and especially fault bends, jogs, and intersections),
and contacts between different lithostratigraphic units can create an environment conducive to increased fluid flow in the system (Craw, 2000; Allibone et al., 2002a; Cox, 2005; Hodkiewicz et al., 2005; Ford and Blenkinsop, 2008).

Both strike-slip and dip-slip faulting are commonly investigated in two-dimensional modelling (Zhang and Sanderson, 1996; Chester and Fletcher, 1997; Sanderson and Zhang, 1999; Chester and Chester, 2000; Oliver et al., 2001; Zhang et al., 2003; McLelland et al., 2004), with three-dimensional modelling experiments generally focusing on dip-slip faulting (Egan et al., 1999; Gow et al., 2002; Sorjonen-Ward et al., 2002; Rawling et al., 2006). However, two dimensional models of strike-slip faulting do not necessarily provide a good representation of fluid flow during deformation. Brankman and Aydin (2004) took steps to address this issue by modelling a constant overstep fault jog geometry in strike-slip deformation using a boundary element code to examine the effect of variation of the stress regime and to reinterpret the deformation history in three-dimensions. No published example has been found of a numerical modelling study of three dimensional strike-slip fault systems examining the effect of variable fault geometry.

Varying fault geometries in coupled deformation and fluid flow models has the potential to produce vastly different outputs. Previous studies of coupled deformation and fluid flow models for investigating mineralizing systems present qualitative approaches for analyzing the results obtained from numerical modelling (Oliver et al., 2001; Gow et al., 2002; Nemčok et al., 2002; Cox and Ruming, 2004; Matthäi et al., 2004; McLelland et al., 2004). Relatively few studies have presented a quantitative analysis of the model outputs (Sanderson and Zhang, 1999; Harris et al., 2003;
Sanderson and Zhang, 2004). While qualitative analysis is important to appraise the significant controlling variables from a large number of model outputs, outputs may also need to be measured quantitatively to understand the relative importance of different factors on model results in detail.

The aims of this paper are to systematically investigate and quantify the effect of different fault bend and jog geometries and rock types on the results of three-dimensional coupled deformation and fluid flow models of the reactivation of pre-existing strike-slip fault systems. These results may assist with mineral exploration.

The Western Succession of the Mount Isa Inlier hosts some of the largest copper deposits within the region, such as Mount Isa, Mammoth, and Esperanza, which are associated with regional steeply dipping N-S striking structures (Van Dijk, 1991; Drummond et al., 1998). Model geometries and subsequent results examined in this study are characteristic of Mount Isa Inlier geology at the time of copper mineralization, and are also a generic exploration of fluid flow in strike-slip fault systems.

**REGIONAL GEOLOGY**

The western Mount Isa Inlier can be separated from the remainder of the outcropping Proterozoic province based on the stratigraphy and seismic refraction data, which shows that a terrain boundary may exist near the Pilgrim Fault (Blake and Stewart, 1992; McDonald et al., 1997). To the west of this line, the stratigraphy is referred to as the Western Succession. The Western Succession is dominated by N-S to NE striking structures (Scott and Taylor, 1982; Bell et al., 1988; Nijman et al., 1992; Queensland Department of Mines and Energy et al., 2000). These structures were formed or
reactivated during the major D$_2$ E-W shortening event (c. 1590 Ma) (Bell et al., 1988; Laing, 1998). Further, possibly strike-slip, reactivation of these faults occurred during D$_3$ (c. 1550 Ma), also an approximately E-W shortening event, and perhaps as late as the Cambrian and Ordovician (Feltrin et al., 2003; Mark et al., 2004). Seismic profiles indicate that the majority of faults in the region are steeply dipping (Drummond et al., 1998; MacCready, 2006).

Major fault zones in the Western Succession include the Western Border, Mount Isa, and Mount Gordon fault zones, which are steeply dipping N-S to NNE striking structures (Van Dijk, 1991; Drummond et al., 1998). Splays off each of these major structures have variable strikes. Previous studies have suggested a spatial relationship between major copper orebodies and fault bends and fault intersections within the Mount Isa Inlier (Oliver et al., 2001; Ford and Blenkinsop, 2007). Figure 1 illustrates a number of copper deposits in the Gunpowder region of the Western Succession proximal to fault bends, fault jogs, and fault intersections.

Copper deposits in the Western Succession are predominantly hosted by brecciated sediments adjacent to faults (Scott and Taylor, 1982; Blake et al., 1990; Van Dijk, 1991). The lithostratigraphic units that host these deposits vary distinctly over the region, and the deposits are commonly proximal to major faults. For example, the Lady Annie Cu deposit in the Lawn Hill Platform is hosted by the McNamara Group, which is dominated by sideritic and locally carbonaceous shales, mudstones, and sandstones, and is proximal to the Western Border fault zone (Van Dijk, 1991). The world class Mount Isa copper deposit is hosted by the Urquhart Shale and sits immediately above
Figure 1: Map illustrating copper deposits (★) in the Gunpowder region of the Western Succession of the Mount Isa Inlier proximal to (a) a fault bend, (b) a fault jog (with a cross-cutting fault), and (c) a fault intersection. Faults are interpreted from the Northwest Queensland Mineral Province Report (Queensland Department of Mines and Energy et al., 2000). Copper deposit locations extracted from the Queensland Mineral Occurrence Database (Queensland Department of Natural Resources and Mines, 2005). Inset illustrates location of the three tectonic divisions of the Mount Isa Inlier with the Western Succession comprising of the Western Fold Belt and the Kalkadoon-Leichhardt Belt (Blake and Stewart, 1992; McDonald et al., 1997).
the Eastern Creek Volcanics (metabasalts) (Wyborn, 1987; Matthäi et al., 2004). The copper deposit lies just to the east of the Mount Isa fault zone, which has been proposed as a fluid and heat conduit in the mineralizing system (Matthäi et al., 2004). The Mammoth and Esperanza copper deposits are both located within the Mount Gordon fault zone north of Mount Isa, near Gunpowder, with Mammoth being hosted by the Myally Subgroup (quartzite, sandstone, and siltstone) and Esperanza hosted by the Esperanza Formation (dolostone and chert) (Scott and Taylor, 1982; Van Dijk, 1991; Nijman et al., 1992).

NUMERICAL MODELLING

This study aims to investigate generic controls on deformation, fluid flow and possible mineralization based on the general Western Succession Mount Isa geology, rather than specific local controls. The effects of different fault geometries, rock types and a combination of the two, are tested in three-dimensional models to determine the most favourable variables in terms of potential for hydrothermal copper mineralization in the Western Succession. Using Fast Lagrangian Analysis of Continua in Three Dimensions (FLAC3D ©) (Itasca Consulting Group, 2002), coupled deformation and fluid flow models were constructed and tested to determine which configurations had the highest mineralization potential based on those with the highest dilation and fluid flux values. Table 1 summarises the models tested.

A simple fault bend geometry is shown in Fig. 2 with the length of the fault bend/jog ($L$), dip ($D$), width of fault ($w$), and orientation of fault bend/jog relative to North ($\theta$,
Table 1: Summary of model configurations tested.

<table>
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<th>Model No.</th>
<th>Bend/Jog</th>
<th>Rock Type(s)</th>
<th>θ</th>
<th>L (m)</th>
<th>D (m)</th>
<th>W (m)</th>
<th>X-Cut Dilation Ratio</th>
<th>IFF Ratio</th>
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ECV = Eastern Creek Volcanics (metabasalts); MSG = Myally Subgroup (quartzite); Syb = Sybella Granite; Urq = Urquhart Shale

* Note: Model 2 and Model 29 failed to run to 10% shortening.
Figure 2: Fault bend geometry (Model 3) indicating values varied during FLAC$^{3D}$ modelling: length of fault bend ($L$), dip ($D$), orientation of fault bend/jog ($\theta=\phi$), and width of fault ($w$).
positive values clockwise from N, negative values anti-clockwise) being varied in the models. Releasing and restraining bends and jogs are examined in order to compare the results with the study of Mickelthwaite and Cox (2004) that suggested both were equally prospective. Figures 3 and 4 illustrate the basic geometry of the fault jog models and intersecting fault models respectively. The effect of parameter variation was evaluated by varying each parameter from a standard geometry in which \( L = 2500 \text{ m} \), \( \theta = -150^\circ \), \( D = 90^\circ \), and \( w = 50 \text{ m} \).

Constitutive relationships and lithological properties

A Mohr-Coulomb constitutive model was used, which is appropriate for representing the elastic-plastic deformation in the mid to upper crust, with fluid flow obeying Darcy’s Law for flow in a porous media (Oliver et al., 2001; McLellan et al., 2004; Oliver et al., 2006). Vermeer and de Borst (1984) summarize the Mohr-Coulomb constitutive model by defining the elastic moduli, yield functions for shear and tensile failure, and the corresponding functions for plastic strain related to yielding. Cohesion, friction angle and tensile strength can be used to define the yield functions. Materials will initially deform elastically up to a yield point, at which point the material will deform plastically (irreversibly). The plastic deformation is associated with shear or tensile failure, which leads to dilatancy in the material. Fluid flux in a system defined by Darcy’s Law is governed by the conductivity and hydraulic head \((H)\), which is related to elevation above a given point, acceleration due to gravity, pore fluid pressure and the fluid density. The equation for Darcy’s law is given by

\[
V_i = k_j \frac{\gamma_f}{H_f} \left( \frac{\partial H}{\partial x_j} \right)
\]
Figure 3: Fault jog geometry (Model 21) indicating values varied during FLAC$^\text{3D}$ modelling: length of fault bend ($L$), dip ($D$), orientation of fault bend/jog ($\theta=\varphi$), and width of fault ($w$).
Figure 4: Fault bend geometry with a cross-cutting fault (Model 18) indicating values varied during FLAC\textsuperscript{3D} modelling: length of fault bend ($L$), dip ($D$), orientation of fault bend/jog ($\theta=\phi$), and width of fault ($w$).
where $H$ is the previously defined hydraulic head, $V_i$ is the Darcy fluid velocity ($\text{ms}^{-1}$), $k_{ij}$ is the permeability tensor ($\text{m}^2$), $\gamma_f$ is the specific weight of the material ($\text{kgm}^2\text{s}^{-2}$), $\eta_f$ is the fluid viscosity ($\text{kgm}^2\text{s}^{-1}$) and $x_j$ is the position of a point in the material (McLellan et al., 2004).

During plastic deformation, high strain can cause positive dilation, which is governed by the dilation angle $\Psi$ where:

$$\sin \psi = \varepsilon_v^p / \gamma^p$$

and $\varepsilon_v^p$ is the plastic volumetric strain rate and $\gamma^p$ is the plastic shear strain rate (McLellan et al., 2004).

This dilation (or contraction) can cause a change in pore pressure, which in turn affects the hydraulic head, and thus the fluid flux within the system. The dilation also leads to changes in the effective stress, thus affecting plastic deformation. This feedback loop between the deformation and fluid flow continues in a coupled manner. More comprehensive explanations of the Mohr-Coulomb constitutive model, Darcy’s Law, and the coupling of deformation and fluid flow are provided by Vermeer and de Borst (1984), Ord and Oliver (1997), Oliver et al. (2001) and McLellan et al. (2004).

The strike of the main faults in the models is N-S, similar to the orientations of the Western Border fault zone (N-S), Mount Isa fault zone (N-S) and the Mount Gordon fault zone (NNE), which are proximal to the most significant copper orebodies in the Western Succession. Additional geometries considered include an E-W striking fault through the middle of the model, similar to a set of faults in this general orientation in the Western Succession (e.g. Fig. 1). Many of these E-W trending faults have been
Table 2: Material Properties for the FLAC\textsuperscript{3D} Models (cf. Oliver et al., 2001; McLellan et al., 2004)

<table>
<thead>
<tr>
<th></th>
<th>ECV</th>
<th>MSG</th>
<th>Sybella</th>
<th>Urquhart</th>
<th>Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m\textsuperscript{3})</td>
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<td>2700</td>
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<td>5</td>
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</tbody>
</table>

ECV = Eastern Creek Volcanics (metabasalts); MSG = Myally Subgroup (quartzite); Sybella = Sybella Granite; Urquhart = Urquhart Shale

interpreted as half-graben structures and have been related to the copper mineralization in the region (cf. Gibson and Hitchman, 2005). The dimensions of all models were E-W=10 km, N-S=8 km and depth=5 km.

Properties of the surrounding host rock were chosen to be representative of the Eastern Creek Volcanics, as this has been suggested as the source of copper at Mount Isa, Mammoth and Esperanza (Scott and Taylor, 1982; Wyborn, 1987; Heinrich et al., 1995; Matthäi et al., 2004). Other rock properties (Table 2) were assigned to be representative of the Mount Isa and Gunpowder regions e.g. the Sybella Granite unit, an Urquhart Shale unit, and/or a Myally Subgroup (quartzite) unit. The top of all the models represents a depth of 5 km, consistent with previous studies indicating that the depth of emplacement of the copper orebody at Mount Isa was between 5 km and 10 km with an average density of 2700 kg/m\textsuperscript{3} for the overburden (Matthäi et al., 2004).

Boundary conditions

The models were initialized with a hydrostatic fluid pressure, which was allowed to vary from hydrostatic to near lithostatic (cf. Oliver et al., 2001; Zhang et al., 2006). The base of the models remained at a fixed elevation. The left, right, front and back
boundaries were constrained to remain vertical. The top of each model was free to move in any direction (cf. Oliver et al., 2001; Sheldon et al., 2006). Thus the initial rectangular prism was deformed into a parallelepiped with a rhombic base. The models were shortened 10% through the application of velocity boundary conditions (250000 timesteps at 0.002 metres/timestep in the direction of shortening) with the shortening direction set at 112.5º to be consistent with previous models of syn-D₃ copper mineralization (McLellan, 2006; McLellan and Oliver, 2007). This boundary condition resulted in dominantly sinistral strike-slip faulting such that the fault bend/jog was releasing with positive $\theta$ and restraining with negative $\theta$. Further models were run with contrasts in rock type and no faults, which allowed comparisons to be made with outputs from the different fault geometries. Models containing both contrasting rock types and faults were also tested.

Several outputs from the models were investigated, which included pore pressure, mean stress, shear strain increment, volumetric strain, and integrated fluid flux. However, this study focuses on absolute values and gradients in volumetric strain (dilation) and integrated fluid flux outputs due to their critical importance in ore genesis. Dilation in this study is dimensionless and the integrated fluid flux is calculated as the volume of fluid to pass through a given area over a specified time and is given in units of $m^3/m^2$.

**RESULTS**

The volumetric strain and integrated fluid flux were evaluated within the fault zone (from the maximum values and 99th percentile values, P99) and in areas proximal to the fault zone (from the 90th percentile values, P90). Detailed examination of several models verifies that the 99th percentile value occurs only within the fault zone, and that
at the 90th percentile, the values are proximal to, but outside the fault zone (with the exception of the models with a cross-cutting fault, in which case the P90 values also occur within the fault zone). These criteria were applied to examine the magnitude of dilation and fluid flow in and around the fault, and to determine how well the fault and/or surrounding host rock acted as fluid flow pathways or barriers.

**Effect of fault dip variation**

There is a variation in dilation of approximately two orders of magnitude for fault bend models, and one order of magnitude for fault jog models, between the maximum values seen in the 45° dip fault models, and the maximum values seen in the remainder of the fault bend models with vertical dips (cf. Fig. 5a). Having a lower dip produces much less contrast in integrated fluid flux values (Fig. 5b). Fault bend models produce higher dilation and integrated fluid flux values than the corresponding fault jog models within the fault zone (Fig. 6).

While models with a lower dip may have the highest maximum dilation and relatively high integrated fluid flux values, these highest values are focused entirely along the fault zone (cf. Fig. 6). There is a considerable drop in values for the dilation and integrated fluid flux in areas proximal to the fault zone (Table 3).

**Effect of fault width variation**

Wide faults produce comparatively high dilation values within the fault zone when compared to changes in other fault geometry variables (Table 3), with little difference observed between the values for the fault bend and fault jog models (Fig. 5c; Fig. 7). The integrated fluid flux was highest in both fault bend and jog models with wider
Table 3: Dilation and integrated fluid flux for each model (parameters defined in Table 1). Min. and Max. are the minimum and maximum values, P99 and P90 are the 99th and 90th percentiles, and results are for 10% deformation with azimuth=112.5°.

<table>
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<tr>
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<td>0.0211790</td>
<td>21.119</td>
<td>9.33520</td>
<td>0.4249</td>
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</table>

* Note: Model 2 and Model 29 failed to run to 10% shortening.
Figure 5: Maximum dilation and integrated fluid flux values for the continuous fault geometry variables from selected fault bend (B) and fault jog (J) models. Illustration of maximum (a) dilation for variation of fault dip, (b) integrated fluid flux for variation of fault dip, (c) dilation for variation of fault width, (d) integrated fluid flux for variation of fault width, (e) dilation for variation of bend/jog angle, (f) integrated fluid flux for variation of bend/jog angle, (g) dilation for variation of bend/jog length, and (h) integrated fluid flux for variation of bend/jog length.
Figure 6: The effect of varying fault dip $D$ on dilation and integrated fluid flux, (a) fault bend dilation dip 90°, (b) fault bend dilation dip 45°, (c) fault jog dilation dip 90°, (d) fault jog dilation dip 45°, (e) fault bend integrated fluid flux dip 90°, (f) fault bend integrated fluid flux dip 45°, (g) fault jog integrated fluid flux dip 90°, and (h) fault jog integrated fluid flux dip 45°.
Figure 7: The effect of varying fault width $w$ on dilation and integrated fluid flux, (a) fault bend dilation width 25m, (b) fault bend dilation width 100m, (c) fault jog dilation width 25m, (d) fault jog dilation width 100m, (e) fault bend integrated fluid flux width 25m, (f) fault bend integrated fluid flux width 100m, (g) fault jog integrated fluid flux width 25m, and (h) fault jog integrated fluid flux width 100m.
faults, with the fault jog models producing slightly higher values than fault bend models (Fig. 5d; Fig. 7).

Dilation for fault bend models in areas proximal to the fault zone was found to drop considerably (Table 3), and these models also produced lower dilation values when compared to changes in other fault geometry variables. For fault jog models, the dilation was highest when compared to changes in other fault geometry variables for areas proximal to the fault. A wide fault produces higher values of integrated fluid flux proximal to the fault zone than a narrow fault (Fig. 7), though the magnitude drops considerably with distance from the fault.

**Effect of bend/jog angle variation**

Fault bends produced higher dilation values within the fault zone as the absolute value of the angle ($\theta$) of the bend decreased, but the fault jogs showed higher dilation as the absolute value of $\theta$ increased (see Table 3; Fig. 5e). The difference in dilation values within the fault zone as $\theta$ is varied is much greater for the fault bends than the fault jogs, with the maximum values for the fault jogs displaying very minor changes with $\theta$. Similar results were obtained for the integrated fluid flux values (Fig. 5f; Fig. 8). It is interesting to note that the models with a restraining bend or jog geometry displayed similar results to the releasing fault geometries (Table 3; Fig. 5e, f). In comparison to other geometry variables, having a favorable fault bend or fault jog angle did not produce particularly high dilation or integrated fluid flux values within the fault zone.
Figure 8: The effect of varying fault bend/jog angle $\theta$ on dilation and integrated fluid flux, (a) fault bend dilation angle $85^\circ$, (b) fault bend dilation angle $45^\circ$, (c) fault jog dilation angle $85^\circ$, (d) fault jog dilation angle $45^\circ$, (e) fault bend integrated fluid flux angle $85^\circ$, (f) fault bend integrated fluid flux angle $45^\circ$, (g) fault jog integrated fluid flux angle $85^\circ$, and (h) fault jog integrated fluid flux angle $45^\circ$. 
In areas proximal to the fault zone, decreased absolute values of $\theta$ produced higher dilation and integrated fluid flux values for fault bend models (Table 3; Fig. 8). However, fault jog models produce higher dilation values proximal to the fault for larger absolute jog angles, and higher integrated fluid flux for smaller absolute jog angles in areas proximal to the fault zone (Fig. 8). As with values within the fault zone, the variation of $\theta$ generates a greater difference in values for the fault bend models than the corresponding fault jog models in areas proximal to the fault zone. The change in integrated fluid flux was not particularly high outside the fault zone in comparison to the changes from variation of other fault geometry parameters. However, the change in dilation for fault bend models outside the fault zone was high in comparison to changes from variation of other parameters did not produce particularly high dilation or integrated fluid flux values within the fault zone.

**Effect of bend/jog length variation**

Varying the length of the fault bends showed that models with longer bends had higher dilation within the fault zone (see Table 3; Fig. 5g; Fig. 9). However, the fault jog models were found to have higher values of dilation for shorter fault jog lengths (Fig. 5g; Fig. 9). The integrated fluid flux values in the fault bend models also displayed higher values within the fault zone for longer fault bend lengths (Fig. 5h; Table 3). Changes in fault bend length had less effect on integrated fluid flux values than other fault geometry variables. Conversely, changing fault jog length produced high increases in integrated fluid flux values in comparison with changes in other fault geometry variables, and produced higher increases than corresponding fault bend models (Table 3). In the areas proximal to the fault zone, the length of the fault bend or fault jog produced the lowest effect on dilation and integrated fluid flux values when
Figure 9: The effect of varying fault bend/jog length $L$ on dilation and integrated fluid flux, (a) fault bend dilation length 1000m, (b) fault bend dilation length 5000m, (c) fault jog dilation length 1000m, (d) fault jog dilation length 5000m, (e) fault bend integrated fluid flux length 1000m, (f) fault bend integrated fluid flux length 5000m, (g) fault jog integrated fluid flux length 1000m, and (h) fault jog integrated fluid flux length 5000m.
compared to varying other fault geometry variables (Table 3). The integrated fluid flux in the area surrounding the fault zone was higher in fault bend models with a longer bend, and in fault jog models with a shorter jog, but the dilation was higher in models with a shorter bend length and in models with a longer jog length (Fig. 9), though these values were all very similar.

**Effect of a cross-cutting fault**

The inclusion of a cross-cutting fault on the fault bend models produced higher dilation within the fault zone than a similar model without the cross-cutting fault (Table 3; Fig. 10). However, an additional fault did not produce as much extra dilation as decreasing the dip of the fault and widening the fault. Within the fault zone, models with a cross-cutting fault generated lower dilation values than other models (Table 3; Fig. 10). The integrated fluid flux within the fault zone was found to be the lowest with the inclusion of a cross-cutting fault compared to the other models for both fault bend and fault jog cases.

The presence of a cross-cutting fault produced considerably higher integrated fluid flux values compared to changes in other fault geometries in areas proximal to the fault zone for both the fault bend and fault jog models (Table 3). However, the dilation values in this area did not vary considerably compared to values from the other models.

**Effect of rock type variation**

Little difference is seen in the dilation values when the fault is replaced by a contrast in rock type. However an increase is seen in the integrated fluid flux at the lithological
Figure 10: The effect of inclusion of an EW cross-cutting fault on dilation and integrated fluid flux (a) fault bend dilation no cross-cutting fault, (b) fault bend dilation with cross-cutting fault, (c) fault jog dilation no cross-cutting fault, (d) fault jog dilation with cross-cutting fault, (e) fault bend integrated fluid flux no cross-cutting fault, (f) fault bend integrated fluid flux cross-cutting fault, (g) fault jog integrated fluid flux no cross-cutting fault, and (h) fault jog integrated fluid flux with cross-cutting fault.
boundary (Table 3; Figure 11a, b, e, f). In areas proximal to the lithological boundaries, the presence of more rock types produces lower dilation than in models with fewer rock types. In contrast, the integrated fluid flux is higher in models with more rock types. In comparison to the variation of the fault geometry parameters, a contrast in rock types generates relatively high changes in dilation and integrated fluid flux. Integrated fluid flux increases proximal to the lithological boundaries are at least an order of magnitude higher than the increases seen in the same area due to varying the fault geometry parameters.

Reintroducing the fault to the models with a contrast in rock types indicates that it is not simply the presence of a greater number of rock types which produces the highest dilation and integrated fluid flux values, but that the different material properties (such as the shear strength) assigned to the rocks have a large effect (Fig. 11c, d, g, h). Higher amounts of dilation (by an order of magnitude) were observed in the models with rock types seen in the Gunpowder region (Eastern Creek Volcanics and Myally Quartzite) as opposed to those models with the rock types seen in the Mount Isa region (Eastern Creek Volcanics, Urquhart Shale, and Sybella Granite). Though the integrated fluid flux values varied much less, slightly higher values were still generated in the Gunpowder rock type models than the Mount Isa rock type models.

**Dilation and integrated fluid flux ratios**

The model results were evaluated by the ratios between the highest and lowest values of dilation and integrated fluid flux respectively (referred to as “dilation ratio” and “integrated fluid flux ratio”), which illustrate the extent to which these parameters are focused within the models. All dilation ratios are negative because they contrast a
Figure 11: The effect of varying rock types on dilation and integrated fluid flux, (a) dilation for two contrasting rock types with no fault, (b) dilation for three contrasting rock types with no fault, (c) dilation for two contrasting rock types separated by fault, (d) dilation for three contrasting rock types separated by faults, (e) integrated fluid flux for two contrasting rock types with no fault, (f) integrated fluid flux for three contrasting rock types with no fault, (g) integrated fluid flux for two contrasting rock types separated by fault, and (h) integrated fluid flux for three contrasting rock types separated by faults.
Figure 12: Dilation and integrated fluid flux ratios for the continuous fault geometry variables from selected fault bend (B) and fault jog (J) models. Illustration of (a) dilation ratio for variation of fault dip, (b) integrated fluid flux ratio for variation of fault dip, (c) dilation ratio for variation of fault width, (d) integrated fluid flux ratio for variation of fault width, (e) dilation ratio for variation of bend/jog angle, (f) integrated fluid flux ratio for variation of bend/jog angle, (g) dilation ratio for variation of bend/jog length, and (h) integrated fluid flux ratio for variation of bend/jog length.
positive maximum value (expansion) with a negative minimum value (contraction)
Some general patterns can be observed for the ratios for variation of a particular
parameter (Fig. 12). Table 1 shows that the dilation ratio in each model is on the order
of -0.0005 for the majority of models. Greater differences between the minimum and
maximum dilation values (lower dilation ratios) are seen for models with a lower dip
(Models 16, 17, 34, and 35), as well as some of the models with a contrast in rock types
that represent the Gunpowder region (Models 41 and 44). Figure 12 illustrates that
wider fault widths, smaller absolute bend angles, larger absolute jog angles, longer bend
lengths and shorter jog lengths show greater differences between the minimum and
maximum dilation values. For the majority of models, the integrated fluid flux ratio is
on the order of 850 (Table 1). Higher integrated fluid flux ratios are seen in models with
a lower dip, and a narrower fault jog. A larger absolute jog angle generates a higher
integrated fluid flux ratio (Fig. 12); however the variation of the ratio for the fault bend
angle does not show a readily definable pattern. Both fault bend and fault jog
geometries show a higher integrated fluid flux ratio for a longer bend or jog.
Considerably higher ratios are seen in models containing a fault and contrast in rock
types, in one case by two orders of magnitude (Model 40). However in the models
containing a contrast in rock types with no fault, the integrated fluid flux ratio is an
order of magnitude lower than in the majority of the models.

**Fluid flow velocities**

Figure 13 shows the fluid flow vectors from the perspective of the front boundary for a
selection of models. The top of the models demonstrates downward fluid flow, with
greater flow occurring within the fault/shear zone. This locally downward flow at the
top of the models reflects a greater degree of dilation around the embedded fault zone,
Figure 13: Fluid flow vectors from (a) fault bend model (Model 3), (b) fault jog model (Model 21), (c) fault intersection model (Model 18), and (d) model with contrast in rock types (Model 42).
thus drawing fluid towards the fault or shear zone from the free top boundary, as observed in other studies (eg. Ord and Oliver, 1997). Draw-down is particularly prominent in numerical models where the top model surface is equated with the Earth’s surface (e.g. Oliver et al., 2006). Fluid flow below the top of the model is in an upward direction, again with the greatest flow occurring within the fault zone. In the model with contrasting rock types downward fluid flow is observed for the top half of the model rather than just at the top boundary.

DISCUSSION

The models within this study have explored the effect of varying the geometry on strike-slip deformation and coupled fluid flow of reactivated faults. The prospectivity of a variety of geological settings through the use of numerical models has been evaluated in previous studies through the examination of variation in permeability (Ord and Oliver, 1997), and stress orientation and magnitude (Rawling et al., 2006; Robinson et al., 2006; Schaubs et al., 2006; McLellan and Oliver, 2007). While it is critical to recognize how variation of these model parameters affect modelling results in order to understand the model implications for the genesis of ore deposits, it is also critical to understand how small changes in the input geometry can affect results (eg. Schaubs et al., 2006).

Evaluation of the fault geometries by quantifying the dilation and integrated fluid flux both within the fault zone and in areas proximal to the fault zone provides an indication of what type of features are important for increasing the potential for mineralization of simple fault bend and jog geometries. Figure 5 illustrates the variation in maximum dilation and integrated fluid flux from selected models for the continuous parameters
investigated in this study (fault dip, fault width, bend/jog angle and bend/jog length). The results suggest that dilation and integrated fluid flux for fault geometries with N-S striking faults containing a fault bend or jog are most affected by lower fault dips, contrasts in rock types, and wide faults. The integrated fluid flux within fault bend models are most affected by wide faults, followed by a contrast in rock types, and a lower fault dip, whereas fault jog models were dominated by wide faults, a cross cutting fault, and a contrast in rock types.

Lower dips have a dominant effect on the outputs, with steep faults penetrating to the same depth as the low dip faults resulting in less dilation and integrated fluid flux. This could be due to two possible effects: the increased down dip extent of a lower angle fault, or the lower dip faults having less normal stress.

Wider faults can allow larger volumes of fluid through than narrower faults as demonstrated by the larger integrated fluid flux values seen in the models with wider faults. It is suggested that this is due a greater volume of higher permeability within the fault zone in which the fluid can be focused.

An important result of the modelling is that dilation and integrated fluid flux values are similar in restraining and releasing fault bends and jogs (cf. Micklethwaite and Cox, 2004). Dilation can occur in restraining geometries in the model because of the Mohr-Coulomb plastic rheology (or any other non-associated rheology) in which shear induces dilatancy (Vermeer and de Borst, 1984; Ord and Oliver, 1997). To the extent that the Mohr-Coulomb rheology is realistic (eg. Oliver et al., 2001), this result
challenges some approaches to prospectivity that focus only on releasing geometries (Allibone et al., 2002b).

The models suggest that similar changes to fault bend and jog geometries have opposite effects on the outputs. Dilation and integrated fluid flux are enhanced by fault bends that are longer and have smaller absolute bend angles, but by fault jogs that are shorter and have larger absolute jog angles. This interesting result can be explained by the effect of the higher fault permeabilities in the models: the faults are 2 to 3 orders of magnitude more permeable than the adjacent rocks. A decrease in absolute fault jog angle or jog length results in higher dilation and integrated fluid flux due to more continuity along the en echelon fault segments, resulting in less interruption to fluid flow. However, an increase in absolute fault bend angle or an increase in the bend length results in greater dilation and integrated fluid flux. The highest dilation values occur in the bend for the highest absolute bend angles. In the models with a bend angle of ±135°, the highest dilation values occur at the tips of the N-S trending part of the fault directly proximal to the bend. It is possible that higher shear strain on the longer fault bends leads to more dilation. Higher shear strain for the larger absolute bend angles is also possible. Further modelling work in the future is required to verify the reasons for fault bend length and angle producing such results.

The presence of the intersecting fault in both the bend and jog models changed the dilation and integrated fluid flux compared to models without the intersecting fault. However changes in other fault geometry variables, particularly having favorable fault dips and widths, produced even greater changes.
In the models containing a contrast in rock type across the fault (Fig. 11c, d, g, h), the faults act as juxtaposition seals (Knipe, 1992, 1993) rather than conduits for fluid flow, because they juxtapose lower permeability rocks contrasted against higher permeability rocks. Figure 13d shows that the reactivation of the fault has started to create a fold at the top of the model that is not visible on the models without a contrast in rock type. The juxtaposition of the lower and higher permeability rocks may a critical factor in the generation of this type of structure. It is also possible that this fold is partly responsible for the increased downward fluid flow seen in Figure 13d.

It is interesting to note that the integrated fluid flux ratios are broadly consistent with the permeability contrast between the fault and the host rocks, such that the variability in ratio can be attributed to geometric factors. The ratios suggest that models with a low fault dip and those with a contrast in lithology across a fault have the greatest capacity for focusing both dilation and integrated fluid flux (Fig. 12). The concentration of dilation and fluid flux in small areas is critical in models for describing the formation of hydrothermal ore deposits (de Wijs, 1951; Turcotte, 1989).

Potential limitations of the numerical modelling performed in this study include the fixed (intrinsic vs. dynamic) and higher permeabilities used for the fault, and the boundary conditions applied. The use of a fixed permeability for the fault and rock types through the model run was so that the effect of simple fault geometries could be examined rather than the effect of varied permeability due to deformation, which would require a more complex analysis. Fault(s) can be transiently permeable during rupture and the models are effectively integrating this increased permeability over time by assignment of a higher permeability fault. Though the shortening direction of 112.5° is
Table 4: Ranking of ingredients for prospectivity analysis in strike slip fault systems in decreasing order of sensitivity.

<table>
<thead>
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<th>Fault Bends</th>
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<td>Low fault dip</td>
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<tr>
<td>Contrast in rock types</td>
<td>Contrast in rock types</td>
</tr>
<tr>
<td>Wide fault</td>
<td>Wide fault</td>
</tr>
<tr>
<td>Cross-cutting fault</td>
<td>Cross-cutting fault</td>
</tr>
<tr>
<td>Large absolute bend angle</td>
<td>Small absolute jog angle</td>
</tr>
<tr>
<td>Long bend</td>
<td>Short jog</td>
</tr>
</tbody>
</table>

considered to be representative at the time of copper mineralization in the Western Succession of the Mount Isa Inlier (McLellan, 2006), this study did not test other shortening directions which may potentially have produced greater dilation and integrated fluid flux values for the fault geometries under investigation. The boundary conditions imposed on each of the models were set to focus on strike-slip deformation (appropriate to the strike slip kinematics of many major faults in the Western Succession), so that, for example, the effect of transpression was not examined. Further, the results presented were analysed only after a shortening of 10%. Preliminary inspection of the models results at lower values suggests that the same patterns reported here are consistent through the deformation history. Each of these limitations opens up the possibility of further work in the future.

Table 4 summarizes the fault geometry variables which could be used as ingredients for prospectivity analysis. These combinations of fault system variables should therefore produce the most favorable conditions for hydrothermal mineralization which can be applied to copper mineralization in the Western Succession of the Mount Isa Inlier and could feasibly be incorporated into an exploration targeting program.

The majority of the effects seen in the models are consistent with the dominant influence of strain induced dilation on fluid flow, combined with the higher
permeabilities ascribed to the faults. These two factors can explain the effects of fault dip, width, and bend and jog length and angle. Some of the results may be challenging to conventional ideas of prospectivity: for example restraining and releasing bends are equally favourable, and the effects of length and angle are the opposite for bends and jogs.

**CONCLUSIONS**

Dilation and integrated fluid flux are critical factors in the genesis of ore deposits. This study shows how numerical modelling of three-dimensional strike-slip coupled deformation and fluid flow models can be used to rank fault geometry variables that are important for generating higher dilation and integrated fluid flux values through quantitative analysis of the model outputs.

Analysis of fault system variables indicates which values for these variables produce higher dilation and integrated fluid flux values. In order of priority, dilation is maximized by: a low fault dip, a contrast in rock types, a wide fault, a cross-cutting fault, and for fault bends, a small bend angle and long bend, and for fault jogs, a large jog angle and a short jog. Integrated fluid flux is maximized in order of priority by a wide fault, a contrast in rock types, and a low fault dip; and for fault bends, a small bend angle and long bend, and for fault jogs, a large jog angle and a short jog length, and a cross-cutting fault. Increasing the length or angle of fault bends has opposite effects to those observed for fault jogs. Restraining and releasing fault bend and jog geometries show similar results, indicating the dominant effect of strain-induced dilatancy in these models. These conclusions can be directly applied to the field so that exploration can focus on areas with most favourable fault system parameters.
CONCLUSIONS

Fractal and multifractal analysis of mineralized systems is an expanding discipline within the geosciences. Evaluating the prospectivity of a region using fractal analysis and/or multifractal techniques represents a new direction for the discipline. Exploration for new mineral deposits in brownfields terrains can represent a large financial risk for many exploration companies. Low risk-low cost techniques for reducing terrain scale exploration targets to smaller regional scale targets are an important step in any exploration campaign.

This study has shown that fractal and multifractal analysis can be used to describe various facets of mineralized systems. Examining the variation of fractal dimension over a study area provides a method for quantifying spatial relationships between mineral deposits and potential geological controls on mineralization.

Chapter 1 demonstrates that there is a strong linear relationship between the degree of clustering of mineral deposits and clustering of geological features and contrast values as determined from Weights of Evidence analysis using copper occurrences from the Mount Isa Inlier as a case study. This result suggests that the geological features controlling the clustering of the mineral deposits may be the same factors controlling their localization. The combination of fractal analysis and weights of evidence has potential implications for brownfields exploration targeting. Further work in this area should focus on application of the methodology to other commodities and other study areas. A more comprehensive analysis of other potential controls on copper mineralization in the Mount Isa Inlier should also be undertaken in order to generate a terrain scale copper prospectivity map.
Chapter 2 illustrates that geological complexity rather than complexity gradients has the closer spatial relationship with copper mineralization in the Mount Isa Inlier. Regions of higher geological complexity have a greater capacity to focus the large volumes of fluid and provide the physico-chemical contrasts necessary for the formation of large hydrothermal ore deposits. The high correlations between geological complexity and copper endowment shown by this study suggest that geological complexity could be used as an exploration targeting tool in underexplored regions of the Mount Isa Inlier. Further work should focus on application of the methodology used in this study to the data used in the previous studies of geological complexity as a control on gold mineralization in the Eastern Goldfields of the Yilgarn craton. This further work should clarify potential reasons for the strongly differing conclusions reached in this study and those reached in previous studies.

Chapter 3 presents an expansion of the de Wijs model for describing the distribution of ore tonnage. The relationship between ore grade distributed using the de Wijs model and ore tonnage using the expanded model is shown to be log-normal. Multifractal analysis of ore tonnage values from the expanded model suggests that ore tonnage is not multifractal. Production data from gold deposits in the Zimbabwe craton illustrates a log-normal relationship between ore grade and tonnage, multifractal grade distributions, and the non-multifractal nature of ore tonnage, as predicted by the expanded de Wijs model. Though limited by the availability of comprehensive regional scale production databases, future work should examine production data from other commodities and study areas and compare the fractal and/or multifractal characteristics of the data to
other existing or newly developed theoretical models for element distribution in the crust.

Chapter 4 demonstrates that small variations in fault geometry parameters can greatly affect the results of three-dimensional coupled strike-slip deformation and fluid flow models. Using dilation and integrated fluid flux as proxies for prospectivity, it is shown that dilation is maximized, in order of priority by: a lower fault dip, contrast in rock types, large fault width, a cross-cutting fault, for fault bends – a large bend angle and a longer bend length, and for fault jogs – a small jog angle and a shorter jog length. Whereas integrated fluid flux is maximized in order of priority: a large fault width, a contrast in rock types, a low fault dip, for fault bends – a large bend angle and a longer bend length, for fault jogs – a small jog angle and a shorter jog length, and a cross-cutting fault. It is demonstrated that increasing the length and angle of fault bends has opposite effects to increasing fault jog length and angle. Further, it is shown that contractional and dilational fault bend and jog geometries produce similar results. The fault geometry parameters that generate higher dilation and integrated fluid flux could be incorporated into either brownfields or greenfields exploration targeting. There is scope for a substantial amount of further work in three-dimensional modelling space. Other fault systems including normal and reverse faults could be analysed using the same approach as this study. While this study only varied one fault geometry parameter at a time, future studies could vary multiple fault geometry parameters as well as the boundary conditions or other model parameters in each numerical model.

Given the scale invariance of many geological phenomena, there is scope for investigating the fractal and/or multifractal properties of many other economic geology
features (e.g. geochemical, geophysical and stratigraphic data) and mineralized systems not addressed in this study (e.g. the Eastern Goldfields of the Yilgarn craton or the Victorian goldfields). The methodologies developed and applied within this thesis have shown that there are direct implications for exploration targeting and resource evaluation as a result of quantitative analysis of different facets of mineralized systems. Given the extensive use of fractals in hydrocarbon exploration and production, the time is appropriate for more extensive application to the minerals industry.
REFERENCES


Blenkinsop, T., and Oliver, N., 2003, Discrimination of Base/Precious Metal Mineralising Systems by Fractal Analysis, Mt Isa, Australia, Geophysical Research Abstracts, Volume 5, European Geophysical Society, p. 14276.


Harris, S.D., McAllister, E., Knipe, R.J., and Odling, N.E., 2003, Predicting the three-dimensional population characteristics of fault zones: a study using stochastic models: Journal of Structural Geology, v. 25, p. 1281-1299.


Hodkiewicz, P., 2003, The interplay between physical and chemical processes in the formation of world-class orogenic gold deposits in the Eastern Goldfields Province, Western Australia [PhD thesis]: Perth, University of Western Australia.


References, A. Ford, PhD 2007


Van Dijk, P.M., 1991, Regional Syndeformational Copper Mineralization in the Western Mount Isa Block, Australia: Economic Geology, v. 86, p. 278-301.


Appendix A-C

Supplementary Data for Section A
Supplementary Data for Section B
Supplementary Data for Section C

APPENDICES ARE NOT AVAILABLE THROUGH THIS REPOSITORY
Appendix D (Part 1/3)

Supplementary Data for Section D

APPENDICES ARE NOT AVAILABLE THROUGH THIS REPOSITORY
Appendix D (Part 2/3)

Supplementary Data for Section D

APPENDICES ARE NOT AVAILABLE THROUGH THIS REPOSITORY
Appendix D (Part 3/3)

Supplementary Data for Section D

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Appendix E

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