Department of Applied Geology

Spatial statistical estimation of undiscovered mineral endowment: Case of komatiite-associated nickel sulphide resources, Kalgoorlie Terrane, Western Australia

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Abstract

The Kalgoorlie Terrane of the Yilgarn Craton, Western Australia, containing about 60% (~11 Mt) of the world's known komatiite-hosted nickel sulphide resources, is the world's best studied and economically most important province for this mineral deposit type. Although increasingly mature in terms of nickel exploration, the Kalgoorlie Terrane is believed to contain significant additional undiscovered nickel endowment. Using the data-rich Kalgoorlie Terrane, this thesis develops a benchmark methodology that combines geological knowledge with spatial analysis and mathematical-statistical methods to estimate undiscovered nickel resources.

In the proposed methodology, nickel sulphide deposits are considered realisations of stochastic mineralisation processes and are analysed within the following framework. Komatiites in the Kalgoorlie Terrane constitute the full sample space or the permissive tract. Disjoint, naturally bound individual komatiite bodies that make up the sample space are used as the spatial analysis units. Some komatiite bodies within the sample space contain nickel sulphide deposits (mineralised) and others do not (unmineralised). In this study, the most explored mineralised komatiite bodies constitute local control areas against which nickel resources in the less explored komatiite bodies can be assessed. The concept of local control areas is analogous to the concept of global control areas which are well explored parts of permissive areas for particular deposit types worldwide.

Spatial point pattern analyses showed that the spatial distribution of mineralised komatiite bodies within the sample space is clustered. In contrast, nickel sulphide deposits in individual komatiite bodies are either randomly distributed or dispersed, and not clustered. This absence of deposit clustering within individual komatiite bodies indicates that the intensity of the deposit pattern of each komatiite body may be adequately expressed as deposit density (number of deposits per km^2). In global quantitative resource assessments, regression analysis of the well established power law relationship between deposit density and size of global control areas provides a robust method for estimating the number of deposits.

In this study a power law relationship reminiscent of that in global models was found between the sizes of control areas and deposit density. In addition, this study establishes another power law relationship between nickel endowment density (nickel metal per km^2) and the sizes of control areas. Deposit and endowment density regression models based on the two power laws suggested that, respectively, 59 to 210 (mean 114) nickel sulphide deposits and 3.0 to 10.0 Mt (mean 5.5 Mt) nickel metal remained undiscovered in demonstrably mineralised komatiite bodies within the Kalgoorlie Terrane. More emphasis is placed on endowment density which may be more intrinsic to the Kalgoorlie Terrane than deposit density because deposit counts are confounded by definitional ambiguities emanating from orebody complexities. Thus the spatial pattern of mineral deposits may not coincide with the spatial pattern of mineral endowment as demonstrated by spatial centrographic analyses in this study.

To estimate the amount of undiscovered nickel metal in the entire Kalgoorlie Terrane and not just in the demonstrably mineralised komatiite bodies, Zipf's law was applied. According to Zipf's law, the size of the largest deposit is twice the size of the second, thrice the size of the third, four times the fourth, and so on. Based on the currently known size of Mt. Keith deposit, the largest nickel sulphide deposit in the Kalgoorlie Terrane, Zipf's law indicates that the terrane is nearly mature in terms of nickel exploration and contains only about 3.0 Mt nickel metal in undiscovered resources. The collective implication of the regression and Zipf's law estimates is that in the Kalgoorlie Terrane, no significant nickel resources are likely to be contained in the known komatiites that are presently not demonstrably mineralised. However if, as widely speculated, the actual size of Mt. Keith deposit is about twice the currently known size, Zipf's law predicts 10.0 Mt nickel metal in undiscovered nickel endowment for the Kalgoorlie Terrane. The additional 7.0 Mt undiscovered nickel metal endowment is attributed to opening up of a new exploration search space through deeper resource delineation, within an otherwise nearly mature terrane.

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List of publications included as part of this thesis

Chapters 3 and 5 of this thesis have been published as journal papers, and Chapter 4 is based on a published paper and two manuscripts submitted for publication. Chapter 1 (introduction), Chapter 2 (geology of the study area), and Chapter 6 (discussion and conclusions) have not at this time been submitted to any journal for publication, but they incorporate material contained in the manuscripts and published papers that constitute chapters 3, 4 and 5. With respect to my published work included in this thesis, I hereby make the following statement:

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The bibliographic details of my published or submitted papers are as follows:

Chapter 3

Mamuse, A., Porwal, A., Kreuzer, O., Beresford, S.W., 2010a. Spatial statistical analysis of the distribution of komatiite-hosted nickel sulfide deposits of the Kalgoorlie Terrane, Western Australia: clustered or not? Economic Geology 105, 229-242.

Chapter 4

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Chapter 5

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Statement of contribution of others

The contribution of the PhD candidate (Antony Mamuse) to each of the co-authored papers is 90 % or more. The candidate's contribution included concept formulation, database compilation, methodology formulation, data analysis, paper structuring, manuscript write-up, and correspondence with editors and publishers. The contributions of co-authors was limited to normal supervisory roles, including guiding direction of research, checking geological database integrity, manuscript reviews and availing background technical information on methods.

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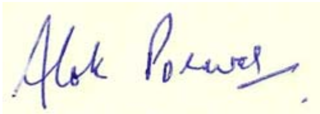
(Full name of candidate) (Signature of candidate)

I, as supervisor, endorse that the above statement of contribution by the candidate is appropriate.

DR. ALOK PORWAL



(Full name of supervisor) (Signature of Supervisor)

List of additional publications not forming part of the thesis

The following abstracts for conference oral or poster presentations are drawn from my PhD research:

Mamuse, A. 2008. A benchmark for best practice in assessing Australia's mineral endowment. Programme and abstracts booklet, Australia Earth Science Convention, Perth, 20July – 24 July, 2008, pp. 34

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Mamuse, A. 2010. New concepts for spatial statistical estimation of mineral endowment: the case of komatiite-hosted nickel resources, Australia. Accepted abstract. SEG 2010 conference, October 2-5, 2010, Keystone, Colorado, USA.

Dedication

This thesis is dedicated to:

My mother, Winnety Sarudzai Mamuse and to my late father, Samson Urombohauurai Mamuse

My wife, Dealia Mamuse

My sons, Precise Paidamoyo Mamuse and Leigh Kuziva Mamuse

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background to this study

The Kalgoorlie Terrane, Yilgarn Craton, Western Australia hosts more than 60% (~11 Mt) of the world's known komatiite-associated nickel sulphide resources (Hoatson et al., 2006) and is Australia's premier nickel and gold mining and exploration province. In 2008-2009, the Kalgoorlie Terrane contributed more than 90% of the 178,000 tonnes of nickel metal produced in Western Australia. The geology and nickel sulphide mineralisation of the Kalgoorlie Terrane are described in detail in Chapter 2.

In their chronicle of the nickel exploration history of the Yilgarn Craton, Hronsky and Schodde (2006) state that all the komatiite belts that host identified nickel sulphide resources in the Yilgarn were known by the end of the 1966-1971 nickel boom. The authors note that most discoveries made after the boom were not genuinely new because they were based on follow-up to known mineralisation. They therefore suggested that the Yilgarn Craton was approaching maturation in terms of nickel exploration, with most nickel-hosting komatiite belts already discovered. They speculated that any nickel belts (mineralised komatiites) remaining to be discovered in the Yilgarn Craton were most probably buried under deep cover.

The concept of following up to known mineralisation is a direct response to the principles embodied in the saying, 'gold is where you find it'. As noted by Carlson (1991), one meaning of the saying is that the area most prospective for gold is that which is near known gold deposits. The same applies to komatiite-associated nickel sulphide deposits – there is higher certainty that new deposits will be found in komatiite belts with known deposits – until exhaustion. Guided by this philosophy, this thesis focuses on appraisal of mineralisation in known komatiites in the Kalgoorlie Terrane. This component of undiscovered nickel endowment is less speculative than that in hypothetical buried komatiite belts and can be more reliably appraised. The known komatiites can be grouped into those that are demonstrably mineralized and those that are not. Using on this grouping, this thesis tests the hypothesis that there is no significant nickel mineralization outside known nickel belts except under cover (Hronsky and Schodde, 2006). As defined, explained and applied in this thesis, the terms ‘near’, ‘komatiite belt’, ‘appraise’, ‘deposit’, and others are loaded with essential spatial statistical significance.

1.2 Objectives of this study

The main objective of this thesis is to develop a spatial statistical methodology for estimating mineral resources. Nickel sulphide deposits in the Kalgoorlie Terrane are well suited to developing and testing the proposed methodology because:

(i) the terrane is the best studied and economically most important nickel sulphide province in the world (Naldrett, 2004). The methods developed here are therefore potentially applicable to komatiite province in Finland and Canada which are moderately explored, and to other komatiites in the world, such as those in Southern Africa and Brazil as more data becomes available with exploration maturation.

(ii) komatiite-associated nickel sulphide deposits are a well understood, geologically and temporally well constrained deposit type (hosted by c. 2.7 Ga old komatiites in the Kalgoorlie Terrane). The unique geological and temporal distinctiveness of this deposit type render the foundational step in mineral resources assessments, namely delineation of permissive areas, achievable relatively easily and accurately. Therefore application of the methodology to a komatiite-associated mineral system may serve as a standard for application to other mineral systems. Although application of the methods is demonstrated by assessing undiscovered nickel endowment in the Kalgoorlie Terrane (Mamuse et al., 2010, submitted; Mamuse and Guj, 2010, submitted), more emphasis is placed on the methods themselves (Mamuse et al., 2009; Mamuse et al., 2010a; Mamuse et al., 2010b) which can be adapted to other mineral systems.

Terms komatiite-associated and komatiite-hosted are often used synonymously. In this thesis, however, the term komatiite-associated is generally preferred in order to avoid the connotation of full containment which may not strictly apply in cases where nickel sulphides are found within non-komatiite rocks due tectonic remobilisation from komatiites. There are some spatial analyses in this thesis which embody the notion of strict containment of sulphides within komatiites; in such cases the term komatiite-hosted may be applied otherwise the more inclusive term komatiite-associated is used.

1.3 Overview of quantitative mineral resources assessments

The generic framework for quantitative mineral resource assessments consists of (i) delineation of permissive areas, (ii) estimation of mineral deposit numbers in the permissive area in a study area and (iii) estimation of mineral endowment in the permissive area. The assessments provide estimates of the possible value of exploration targets and whether the value would be worth the risk, making them critical in planning exploration strategy, land-use, and economic development (Singer, 1993; Berger et al., 1999; Singer, 2010). Permissive areas or permissive tracts are those areas where the geology permits the existence of deposits of the specified type (Singer 1993; Singer et al., 2001).

Several methods have been proposed for, but not many have been widely applied to, mineral resources assessments. Two methods of relevance to this study are the widely used United States Geological Survey's (USGS) three-part assessment system, and the Zipf's law which is presently not as widely used. The three-part system is described here because of its wide usage and because it is described in detail (Singer, 1993), and sets the standard for other methods. Importantly, some concepts utilized in this thesis are local versions of those espoused in the more global three-part assessment system. Zipf's law is described here because it is a good predictor of the cumulative mineral endowment of a terrane thereby providing an upper estimate against which estimates obtained from the local approach in this study may be reconciled. Proposed methods that hitherto have not been widely used in mineral resources assessments include the complex systems approach (Gettings et al., 2004), and fractal analysis (Blenkinsop, 2004).

The USGS three-part assessment system and Zipf's law are summarized below.

1.3.1 Three-part assessments

The United State Geological Survey's (USGS) three-part assessment (Singer, 1993) system is widely used in quantitative mineral resources assessments. The three parts of the USGS three-part assessment system are (Singer, 2010): (i) delineation of permissive tracts of the specified deposit type, (ii) estimation of grades and tonnages of undiscovered deposits using pre-constructed grade and tonnage models, (iii) probabilistic estimation of the number of undiscovered deposits. The number, grades and tonnages of the undiscovered deposits are combined via Monte Carlo simulation algorithms such as those developed by Root et al. (1992).

Permissive tracts are delineated on geological maps by discriminating mineralised from barren environments on the basis of geologic criteria embodied in mineral deposit models (Singer, 1993; 2010). Boundaries of the permissive tracts are constructed such that the probability of the targeted deposit type occurring outside the boundary is less than 1 in 100, 0000 as estimated from an appraisal of geology, terrane maturity and the presence of barren overburden exceeding some pre-determined thickness (Singer, 1993; Scott and Dimitrakopoulos, 2001).

The grades and tonnages of undiscovered deposits are estimated from grade and tonnage models (Cox and Singer, 1986), which are frequency distributions of tonnages and average grades of well-explored deposits of the same type and in similar geological settings as the type being assessed (Singer, 1993, 2010). Local grade and tonnage models are used if local deposits are found to significantly depart from the general model (Singer, 2008; 2010).

The estimation of the number of undiscovered deposits evolved from methods in which final estimates were made subjectively by experts to the present situation where mineral deposit density models are used (Singer, 1993; Cox, 1993; Singer et al., 2001; Singer, 2008, 2010). A key guideline is that the estimates should be by made by deposit type and be consistent with the grade and tonnage models (Singer, 1993; 2010). To avoid deposit miscounting, the term deposit is restricted to those deposits explored in three dimensions and have published grades and tonnages, otherwise they are prospects even if they are being mined (Singer, 2010).

Deposit density models for estimating the number of deposits which are now available for a wide variety of mineral deposit types provide robust method for estimating the number of deposits (Bliss and Menzie, 1993; Singer, 1994, 2008; Singer et al., 2001; 2005; Mosier et al., 2007). These models represent the frequency distribution of the number of deposits per unit area in control areas around the world. Control areas are well-explored, geologically-well understood areas within permissive tracts (Singer et al., 2005).

The mean, median or percentile deposit densities of control areas may be used to estimate the number of deposits but such estimation does not take into account the variability of deposit density with size of permissive area (Singer et al., 2005; Singer, 2010). One way to incorporate the variability of deposit density with the size of permissive area is by regression analysis. Deposit density studies (Singer et al., 2001, 2005; Singer, 1994, 2008, 2010; Mosier et al., 2007) established that a power law relationship exists between mineral deposit density and the size of the host control area for several deposit types. These authors showed that, based on the power law, regression of deposit density on the size of permissive areas constituted a robust model for estimating the number of deposits in less explored geologically similar areas. The use of deposit densities for estimating the number of undiscovered deposits is increasingly becoming the key method for making estimates in the context of the USGS three-part assessment method. Universal regression equations have been developed for this purpose (Singer, 2008).

Multiplying the estimated number of deposits by the average contained metal for a deposit type gives an estimate of the undiscovered metal endowment, but such an estimate ignores the variability in metal endowment across permissive areas and does not indicate the proportion of economic metal endowment (Singer, 2010). Thus, in three part assessments, it is recommended that the estimates of the number of undiscovered deposits be combined with grade and tonnage models using Monte Carlo simulation to determine the proportion of metal that is economic under stated conditions (Singer, 2010). This is usually achieved using the methods and software of Root (1992).

In summary, the key to successful implementation of the USGS three-part system is the consistent integration of carefully developed models that helps reduce errors although this can be a burden (Singer, 2010). Although the global nature of the key input models such as grade-tonnage models and deposit density models may lead to less context-sensitive estimates when applied locally (Gettings et al., 2004; Singer, et al., 2008), the estimates are robust guidelines which should only be replaced if viable local models, significantly different from the global models, are available (Singer, 2008; 2010).

1.3.2 Zipf's law

Zipf's law, a mathematical relationship states that the size of a natural phenomenon in a population is inversely proportional to its rank (Zipf, 1949) has been applied to estimate the size of undiscovered mineral and petroleum resources (Folinsbee, 1977; Rowlands and Sampey, 1977; Paliwal et al., 1986; Merriam et al., 2004; McCuaig and Guj, 2006; Fagan, 2006; Guj et al., 2007; Guj et al., 2010, submitted; Mamuse and Guj, submitted). According to Zipf's law, the size (y) distribution of contained metal among deposits in a terrane can be generated from the formula:

$$y = cr^{-k}$$

where c is the size of the largest deposit or deposit group (rank 1), r the rank of a deposit or deposit group with size y, and k a constant that in geological systems approximates a value of 1 (Paliwal et al., 1986). The amount of undiscovered metal in a terrane is obtained by subtracting the known amount of contained metal from the Zipf-predicted estimate.

In application of the Zipf's law, the most direct output is the total undiscovered metal endowment. Although attempts may be made to make inferences about the possible number of deposits, and even to apportion the global endowment to individual deposits, this exercise is fraught with uncertainties and is not attempted in this chapter. The uncertainties stem from the inadequate and non-uniform deposit delineation within a terrane which creates ambiguities in interpretation of ranks.

In this thesis Zipf's law is put to the specific use of obtaining a single global estimate of nickel endowment of the Kalgoorlie Terrane which is complemented by estimates obtained from regression analyses. Thus whereas the Zipf law provides a global endowment estimate for the entire terrane, regression estimates return estimates for individual komatiite bodies, or local estimates.

1.4 Approach to mineral resources assessment in this study

In the USGS three-part system, mineral deposit density models are one of the main tools for estimating the number of deposits in permissive tracts. Deposit density models are based on the number of deposits per unit area in control areas distributed worldwide. These global models are used to estimate the number of undiscovered deposits in geologically similar but less explored areas elsewhere in the world. Although these global models may yield useful estimates, specific local deposit density models, if available, may lead to better estimates with lower statistical variances (Singer, 2008).

In this thesis local deposit density models are developed using local control areas within the Kalgoorlie Terrane (Mamuse et al., 2010b). Plots of the deposit densities against areas of host komatiite bodies exhibit power law relationships reminiscent of those established in global deposit density regression models (Singer, 1994, 2008; Singer et al., 2001; 2005; Mosier et al., 2007). This permits regression analysis of these relationships to estimate the number of nickel sulphide deposits, in the same way that global models are applied in global deposit density models.

Importantly, this thesis introduces the concept of metal endowment density (metal/ km^2) which can be used to directly estimate the amount of metal (Mamuse et al., 2010b, 2010, submitted) without the need of fitting deposits to pre-constructed grade-tonnage models and estimating endowment via Monte Carlo simulation. This thesis proposes that within a given terrane, the mineral endowment can be estimated directly from regression analysis of the amount of metal/ km^2 on the area (size in km^2) of permissive host rocks in the same way that deposit densities are used to estimate the number of deposits. The plot of the distribution of contained nickel metal against the area of the control area komatiite bodies in the Kalgoorlie Terrane follows a statistically significant power law relationship (Mamuse et al., 2010b), permitting regression analysis.

The amount of metal per km^2 of host komatiite is termed nickel endowment density in this thesis. Whereas nickel deposit density denotes the probability of deposit occurrence within a komatiite body, nickel endowment density may be thought of as the nickel 'grade' of a komatiite body.

1.5 Concepts underlying mineral resources assessment methods in this study

Interrelated geological, mathematical-statistical and spatial analysis concepts underpin the mineral resource assessment approach used in this thesis. These concepts, briefly described below, facilitate translation geological descriptions into quantitative models applied in mineral resources assessments.

1.5.1 Delineation of permissive tracts: geological concepts

Delineation of permissive tracts and identification of control areas primarily utilise geological maps and descriptive mineral deposit models (Singer, 1993, 2008, 2010; Singer et al., 2005). Descriptive mineral deposit models are the key to delineation because they define the geological environment and the diagnostic characteristics of the deposits (Singer, 1993, 2008, 2010), both of which can be depicted on geological maps of adequate scale. Geological maps are therefore the primary tool for delineation (Singer, 1993). In classical USGS three-part assessments, boundaries of permissive tracts are drawn such that the probability that deposits of the targeted type occur outside the boundaries is less than 1 in 100,000 (Singer, 1993; Singer et al., 2005; Singer, 2008, 2010). Application of this criterion results in a broad binary division of an area into permissive and non-permissive parts. However, the permissive areas could contain tracts with variable degrees of mineral prospectivity.

Although three-part assessments have traditionally focused on entire permissive tracts (Singer, 1993), accuracy of the assessments could be improved by using favourable areas within permissive tracts (Drew et al., 1999). The main limitation to using favourable areas instead of permissive areas in three part assessments is the difficulty of defining the term favourable (Singer, 2010), which seems to be the case for many deposit types. As indicated in section 1.1, the favourable areas for komatiite-associated deposits are amenable to more accurate delineation than many deposit types. As explained in Chapter 2, komatiites in the Kalgoorlie Terrane are conceptually designated as 'favourable' or 'unfavourable' to nickel mineralisation based on volcanological and geochemical criteria (Lesher et al., 2001; Barnes et al., 2004; Barnes, 2006a, b; Fiorentini et al., 2008), providing sound rationale for using favourable areas instead of generalised permissive tracts. A good mappable criterion for making this distinction is the presence of magma pathways (loci of maximal magma flux) in favourable komatiites and their absence in unfavourable komatiites (Fig. 1.1, Barnes, 2006a; Beresford et al., 2007). However at present, not all komatiite bodies in the Kalgoorlie Terrane are mapped to the level of detail that permits recognition of this distinction uniformly across the terrane. Therefore, among favourable komatiite bodies this study distinguishes between demonstrably mineralised komatiite bodies and the rest that are not demonstrably mineralised (Fig. 1.1). This is the distinction emphasised in practical applications in this thesis such as spatial analyses (Chapter 3: Mamuse et al., 2010a) and estimation of resources (Chapters 4: Mamuse et al., 2010b, Mamuse et al., 2010, submitted).

1.5.2 Distribution of nickel sulphide deposits and host komatiite bodies: spatial analysis concepts

The spatial distribution of mineral deposits - whether they are randomly distributed, dispersed or clustered - is a critical component of predictive estimation of undiscovered mineral resources which must be sensitively assessed to avoid erroneous estimates (Singer and Menzie, 2008; Ford and Blenkinsop, 2008). In mineral resources assessments based on the knowledge or assumption of clustered deposit patterns, the presence of known deposits increases the likelihood of finding additional deposits in the vicinity (Singer and Menzie, 2008). In general, one should establish whether clusters are genuine or they are merely due to some obvious a priori heterogeneity in the study area (Gatrell et al., 1996). In other words, are they genuine mineral deposit clusters or clusters of favourable geological settings (Singer and Menzie, 2008)?

The above question can be addressed through a clearly defined spatial analysis framework. The spatial analysis framework applied in this study is depicted in Figure 1.1. All mapped komatiites in the Kalgoorlie Terrane (see Chapter 2) collectively constitute the permissive tract or, in spatial analysis terminology, sample space. On bedrock geological maps such as GSWA (2008), the komatiites are not continuous rock masses, but are mapped as discrete bodies surrounded by non-komatiite rocks. These disjoint subregions of the sample space are naturally bound and therefore constitute well-defined entities. Nickel sulphide deposits are generally confined to the naturally bound komatiite bodies. The komatiite bodies can therefore be used as spatial analysis units (Fig. 1.1) for assessing the deposit component of clustering (Mamuse et al., 2010a). However, not all komatiite bodies contain nickel sulphide deposits (Fig. 1.1). It is therefore possible to describe the spatial distribution of demonstrably mineralised komatiite bodies with respect to the full sample space made up of all komatiite bodies (Mamuse et al. 2010a). For the actual analyses, Mamuse et al. (2010) used *K* function analysis and nearest neighbour analysis methods. Spatial analysis units, also known as analytical windows, are required to be accurately demarcated because spatial analyses are area-sensitive (Baddeley, 2008; Singer and Menzie, 2008).

1.5.3 Deposit and endowment density modelling: mathematical-statistical modelling concepts

Mathematical-statistical modelling, which involves the concise expression of geologic knowledge in mathematical terms (Knoring and Dech, 1993), is at the core of this study. In fact the generic mineral resources assessment method spelt out in section 1.2 may be viewed simply as a specific form of mathematical-statistical modelling of mineral resources. Mathematical-statistical modelling is similarly applied to other natural systems such as ecological, atmospheric, chemical and biological systems that, like the geological system, are subject to physical, chemical and biological processes (Knoring and Dech, 1993; Thiergärtner, 2006). The main steps in mathematical-statistical modelling (Knoring and Dech, 1993), with examples from this study are shown in Table 1.1.

In mathematical-statistical modelling, the most crucial stage is model derivation because subsequent analyses depend on model quality (Knoring and Dech, 1993). Mathematical-statistical models are products of objective and subjective components of reasoning and their success depends on profound knowledge of the phenomenon and adequate command of the mathematical methodology (Knoring and Dech, 1993; Thiergärtner, 2006). In this thesis model derivation is intertwined with geological concepts (described in detail in chapter 2) and delineation of spatial analysis units as described above, and within the framework proposed in Figure 1.1.

Models are simplifications meant to depict only the most characteristic features of the studied phenomenon without requiring photographic accuracy (Knoring and Dech, 1993; Thiergärtner, 2006). Mathematical-statistical models can be derived deductively from empirical data or inductively as theoretical hypotheses subsequently supported by empirical evidence (Knoring and Dech, 1993; Thiergärtner, 2006). Local deposit density and endowment density regression models in this study (Mamuse et al., 2010b, 2010, submitted) were developed independently and were subsequently found to be consistent with well established empirically derived global models (Bliss and Menzie, 1993; Singer, 1994, 2008; Singer et al., 2001; 2005; Mosier et al., 2007).

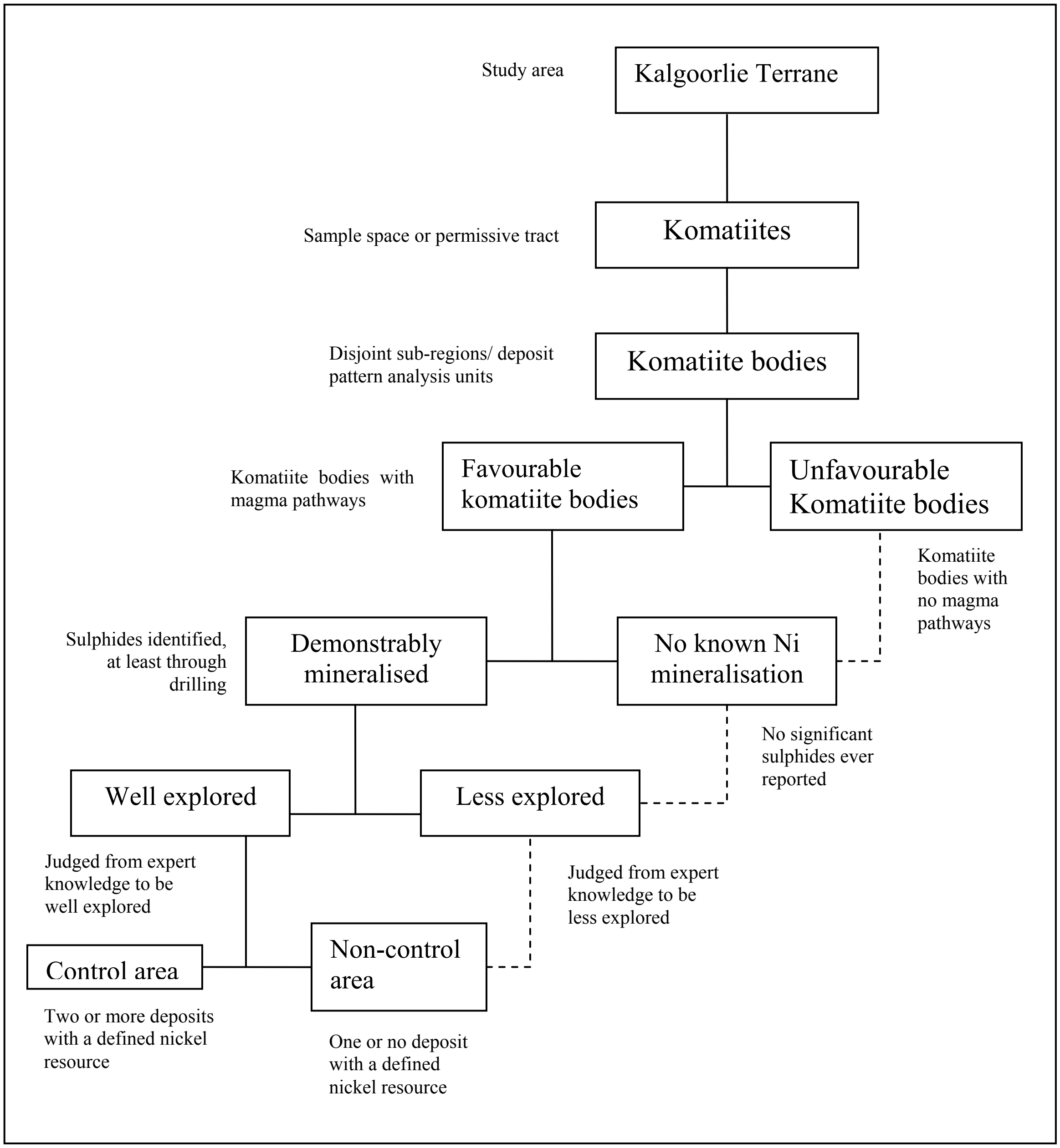

Fig. 1.1 Spatial analysis framework applied in this thesis

TABLE 1.1 Steps for mathematical statistical modelling (after Knoring and Dech, 1993).

Step	Description	Examples of implementation in this thesis
1	Data generalisation, hypothesis formulation and statement of assumptions	Generalisations – representation of mineral deposits as points; delineation of komatiite bodies; deposit groupings Hypotheses – Deposits and komatiite bodies are not clustered; global deposit density models can be replicated at the local scale, endowment can be estimated through regression analysis, spatial distribution of endowment can be estimated from centrographic analyses. Assumptions – data used (e.g. locations of deposits, outlined of komatiite bodies, nickel resources figures) are assumed to be reasonably accurate; mineral deposits can be modelled as points, the parent population of nickel sulphide deposits in the Kalgoorlie Terrane follows a Zipf's distribution
2	Mathematical formulation of the problem or model construction	Mathematical formulation – development of spatial analysis framework (Fig. 1.1); mathematical expressions for deposit and endowment densities; Zipf's law equation; algorithm for centrographic analysis. Model construction; Deposit and endowment density modelling; regression modelling, Zipf's law modelling
3	Application of the model	This involved testing hypotheses above, e.g., mineral deposits *K* function analysis of deposit patterns, centrographic analysis of nickel endowment; estimation of nickel sulphide deposits and endowment by regression modelling and Zipf's law.
4	Model validation	Statistical significance testing of spatial analysis results, statistical significance testing of regression models; cross-validation of regression and Zipf's law estimates.
5	Model interpretation	Deposit clustering is distinct from clustering of favourable geological settings, local power law exists between area of komatiite bodies and deposit/ endowment density
6	Conclusions and insights from the model	Clustering models are inappropriate for assessing nickel sulphide resources within komatiite bodies, centrography provides a geometric option of delineation, endowment density is a more intrinsic property of terranes than deposit density.

1.6 Outline of this thesis

According to Curtin University guidelines for thesis by publication (http://research.curtin.edu.au/local/docs/graduate/GS-ThesisByPubGuidelines.pdf), this thesis, which is predominantly a typescript thesis comprising chapters based on published (or submitted) articles in peer-reviewed international journals, constitutes a hybrid thesis. A hybrid thesis embodies the advantages of a thesis by series of published papers in terms of additional valuable feedback from experts who are external to the University, as well as the advantages of a normal typescript thesis in terms of a coherent and cohesive narrative.

This thesis consists of 6 chapters, of which Chapters 3 and 5 have been published in peer-reviewed journals under Mamuse et al. (2010a) and Mamuse et al. (2009), respectively. Chapter 4 draws from a published paper (Mamuse et al., 2010b) a submitted manuscript (Mamuse et al. 2010, submitted) and a manuscript that was in review (Mamuse and Guj, 2010, submitted) at the time of finalising this thesis. In order to avoid redundancy and repetition, contents of the journal papers have been edited in this thesis.

Chapter 2 is a detailed compilation of the geology of the Kalgoorlie Terrane (study area). The geological information is of prime importance because it forms the basis for delineating permissive areas, a critical procedure in quantitative mineral resources assessments. Moreover, as mentioned above in section 1.4.3, successful mathematical-statistical modelling of mineral endowment requires a clear understanding of the geological context of the mineral deposit-type under consideration. Because this paper draws heavily from previously published work, it was not submitted for publication. However Chapter 2, as well as chapters 1 and 6 contain substantial contained in the papers published or submitted in this course of this PhD (as identified above, and detailed below).

Chapter 3, published in *Economic Geology* (Mamuse et al., 2010a), explores the spatial distribution of nickel sulphide deposits in the Kalgoorlie Terrane. This is a crucial initial investigation because subsequent mineral resources assessments can be strongly affected by whether the deposits are clustered or not. It is generally thought that mineral deposits occur in clusters and can therefore be suitably represented by the negative binomial distribution and the Neyman-Scott distribution (Carlson, 1991; Bliss and Menzie, 1993). However, *K* function and nearest neighbour analyses suggest that although mineralised host komatiite bodies in the Kalgoorlie Terrane are clustered, nickel sulphide deposits within them are randomly distributed or dispersed, and not clustered. Therefore the negative binomial and the Neyman-Scott distributions may not be suitable for assessing nickel sulphide resources within komatiite bodies in the Kalgoorlie Terrane, leaving the Poisson distribution as one possibility. Importantly, lack of clustering indicates that the intensity of the deposit pattern in each komatiite body can be adequately represented by the deposit density (no. of deposits per km^2). Another key outcome of Chapter 3 is that the komatiite bodies represent suitable analysis units for the spatial analysis of nickel sulphide deposits in the Kalgoorlie Terrane. This has direct implications for quantitative mineral resources assessment models developed in Chapter 4 and applied in Chapter 5.

Chapter 4 draws from a paper published in *Ore Geology Reviews* (Mamuse et al., 2010b), a submitted manuscript (Mamuse et al., 2010, submitted), and a manuscript in review (Mamuse and Guj, 2010, in review). In this chapter the number of undiscovered nickel sulphide deposits and the amount of undiscovered nickel endowment in the Kalgoorlie Terrane are estimated using deposit density and endowment density regression models (Mamuse et al., 2010b; Mamuse et al., 2010, submitted) and Zipf's law (Mamuse and Guj, 2010, in review). Regression estimates include the mean regression estimates and the 95 % confidence and prediction intervals. More emphasis is placed on endowment estimates (3.0 to 10.0 Mt nickel metal) than on estimates of the number of deposits (59 to 210 deposits). The regression estimates pertain only to selected demonstrably mineralised but relatively less explored komatiite bodies in the Kalgoorlie Terrane. The underlying regression models mimic global deposit density models (Singer, 1994, 2008; Singer et al., 2001; 2005; Mosier et al., 2007), which may ensure that the estimates are more context-sensitive.

Application of Zipf's law in the same chapter suggests that the amount of undiscovered nickel metal is about 3.0 Mt nickel metal, assuming that the largest deposit (Mt. Keith) is fully delineated or 10.0 Mt nickel metal assuming that Mt. Keith partially delineated. The difference between the Zipf's law and regression estimates is interpreted as approximately indicative of the amount of undiscovered nickel endowment in komatiite bodies in the Kalgoorlie Terrane that are presently unexplored. This is because the Zipf estimate pertains to the entire Kalgoorlie Terrane whereas the regression estimate pertains to only those komatiite bodies in the terrane that are presently demonstrably mineralised. As shown in this thesis, the two methods collectively suggest that there may not be significant nickel sulphide resources outside the known demonstrably mineralised komatiite bodies in the Kalgoorlie Terrane.

Chapters 3 and 4 embody the idea that nickel sulphide deposits in komatiite bodies in the Kalgoorlie Terrane are not clustered. What about the distribution of nickel endowment? Can the distribution of deposits, which are only chaotic manifestations of the mineralisation processes (Hronsky and Groves, 2008), satisfactorily mimic the distribution of nickel endowment whose distribution is a more fundamental property of a terrane than that of deposits (Mamuse et al., 2010b, 2010, submitted)? Slices of a terrane, rather than individual deposits may be statistically more representative of a terrane's endowment, as illustrated in Chapter 5 of this thesis. Chapter 5, published in *Ore Geology Reviews* (Mamuse et al., 2009) presents a centrographic approach that characterises nickel sulphide endowment in the Kambalda region of the Kalgoorlie Terrane using statistical slices derived using the concepts of standard distance circle and standard deviational ellipse. The work showed that certain spatio-geometric slices based on the distribution of nickel sulphide deposits are good proxies for the distribution of the Kambalda Komatiite. This kind of analysis is potentially useful in delineating mineralised rock packages in mineral systems (e.g. orogenic gold) wherein the host rock types are not as distinctive as they are in the komatiite-associated nickel system.

In concluding this thesis (Chapter 6) it is submitted that this PhD research shows that the komatiite-hosted nickel sulphide system is amenable to spatial-statistical and mathematical-statistical manipulation because of its relatively more clearly defined boundary conditions (i.e. syngenetically hosted by easy-to-delineate komatiites, and firm age constraints on the deposits). However, there are some uncertainties in implementing these methods as indicated in the chapter. The chapter also discusses implications of the results of the Zipf's law analysis which predicts a residual endowment of 3.0 Mt if Mt Keith is assumed to be fully delineated and that of 10.0 Mt if Mt Keith is assumed to twice the currently known size. These results are explained in terms of the concept of exploration search space, in which the projected size of Mt. Keith represents a new set of geological, economic and technological variables in the Kalgoorlie Terrane. Based on the concept of exploration search space the Kalgoorlie Terrane is probably approaching maturity in terms of the current search space epitomized by the current size of Mt. Keith deposit. The undiscovered 3.0 Mt nickel metal in the initial search space plus 7.0 Mt nickel metal in the next search space make up the 10.0 Mt nickel metal predicted by projecting Mt. Keith to 4.15 Mt nickel metal. Thus the prospectivity of a 'mature' terrane can be restored by generation of a new exploration search space.

The methods presented in this thesis are potentially applicable to other relatively well explored komatiite provinces such as those in Canada and Finland. They could become applicable to komatiite provinces in Southern Africa and Brazil when these provinces attain sufficient exploration maturity. Crucially, it can be argued that the case presented in this thesis illustrates that with care and appropriate analogy, spatial statistical methods can be applied to assess mineral resources in any mineral system, as shown schematically in Chapter 6 (Fig. 6.1).

References

Barnes, S.J., 2006a. Komatiite-hosted nickel sulphide deposits: geology, geochemistry, and genesis, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, p. 51-97.

Barnes, S.J., 2006b. Komatiites: petrology, volcanology, metamorphism, and Geochemistry, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists, Special Publication 13, p. 13-49.

Baddeley, A., 2008. Analysing spatial point patterns in R. Workshop Notes, version 3.Available: www.csiro.au/resources/pf16h.html<http://www.csiro.au/resources/pf16h.html (accessed August 14, 2009).

Berger, R.B., Drew, L.J., Singer, D.A. 1999. Quantifying mineral-deposit models for resource assessment, in: Deposit modeling and mining-induced environmental risks, Geologica-Hungarica Series Geologica, Tomus 24: 41-54.

Blenkinsop, T.G., 2004, Applications of fractal geometry to mineral exploration, in: Muhling, J., Goldfarb, R., Vielreicher, N., Bierlein, F., Stumpfl, E., Groves, D., Kenworthy, S. (Eds.), Predictive Mineral Discovery Under Cover, Extended Abstracts. SEG 2004 Conference, 27 September-1 October 2004 Perth, Western Australia, p. 158-161.

Bliss, J.D., Menzie, W.D., 1993. Spatial mineral-deposit models and the prediction of undiscovered mineral deposits, in: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), Mineral deposit modeling. Geological Association Canada Special Paper 40, p. 693-706.

Cox, D., 1993. Estimation of undiscovered quantitative mineral resource assessments-Examples from Venezuela and Puerto Rico, Nonrenewable Resources 2, 82-91.

Curtin University of Technology, 2009. Guidelines for Thesis by publication (series of published papers), version date: 30/092009. http://research.curtin.edu.au/local/docs/graduate/GS-ThesisByPubGuidelines.pdf. Accessed January 17, 2010.

Drew, L.J. Singer, D.A., Menzie, W.D., Berger, B.R. 1999. Mineral resource assessment-state of the art. Geologica Hungarica Series Geologica, Tomus 24, 31-40.

Fagan, R.K., 2006. Modelling how much gold is left to be found in the Eastern Goldfields of W.A. Outcrop to orebody: innovative geoscience in exploration and mining, Abstract Volume. Kalgoorlie 2006 Conference, 30 April to 4 May 2006, Kalgoorlie. Australian Institute of Geoscientists Bulletin 44, 23-25.

Fiorentini, M.L., Beresford, S.W. and Barley, M.E., 2008. Ruthenium-chromium variation: a new lithogeochemical tool in the exploration for komatiite-hosted Ni-Cu-(PGE) deposits, Economic Geology 103, 431-477.

Folinsbee, R.E., 1977. World's view-from Alph to Zipf. Geological Society of America Bulletin 88, 897-907.

Ford, A., Blenkinsop, T.G., 2008. Combining fractal analysis of mineral deposit clustering with weights of evidence to evaluate patterns of mineralisation: application to copper deposits of the Mt. Isa inlier, NW Queensland, Australia. Ore Geology Reviews 33, 435-450.

Gettings, M. E., Bultman, M.W., Fisher, F.S. 2004. A complex systems model approach to quantified mineral resource appraisal. Environmental Management 33, 87-98.

Guj P., McCuaig, T.C., Garzon, R., 2007. Can the petroleum industry's probabilistic approach to targeting and resources definition be applied in predicting mineral discoveries?. Conference Proceedings, Mineral Exploration and Research: Digging Deeper. 9th Biennial SGA Meeting.

Guj, P., Fallon, M., McCuaig T.C., Fagan R., 2010, submitted. A time-series audit of the Zipf's law as a measure of terrane endowment and maturity in mineral exploration. Economic Geology.

Hoatson, D.M., Subhash, J., Jaques, A.L., 2006. Nickel sulphide deposits in Australia: characteristics, resources and potential. Ore Geology Reviews 29, 177-241.

Hronsky, J.M.A., Schodde, R.C. 2006. Nickel exploration of the Yilgarn Craton: from the nickel boom to today. Society for Economic Geologists Special Publication 13: 1-11.

Knoring, L.D. and Dech, V.N., 1993. Mathematics for geologists, in: Zeidler, R.B., (Ed.), Geotechnika 10, Netherlands, A.A. Balkema, 200 pp.

Lesher, C.M., Burnham, O.M., Keays, R.R., Barnes, S.J., Hulbert, L., 2001. Geochemical discrimination of barren and mineralized komatiites associated with magmatic Ni-Cu-(PGE) sulfide deposits. Canadian Mineralogist 39, 673-696.

Mamuse, A., Guj, P., submitted. Rank statistical analysis of nickel sulphide resources of the Norseman-Wiluna Greenstone Belt, Western Australia. Mineralium Deposita.

Mamuse, A., Porwal, A., Kreuzer, O.P., and Beresford, S., 2009. A new method for centrographic analysis of mineral deposit clusters: Ore Geology Reviews, v. 36, 293-305.

Mamuse, A., Porwal, A., Kreuzer, O., Beresford, S.W., 2010a. Spatial statistical analysis of the distribution of komatiite-hosted nickel sulfide deposits of the Kalgoorlie Terrane, Western Australia: clustered or not? Economic Geology 105, 129-142.

Mamuse, A., Beresford, S., Porwal, A., and Kreuzer, O.P., 2010b. Assessment of undiscovered nickel sulphide resources, Kalgoorlie Terrane, Western Australia. Part 1. Deposit and endowment density models. Ore Geology Reviews. doi:10.1016/j.oregeorev.2010.02.004.

Mamuse, A., Beresford, S., Porwal, A., Kreuzer, O.P., 2010, submitted. Assessment of undiscovered nickel sulphide resources, Kalgoorlie Terrane, Western Australia. Part 2. Estimates from local deposit and endowment density models. Ore Geology Reviews.

McCuaig, T.C., and Guj, P., 2006. Balancing risk and reward in the face of increasing global exploration maturity. Outcrop to orebody: innovative geoscience in exploration and mining, Abstract Volume. Kalgoorlie 2006 Conference, 30 April to 4 May 2006, Kalgoorlie. Australian Institute of Geoscientists Bulletin 44, 3-8.

Mosier, D.L., Singer, D.A., Berger, V.I., 2007. Volcanogenic massive sulfide deposit density. US Geological Survey Scientific Investigations Report 2007-5082, 21 p. Available http://pubs.usgs.gov/sir/2007/5082/ (accessed August 29, 2009).

Paliwal, H.V., Bhatnagar, S.N., Haldar, S.K., 1986. Lead-zinc resource prediction in India: an application of Zipf's law: Mathematical Geology 18, 539-549.

Root, D.H., Menzie, W.D., Scott, W.A., 1992. Computer Monte Carlo simulation in quantitative resource estimation: Nonrenewable Resources 1, 125–138.

Rowlands. N.J., Sampey, D., 1977. Zipf's law-an aid to resource inventory prediction in partially explored areas. Mathematical Geology 9, 383-391.

Scott, M., Dimitrakopoulos, R., 2001. Quantitative analysis of Mineral Resources for Strategic Planning: Implications for Australia Geological Survey. Natural Resources Research 10, 159-177.

Singer, D.A., 1993. Basic concepts in three-part quantitative assessments of undiscovered mineral resources. Nonrenewable Resources 2, 69-81.

Singer, D.A., 1994. Conditional estimates of the number of podiform chromite deposits. Nonrenewable Resources 3, 200–204.

Singer, D.A., 2008. Mineral deposit densities for estimating mineral resources, Mathematical Geosciences 40, 33-46.

Singer, D.A., 2010. Progress in integrated quantitative mineral resource assessments. Ore Geology Reviews, doi:10.1016/j.oregeorev.2010.02.001

Singer, D.A., Menzie, W.D., 2008. Map scale effects on estimating the number of undiscovered mineral deposits. Natural Resources Research 17, 79-86.

Singer, D.A., Menzie, W.D., Sutphin, D., Mosier, D.L., Bliss, J.D. 2001. Mineral deposit density - an update, in: Schulz, K.J. (Ed.), Contributions to global mineral resource assessment research. US Geological Survey Professional Paper 1640-A, A1–A13. (also available online at http://pubs.usgs.gov/prof/p1640a/)

Singer D.A., Berger, V.I., Menzie, W.D., Berger, B.R., 2005. Porphyry copper density. Economic Geology 100, 491–514.

Thiergärtner, H., 2006. Theory and Practice in Mathematical Geology - Introduction and Discussion. Mathematical Geology 38, 659-665.

Zipf, G.K. 1949. Human behaviour and the principle of least effort: an introduction to human ecology. Addison-Wesley, Reading, MA, 573 pp.

CHAPTER 2

GEOLOGICAL SETTING AND NICKEL MINERALIZATION OF THE KALGOORLIE TERRANE, YILGARN CRATON, WESTERN AUSTRALIA

Geology is a critical input in mineral resources assessments of an area because it contextualises the mineralisation styles and is the basis for the delineation of permissive tracts. This chapter describes the geological setting of the Kalgoorlie Terrane, with particular emphasis on komatiite geology and associated nickel sulphide mineralisation. In terms of mineral resources assessments, komatiites in the terrane constitute the permissive tract or, equivalently, the sample space. As described in this chapter, the komatiite sample space is not one homogenous unit but consists of multiple spatially distinct but scale dependent entities. The mineral resources assessment methodology proposed in this thesis is based on identification of entities of the sample space that constitute suitable spatial analysis units, as demonstrated from Chapter 3 onwards.

2.1 Regional geological setting

The Yilgarn Craton of Western Australia (Fig. 2.1a) predominantly consists of granite-greenstone rocks that were emplaced between 3.0 and 2.6 Ga, and a minor gneissic component older than 3.0 Ga that is found along the western margin of the craton (Myers and Hickman, 1990; Cassidy et al., 2006). The greenstones comprise mafic-ultramafic volcanic rocks formed from submarine lava plains or local volcanic centres, and layered gabbroic sills (compositionally ranging from dunite-pyroxenite to dolerite-gabbro-leucogabbro-anorthosite) and the metasediments include banded iron formations and rocks that were derived from felsic volcanics (Myers and Hickman, 1990).

Granitoids in the Yilgarn Craton were emplaced in several episodes. An early episode which intruded c. 3.0 Ga greenstones in the northwestern part of the craton, was followed by a craton-wide 2.7 to 2.6 Ga episode, which in turn was succeeded by plutonic intrusion at c. 2.6 Ga (Myers and Hickman, 1990). The Yilgarn Craton amalgamated during the Neoarchaean orogeny (which coincided with the main 2.7 to 2.6 Ga granitic intrusion). After cratonisation at about 2.5 Ga, the carton was intruded by east-trending Proterozoic dyke swarms (Swager et al., 1995; Myers and Hickman, 1990; Cassidy et al., 2006).

Various tectono-stratigraphic frameworks have been proposed for dividing greenstones of the Yilgarn Craton (Swager et al., 1995; Myers, 1990, 1995, 1997; Myers and Swager, 1997; Barley et al., 2003; Cassidy et al., 2006). According to the framework proposed by Cassidy et al. (2006) the hierarchy of tectono-stratigraphic units of the Yilgarn Craton is: Craton> Superterrane> Terrane> Domain. In this framework, a domain is the basic fault bounded geologically contiguous tectonic unit or block, a terrane is a group of domains with the same stratigraphy and geological history and a superterrane is a grouping of related terranes (Swager, 1995; Cassidy et al., 2006). On this basis, Cassidy et al. (2006) identified six tectono-stratigraphic terranes within the Yilgarn Craton, three (Kalgoorlie, Kurnalpi and Burtiville) of which constitute the Eastern Goldfields Superterrane (Fig. 2.1a).

2.2 The Kalgoorlie Terrane

This thesis focuses on the Kalgoorlie Terrane, the westernmost terrane of the Eastern Goldfields Superterrane (Fig. 2.1a). The Kalgoorlie Terrane is defined as a distinct tectono-stratigraphic, fault-bounded entity mainly on the basis of a consistent c. 2.7 Ga volcano-sedimentary stratigraphy that features a regional komatiite marker unit (Swager and Griffin, 1990; Swager et al., 1990; Swager, 1995; Cassidy et al., 2006). The Kalgoorlie Terrane is the most well defined and most extensive of the three terranes within the Eastern Goldfields Superterrane (Swager, et al., 1995; Groenewald and Riganti, 2004) and consists of ten tectonic domains (Fig. 2.1).

The upward greenstone stratigraphic succession of the Kalgoorlie Terrane consists of lower basalt (intercalated with felsic volcaniclastic rocks), komatiite unit, upper basalt unit and a felsic-volcanic rock unit overlain by localized coarse clastic sequences (Swager et al., 1995; Swager, 1997; Groenewald and Riganti, 2004; Cassidy et al., 2006). The mafic-ultramafic component of the stratigraphy is most complete in the Kambalda and Ora Banda domains (Fig. 2.1b, c) which include well-developed upper basalt which is absent or obscure in adjacent domains (Swager, 1997; Groenewald and Riganti, 2004). In the Boorara Domain (Fig. 2.1b, c), komatiite volcanism was accompanied by significant but volumetrically restricted felsic volcanism (Swager, 1997; Trofimovs et al., 2004; Beresford et al., 2007). As will be discussed later, the komatiite-felsic volcanic association is a key feature of nickel mineralization in the Boorara Domain (Hill et al., 1990, 2004; Beresford et al., 2007).

2.3 Overview of nickel mineralization in the Kalgoorlie Terrane

The Kalgoorlie Terrane of the Yilgarn Craton, Western Australia which accounts for approximately 60% (~11 Mt nickel metal) of the world's known komatiite-associated nickel sulphide resources is the world's premier province for this nickel sulphide deposit type (Hoatson et al., 2006). However, komatiites are not unique to the Yilgarn Craton where, in addition to the Kalgoorlie Terrane, these rocks also occur in the Youanmi and Kurnalpi terranes (Fig. 2.1a). In fact, komatiites are relatively common in Archaean greenstone belts worldwide and economic komatiite-associated nickel sulphide deposits occur in Archaean greenstone belts in Canada, Brazil, Zimbabwe and Finland (Naldrett, 2004; Barnes, 2006a). Komatiite-associated nickel sulphide deposits are interpreted to have formed in dynamic lava channels or magma conduits from sulphide undersaturated komatiitic magmas by magmatic processes (crystallisation, differentiation and concentration), and assimilation of crustal sulphur (Keays, 1995; Lesher et al., 2001).

The terms komatiite-associated and komatiite-hosted are often used synonymously. In this thesis, however, the term komatiite-associated is generally preferred and includes nickel sulphide deposits contained within komatiites as well as those that are interpreted to have been tectonically remobilised from their komatiite host rocks into surrounding country rocks. In the case of remobilised ore the element of containment implied by the term komatiite-hosted does not strictly apply. Thus in this thesis the term komatiite-hosted is only used in the context of spatial analyses which take into account strict containment of nickel sulphide ore within komatiites.

In the Kalgoorlie Terrane, komatiites are regionally extensive sequences (Fig. 2.1b, c) with a narrow age range of 2.71 to 2.70 Ga (Myers and Hickman, 1990; Nelson, 1998) and distinctive stratigraphic facies (Hill et al., 1990; 1995). Conceptually, the komatiites in the Kalgoorlie Terrane can be 'favourable' or 'unfavourable' to nickel mineralisation based on volcanological and geochemical criteria (Lesher et al., 2001; Barnes et al., 2004; Barnes, 2006a, b; Fiorentini et al., 2008). Komatiitic peridotites with pathway subfacies (e.g. Kambalda), or komatiitic dunites with dunite lens subfacies (e.g. Mt. Keith) are considered favourable whereas thin differentiated flows (e.g. Monument ultramafic unit), dunite sills (e.g. Walter Williams Formation and Wiluna) may not be favourable. Geochemically, favourable environments exhibit characteristic crustal contamination signatures (e.g. Th-U-LREE enrichment, negative Nb-Ta-Ti anomalies) or sulfide segregation signatures (e.g. Co-Ni-Cu-PGE depletion) making their distinction from unfavourable environments theoretically possible.

Komatiitic peridotites with pathway subfacies and komatiitic dunites with dunite lens subfacies are associated with almost all known nickel sulphide deposits in the Kalgoorlie Terrane (Hill et al., 1990; 1995; Barnes, 2006a). This strong association has led to classification of the nickel sulphide deposits in the Kalgoorlie Terrane into komatiitic peridotite-associated and komatiitic dunite-associated deposits (Marston et al. 1981; Marston, 1984; Donaldson et al., 1986; Lesher and Keays, 2002; Beresford et al., 2004; Rosengren et al., 2005). Komatiitic dunite-associated deposits dominantly occur in the northern part of the Kalgoorlie Terrane, whereas komatiitic peridotite-associated deposits are largely confined to the southern part of the terrane (Fig. 2.1b, c).

Apart from the above lithological classification scheme, komatiite-associated deposits are also divided into type 1 and type 2 deposits according to type of the nickel sulphide ore (Hill and Gole, 1990; Lesher and Keays, 2002; Naldrett, 2004). Type 1 ores (e.g., Kambalda, Widgiemooltha, Tramways, St. Ives, Black Swan, Cosmos; Fig. 2.1c, 2) consist of massive and net-textured or matrix ores at the base of komatiite lava flows. Type 2 ores (e.g., Mt. Keith, Honeymoon Well, Yakabindie; Fig. 2.1, 2.2) are disseminated low-grade nickel sulphide ores centrally disposed within thick olivine

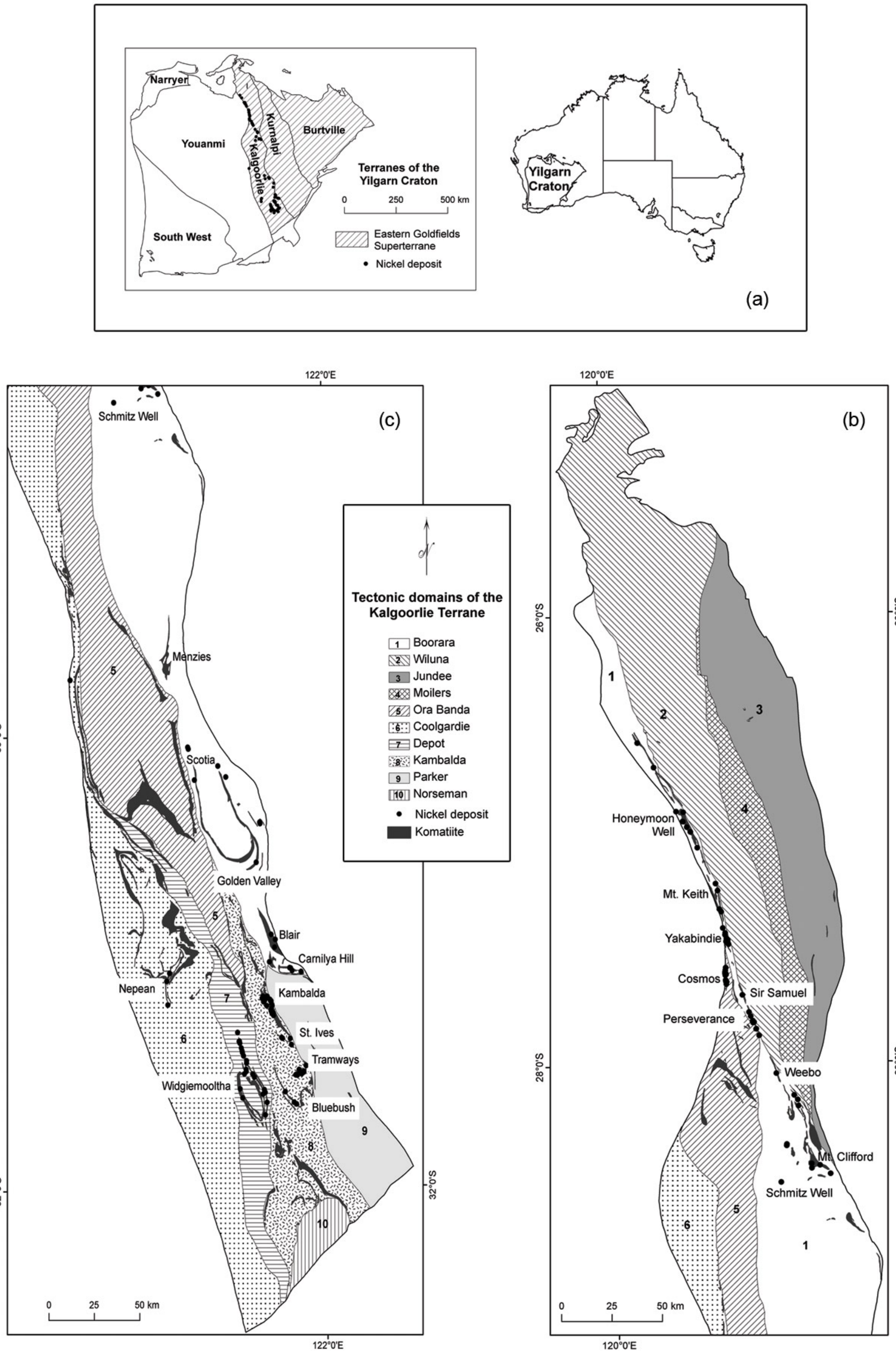

Fig. 2.1 The study area, (a) terranes of the Yilgarn Craton, and komatiites and nickel sulphide deposits of (b) the northern and (c) southern parts of the Kalgoorlie Terrane. (Geology from GSWA, 2008; terranes and domains after Cassidy et al., 2006)

cumulate bodies (Hill and Gole, 1990; Barnes, 2006b). Most komatiitic peridotite-associated deposits are type 1 deposits whereas komatiitic dunite-associated deposits appear to be both type 1 deposits (e.g., Perseverance, Cosmos, Silver Swan, and Wedgetail) and type 2 deposits (e.g., Mt. Keith, Corella and Six Mile Well).

A common observation is that nickel sulphide deposits in the Kalgoorlie Terrane tend to occur in groups or clusters (Marston et al., 1981; Marston, 1984; McCall et al., 1995; Barnes and Perring, 2006), fifteen of which are listed in Barnes and Perring (2006). The spatio-statistical veracity of these clusters is explored in Chapter 3 (Mamuse et al., 2010a) because presence or absence of clusters can significantly impact mineral resources assessments.

Of the ten tectonic domains in the Kalgoorlie Terrane, only five (Boorara, Kambalda, Coolgardie, Depot and Ora Banda) contain one or more known nickel sulphide deposits, whereas no nickel sulphide mineralization is currently known in the other five tectonic domains (Fig. 2.1). As discussed in section 2.4.6 the only deposit camp attributed to the Ora Banda Domain on the basis of the tectonic framework of Cassidy et al. (2006), may actually be part of the Boorara Domain. A total of 156 main nickel sulphide localities in the Kalgoorlie Terrane, consisting of 97 deposits that currently have or historically have had a published nickel resource, and 59 prospects with drill-intersected nickel sulphides are listed in Appendix 1. This deposit dataset was compiled mainly from the MINEDEX (Western Australian Department of Mines and Petroleum) and MINMET (Intierra Resources Pty Ltd.) databases and technical reports of exploration companies. In sections below, the geology of nickel mineralization of each of the five mineralized domains, and the distribution of the deposits and prospects is described.

2.4 Geology and nickel sulphide mineralization of the Boorara Domain

Of the 97 nickel sulphide deposits in the Kalgoorlie Terrane with a published nickel resource, the 29 deposits (30 %) located in the Boorara Domain contain a total of 8.2 Mt nickel metal representing the 76 % of the terrane's currently known nickel endowment (Appendix 1). This indicates that most of the known nickel endowment of the Kalgoorlie

Terrane is hosted by few large, but relatively low-grade komatiitic dunite-associated deposits of the Boorara Domain.

A characteristic geologic feature of nickel mineralization in the Boorara Domain is the association of host komatiitic dunites (e.g. Mt. Keith, Yakabindie and Black Swan) with felsic volcanics, and of unmineralised komatiitic dunite sheets (e.g. Agnew and Walter Williams) with basaltic country rocks (Hill et al., 1990, 2004; Trofimovs et al., 2004; Beresford et al., 2007). This association has been interpreted by Hill et al. (1990) as reflecting the higher capacity of basaltic substrate to impede channel incision by komatiite lava. In contrast, Beresford et al. (2007) suggest that the distribution of felsic and basaltic units may reflect their spatial distribution in a palaeo-rift system wherein felsic volcanics were localized close to the focus of magmatism (rift centres) due to their higher viscosity compared to basalts. Either way, the komatiite-felsic volcanic association may indicate locally favourable environments for nickel mineralization in the Boorara Domain.

The main nickel sulphide deposit camps or groups (Marston 1984; Barnes and Perring, 2006) within the Boorara Domain are Honeymoon Well, Mt Keith, Yakabindie, Perseverance, Mt Clifford, Carnilya Hill, Blair and Black Swan (Fig. 2.1c). The Agnew-Wiluna Greenstone Belt (Hill et al., 1990; Beresford et al., 2004; Fig. 2.2) section of the Kalgoorlie Terrane hosts the first five camps in the above list. Below, a summarized description of the geology and nickel mineralization of the Agnew-Wiluna Belt is presented. This is followed by brief descriptions of the geology and nickel mineralization of each of the camps within the Boorara Domain.

2.4.1 The Agnew-Wiluna Greenstone Belt

The Agnew-Wiluna Greenstone Belt (Fig. 2.2) contains several large nickel deposits such as Mt. Keith (2.8 Mt Ni), Perseverance (1.1 Mt Ni) and Six Mile Well (1.2 Mt Ni), making it one of the most highly endowed nickel belts in the world (Hill et al., 1995; Beresford et al., 2004; Hoatson et al., 2006; Fiorentini et al., 2007). The stratigraphy of the Agnew-Wiluna Greenstone Belt was previously considered in terms of Upper and

Lower Greenstones (Naldrett and Turner, 1977). More recently the stratigraphy has been divided into Eastern and Western Greenstones (Eisenlohr, 1988) which are, respectively, broadly equivalent to the Upper and Lower Greenstones. All known significant nickel sulphide deposits in the Agnew-Wiluna Greenstone Belt are confined to the Eastern Greenstones, which exhibit the following upward succession: (i) tholeiitic basalt unit including minor high magnesian variants, (ii) thin chert, (iii) thick felsic to ultramafic volcaniclastics (and minor pelitic sediments and black shales), (iv) a 2.5 km thick zone, continuous over a strike length of 100 km, consisting of komatiitic volcanics interspersed with layered gabbroic units, high magnesium and tholeiitic basalts and subordinate felsic volcanic rocks (Naldrett and Turner, 1977; Eisenlohr, 1988; Hill et al., 1990, 1995). The Western greenstones predominantly consist of tholeiitic basalt and sulphidic interflow sediments, spinifex-textured komatiites and minor felsic sedimentary rocks.

The komatiite stratigraphy and volcanology of the Agnew-Wiluna Greenstone Belt described by Barnes et al. (1988) and Hill et al. (1990, 1995) has been reinterpreted by Beresford et al. (2004), Rosengren (2004), Trafimvos (2004) and Rosengren et al. (2005). Controversy surrounds the origin of komatiitic dunite lenses consisting of olivine adcumulates and mesocumulates that coincide with komatiite thickening within the belt. Whereas some authors (Donaldson et al., 1986; Barnes et al. 1988; Hill et al., 1990, 1995; Barnes, 2006a) consider the dunite lenses to be integral parts of komatiite volcanic stratigraphy in the belt, others (Naldrett and Turner, 1977; Beresford et al., 2004; Rosengren et al. 2005; Duuring et al., 2004, 2010) interpret the lenses as subvolcanic sills that may be co-magmatic with, but not integral or necessary parts of, overlying komatiitic flows. These dunite lenses are geologically and economically important because many of them host large low-grade disseminated type 2 nickel sulphide deposits, such as Mt. Keith, Honeymoon Well, Goliath North and Six Mile Well.

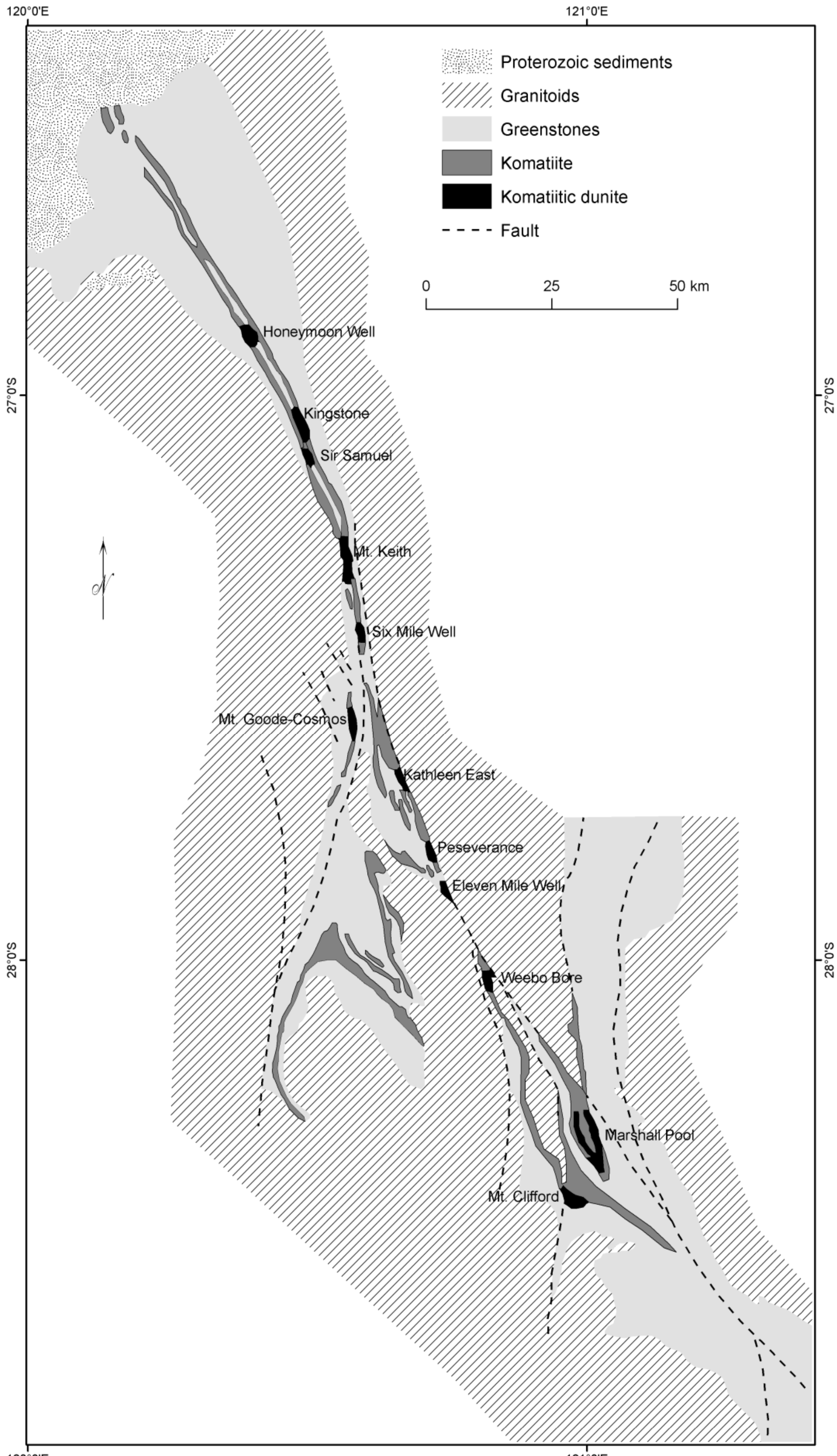

Fig. 2.2 The Agnew-Wiluna Greenstone Belt (modified from Hill et al., 1990).

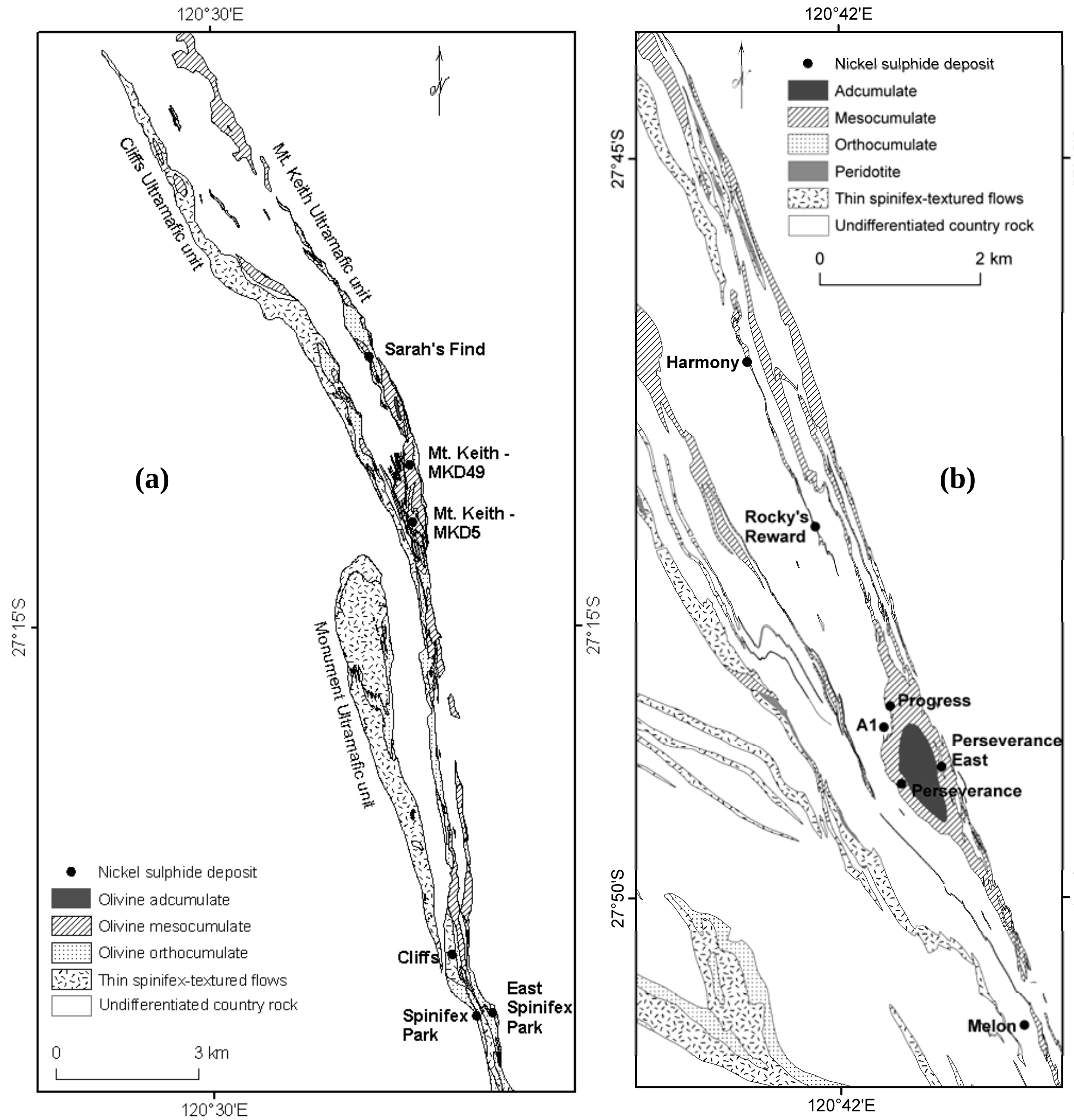

Fig. 2.3 Geology of (a) the Mt. Keith area (after Hill et al., 1990; Beresford et al., 2004), and (b) the Perseverance area (after Hill et al., 1990; Gole et al., 1998 and Beresford et al., 2004).

2.4.2 The Mt. Keith area

The Mt. Keith area is located on the most attenuated part of the Kalgoorlie Terrane (Figs. 2.2, 2.3; Hill et al., 1990; 1995; Beresford et al., 2004; Rosengren, 2004; Rosengren et al., 2007). The greenstone stratigraphy in the Mt. Keith area includes three komatiite units that were initially termed Eastern (lowermost), Central and Western (uppermost) ultramafic units (Hill et al., 1990, 1995). The units, separated by volcaniclastic metasediments, can be traced between the Yakabindie camp in the south and the Honeymoon Well camp in the north beyond which the stratigraphic correlations become increasingly uncertain (Hill et al., 1990; 1995; Grguric, 2006). The Eastern, Central and Western ultramafic units have been renamed Mt. Keith, Cliffs and Monument ultramafic units as an indication of the geographic limits within which he stratigraphic correlations are currently known to apply (Beresford et al., 2004; Rosengren, 2004; Grguric et al., 2006; Rosengren et al., 2007). In the Mt. Keith area the three ultramafic units dip steeply to the west although east facings and shallow dips, associated with a shallowly plunging tight to isoclinal syncline, occur locally (Rosengren, 2004).

The Mt. Keith and Cliffs ultramafic units are mineralized whereas no nickel sulphide mineralization is currently known to occur within the Monument ultramafic unit (Fig. 2.3; Fiorentini et al., 2007). The Mt. Keith ultramafic unit consists of adcumulate-textured pods and lenses flanked by mesocumulate- and orthocumulate-textured units, and disseminated nickel sulphide mineralization mainly within the lensoidal areas (Fiorentini et al., 2007). The mineralized, lensoidal areas include the very large, low grade (2.7 Mt Ni @ 0.6%) type 2 Mt. Keith MKD5 deposit and the Mt. Keith MKD49 prospect (Fig. 2.3). In contrast, Sarah's Find (Fig. 2.3) is a type 1 massive sulphide deposit confined within the basal orthocumulate or peridotite unit of the Mt. Keith ultramafic unit (Fiorentini et al., 2007).

The Cliffs ultramafic unit is considered to be a Kambalda-style extrusive flow system with channelized basal accumulation of massive sulphides, such as at the Cliffs deposit (Rosengren, 2004; Fiorentini et al., 2007) and at the Spinifex Park prospect (Fig. 2.3). Adjacent to the Spinifex Park prospect to the east within the Mt. Keith ultramafic unit is a prospect containing disseminated type 2 nickel sulphides labelled East Spinifex Park in Figure 2.3.

2.4.3 The Yakabindie area

The geology and nickel sulphide mineralization of the Yakabindie area (Fig. 2.2, 2.4) has been the subject of several studies (Naldrett and Turner, 1977; Donaldson et al., 1986; Hill et al., 1990, 1995; Grguric et al., 2006). In this area, the Mt. Keith ultramafic unit contains six mineralized olivine adcumulate lenses, namely Six Mile Well, Betheno, David, Goliath North, Goliath Central and Goliath South, all within a strike length of 5 km. The lenses, exposed as small lateritic-silica-capped hills, are at the same stratigraphic level and are enclosed in, and gradational to, marginal zones of orthocumulates which may have originally linked them (Hill et al., 1995).

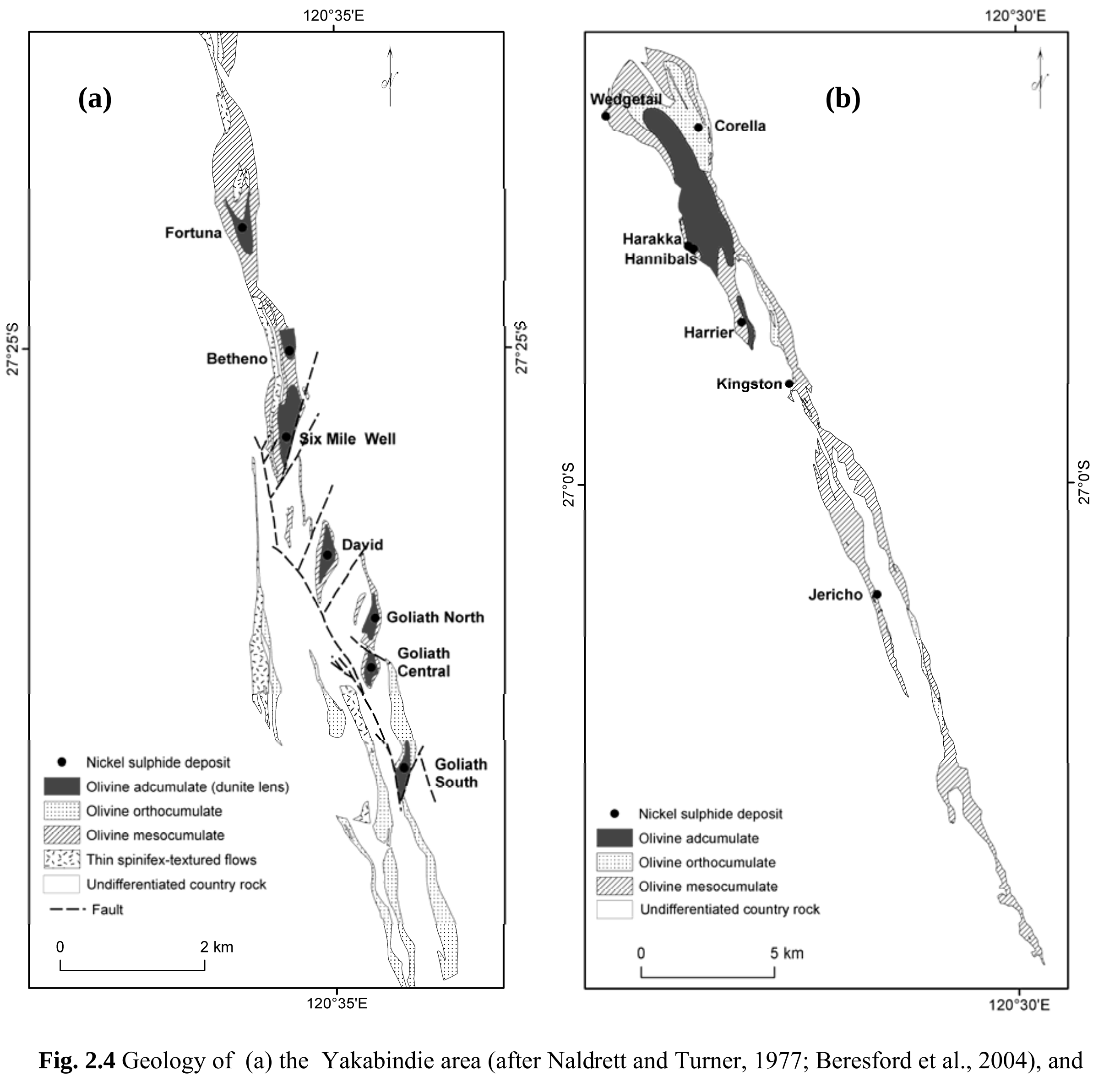

Fig. 2.4 Geology of (a) the Yakabindie area (after Naldrett and Turner, 1977; Beresford et al., 2004), and (b) the Honeymoon Well area (after Hill et al., 1990; Gole et al., 1998 and Beresford et al., 2004).

The geological characterization of the lenses is based on studies of the better explored Six Mile Well deposit. The host Six Mile Well ultramafic complex is concordant with the west-facing stratigraphy, has a steep south-easterly plunge, is in gradational contact with olivine orthocumulates in the north and its eastern and southern peripheries are faulted (Naldrett and Turner, 1977; Hill et al., 1990, 1995; Grguric et al., 2006). The Six Mile Well deposit consists of three lithologic units (Naldrett and Turner, 1977; Hill et al., 1990, 1995; Grguric et al., 2006): (i) a basal adcumulate dunite which grades into, (ii) a mesocumulate peridotite that is overlain by, (iii) an orthocumulate peridotite. The bulk of the resources are hosted by (i) and (ii).

At Goliath North, nickel grades tend to increase with depth raising the possibility that the drilled upper part of the deposit may be a type 2 lower grade disseminated halo around a higher grade type 1 deposit, a hypothesis that has led to deeper exploration drilling in the Goliath Deeps program (Grguric et al., 2006). The hybrid Type 2/Type 1 deposit has a resource which is one third that of Six Mile Well but has more continuous mineralisation (Grguric et al., 2006).

2.4.4 The Perseverance area

The geology of the Perseverance area (Fig. 2.2, 2.3b), which is dominated by the Perseverance ultramafic complex, is described by Barnes (1988; 2006b), Hill et al. (1990, 1995) and Duuring et al. (2004, 2010). According to the descriptions, the Perseverance ultramafic complex consists of a central nickel sulphide-poor, 700-m thick Perseverance dunite lens stratigraphically underlain by a nickel sulphide-bearing sequence dominated by layers of olivine orthocumulate and adcumulate to the north and south. The stratigraphy of the complex dips steeply to the west and is overturned.

The Perseverance complex was originally (Martin and Allchurch, 1975; Marston et al., 1981; Ross and Travis, 1981), and recently (Duuring et al., 2004, 2010) interpreted as an intrusive dunite. The complex has alternatively been interpreted as a thick sequence of komatiite flows that eroded underlying footwall rocks until they stratigraphically overlay a nickel sulphide bearing komatiite (Barnes et al., 1988).

Mineralisation at the Perseverance mine consists of gradational massive ore types: (i) primary ores in contact with metakomatiite and matrix ore at or close to the dunite lens margin, and (ii) remobilized massive breccia ore developed in shear zones extending out into the felsic country rocks to the north of the dunite lens, forming the main 1A shoot and other subsidiary shoots. The massive sulphide 1A shoot contains slivers of sheared ultramafic rocks and has been interpreted as a highly tectonised fault zone into which the massive sulphides were physically remobilized.

The Rocky's Reward deposit (Fig. 2.3b) is a complexly folded and faulted massive sulphide orebody separated from the Perseverance ultramafic complex by a thickened section of felsic country rocks. The deposit has been interpreted to have been originally stratigraphically continuous with the 1A deposit on account of tectonised komatiite slivers traceable between the two deposits (Barnes et al., 1988; De Vitry et al., 1998; Trofimovs, 1999). However this interpretation has not been corroborated by drilling (Duuring et al., 2004, 2010).

About two kilometres to the northwest of Rocky's Reward is the smaller Harmony deposit (Fig. 2.3b) consisting of massive (85 % of resource) and lesser (15 % of resource) disseminated sulphides largely concentrated near the western sheared footwall. The host komatiite is thickest in the centre of the deposit, thins towards the north and south. Disseminated sulphides occur mainly in the hangingwall to the massive sulphides and include pyrrhotite, pentlandite, pyrite and violarite. Stringers of 1 to 10 cm thick remobilised massive sulphides and metamorphosed komatiites and are interpreted to represent post metamorphic remobilised massive sulphides. Duuring et al. (2008) contains detailed geological and structural descriptions of the Harmony deposit.

2.4.5 The Honeymoon Well area

The geology and nickel mineralization of the Honeymoon Well area (Fig. 2.2, 2.4) consists of a north-south trending ultramafic succession dominated by a large lenticular dunite body, flanked to the east and west by west-facing spinifex-textured flows that correlates with the succession at Mt. Keith (Hill et al. (1990; Barnes 2006b). These authors describe the mineralized dunite as a coarse grained, completely serpentinised olivine adcumulate and interpret the whole succession as a D_1 thrust duplex exhibiting extensive stratigraphic duplication and overturning. Five nickel sulphide deposits are located on the contact of the dunite body with the country rock: Harrier, Hannibals, Corella, Harraka (all disseminated), and Wedgetail (massive).

2.4.6 The Cosmos area

The Cosmos nickel sulphide deposit camp, associated with the Mt. Goode dunite lenses (Fig. 2.2), contains both high-grade type 1 deposits (e.g., Cosmos and Alec Mairs) and low-grade disseminated type 2 deposits (e.g., Cosmos South). Three geological zones recognized locally within the camp are the Eastern Zone (N-striking, E-dipping felsic, and mafic-ultramafic volcanics, and sedimentary rocks), the Western Zone (NE-striking, SE-facing tholeiits, gabbroic sills, chloritic schists and the Central Zone (mixed package of conglomerate, and felsic, mafic and ultramafic volcanics, and felsic volcanoclastic sedimentary rocks, and doleritic and porphyry intrusions) which separates the eastern and western zones (Langworthy, 2004).

The Cosmos camp is located close to an intensely deformed, structurally complex area at the junction of the Kilkenny tectonic zone and the Miranda shear zone (Langworthy, 2004). This geological complexity explains why there is no consensus as to whether the Cosmos camp is within the Boorara Domain (Fig. 2.2, Hill et al., 1990, Langworthy, 2004) or the northern tip of the adjacent Ora Banda Domain (Cassidy et al., 2006). Although it is widely believed that the Cosmos camp actually lies within the Boorara Domain (S. Beresford, personal communication, June, 2009), in this thesis the Cosmos camp is placed within the Ora Banda camp (Appendix 1) in line with tectonic framework of Cassidy et al. (2006) that is adopted in this thesis (section 2.1; Fig. 2.1).

2.4.7 The Mt. Clifford area

Marston (1984) and Hill et al. (1990) describe the Mt. Clifford area (Fig. 2.2, Fig. 2.5) as a triangular fault-bounded syncline plunging 45 degrees to the northeast that is

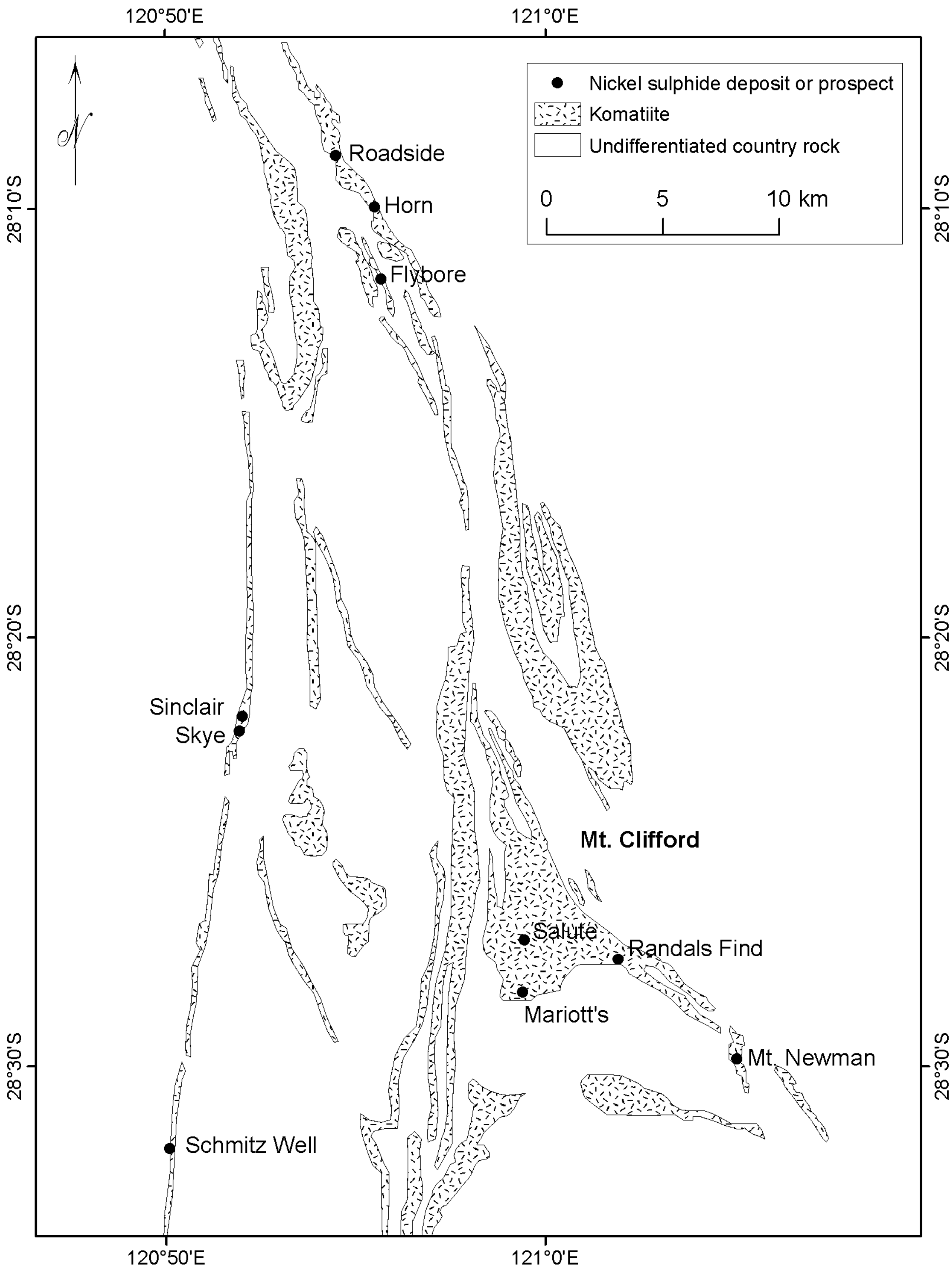

Fig. 2.5 Komatiites and nickel sulphide deposits in the Mt. Clifford and surrounding areas (geology after Jubilee Mines N.L., 2007b and GSWA, 2008).

dominated by the Mt. Clifford ultramafic pile. The Mt. Clifford ultramafic consists of 1,500 m of spinifex textured flows and olivine orthocumulates, underlain in the southwest by a 1,000 m thick olivine adcumulate body. The olivine adcumulate body is conformably underlain by a thick sequence of pillowed tholeiitic metabasalts, the two being separated by a thin chloritic sedimentary unit.

The adcumulate body is overlain by a layered gabbroic unit which is in turn locally overlain by a laterally restricted 150-m thick amygdaloidal olivine orthocumulate unit that hosts the Marriot's nickel sulphide deposit. The mineralized olivine orthocumulate dips northwards at 30 to 35 degrees and is overlain by metasediments and multiple thin spinifex-bearing komatiite flows (Marston, 1984). Marriott's deposit is classified as a type 2A deposit wherein the ore is characterized by an association of globular spherical sulphide blebs with coarse skeletal and harrisitic olivines (Hill et al.; 1990; Barnes 2006b). The sulphide blebs are unusually metal-rich and sulphur deficient, and contain unusual mineralogical phases like awaruite, heazlewodite, and trevorite. These features are thought to be related to sulphur loss during vesiculation (Barnes, 2006b).

Other nickel sulphide prospects within the Mt. Clifford area include the Mt. Newman prospect to the southeast, and at a number of prospects to the north of Marriot's prospect, such as Randal's Find (Fig. 2.5). Further north (Flybore, Roadside and Horn) and east (Sinclair, Skye and Schmitz Well) several prospects occur within emerging nickel sulphide camps in the Boorara Domain (Fig. 2.5). Sinclair and Skye occur on a basal contact between ultramafic rocks and the underlying footwall basalt rocks. The contact is interpreted to be part of a large scale, north plunging synformal fold structure, with mineralisation occurring on both limbs and at the base of the syncline (Jubilee N.L., 2007a).

2.4.8 The Black Swan area

The following descriptions of the nickel sulphide deposits of the Black Swan area (Fig. 2.1b) draw from Hill et al. (2004), Dowling et al. (2004), Barnes et al. (2004), and Sulway et al. (2005). The stratigraphy of the Black Swan area consists of a relatively well preserved bimodal succession of dacitic and komatiitic volcanic rocks. In upward succession, the stratigraphy is made up of: (i) plagioclase-phyric dacitic breccias overlain by, (ii) a komatiite sequence containing two magma pathways occupied by olivine mesocumulates, separated along strike by a broad zone dominated by less magnesian olivine orthocumulates, and (iii) a sequence of quartz-plagioclase phyric komatiite-intercalated dacite breccias and tuffs that rests directly on the komatiite sequence. This sequence has a central pathway and hosts the disseminated type 2 Black Swan orebody.

The Cygnet deposit contains a mixture of disseminated and net-textured ore located close to the base of a thick cumulate-rich flow unit within a pathway that also hosts the massive sulphide White Swan satellite deposit. Silver Swan (together with the Black Duck and Gosling satellite deposits) is a type 1 massive deposit hosted by a separate secondary pathway or lava tube.

2.4.9 The Blair area

Blair and Blair South are the only two significant deposits currently known in the Blair camp (Fig. 2.1b). The mineralization consists of disseminated (0.5% to 3.0% Ni), matrix (up to 6.0% Ni) and massive (up to 20% Ni) Kambalda-style contact mineralization in narrow ore shoots with a strike length of 20 to 25 metres (Australian Mines Limited, (http://www.australianmines.com.au/operations.29.html).

2.4.10 Carnilya Hill

The Carnilya Hill camp (Fig. 2.1b) comprises Carnilya Hill East and Zone 29 deposits, and Dunlop and Goodyear prospects described by Marston (1984), as summarized here. The deposits are associated with the Carnilya Hill ultramafic formation, an interpreted flow sequence. At Zone 29 deposit, nickel mineralization is concentrated at the base of the third flow unit which is about 65 m stratigraphically above the base of the formation, and consists of 21 m of serpentinite, overlain by about 2 m of spinifex-textured serpentine-chlorite-tremolite rock. The mineralization consists of small (1- to 2-m thick) lenses of massive and matrix sulphides with a strike length of 450 m and vertical depth of 150 m. Two mineralized horizons, separated by 7 m of ultramafic rocks, occur at the west end of the shoot, with barren sulphides occurring downdip of the shoot. The mineralization style and setting of the Carnilya Hill deposit have been likened to those of hanging wall ores at Kambalda.

At the Carnilya Hill East deposit, foliated fine grained tholeiitic basalt is in contact with the ultramafic formation to the north and south. The mineralized southern contact is characterized by vein quartz and massive foliated hybrid rocks containing quartz, feldspar, chlorite, tremolite rosettes and small carbonate porphyroblasts. Nickel sulphide mineralization in the contact zone occurs over a strike length of 420 m and to a vertical depth of 160 m where the deposit may be terminated by a north-dipping reverse fault.

2.4.11 The Scotia area

Page and Schmulian (1981), Stolz and Nesbitt (1981) and Marston et al. (1984) described the stratigraphy of the Scotia area (Fig. 2.1b) as consisting of footwall basalt, footwall sediments, host ultramafic rocks, lower lava sequence, upper lava sequence and a sedimentary sequence. The ore environment, marked by thickening of the overall ultramafic sequence, is within a pronounced embayment at the basal contact of a massive dunitic unit which itself is the basal unit of a thick komatiite sequence. The dunite attains a maximum thickness of 45 m, and consists of close-packed medium to coarse-grained partly serpentinised, granular olivine and has no spinifex textured top or other obvious flow features. The orebody (up to 20 m thick) consists of, (i) a discontinuous layer of massive sulphide at the base of the central portion of the ore-bearing ultramafic within a local embayment subsidiary to the major embayment in the basal ultramafic contact, and (ii) an overlying zone of disseminated nickel sulphide mineralization, constituting 30 percent of the ore zone, and containing 3 to 35 % sulphide.

2.5 Geology and nickel sulphide mineralization of the Kambalda Domain

The Kambalda Domain (Fig. 2.1, 2.6) is the world’s type locality for komatiite-associated Type 1 nickel sulphide deposits (Naldrett, 2004; Barnes, 2006b; Beresford, 2007). The 46 known nickel sulphide deposits in the Kambalda Domain (Appendix 1) occur in four deposit camps (Fig. 2.6), namely Kambalda (23 deposits, Fig. 2.7), St. Ives (four deposits), Tramways (16 deposits, Fig. 2.8) and Bluebush (three deposits) (Appendix 1). Of the 97 deposits in the Kalgoorlie Terrane that have a published nickel sulphide resource, the 39 (40%) within the Kambalda Domain account for 1.6 Mt nickel metal or 14% of the currently known nickel resources within the Kalgoorlie Terrnane.

In addition to the four komatiitic peridotite-associated nickel sulphide deposit camps within the Kambalda Domain, the southern part of the Kalgoorlie Terrane also hosts the Widgiemooltha camp located in the Depot Domain (Fig. 2.6). The geology and style of nickel mineralization of the Widgiemooltha camp are similar to those of the Kambalda camp. A key feature of these type 1 nickel sulphide deposits is their spatial and genetic association with magma pathways or channels (Barnes 2006b). Eleven such channels have been identified within the Kambalda camp (Fig. 2.7, Gresham, 1986; Reliance Mining Limited, 2004; 2005; Independence Mining Group N.L., 2009) and 10 channels have been identified within the Tramways camp (Fig. 2.8, Panoramic Resources Limited undated; Panoramic Resources Limited, 2009). Presently, the available information is inadequate for detailed interpretation of channels within the Widgiemooltha and other camps.

The four nickel sulphide deposit camps within the Kambalda Domain are described below; those of the Widgiemooltha camp are described in section 1.3.3.

2.5.1 The Kambalda camp

The Kambalda nickel sulphide deposits are situated on the Kambalda Dome in the south central part of the Kalgoorlie Terrane (Figs. 2.6, 2.7). The upward succession of the well established stratigraphy of the Kambalda Dome (Gresham and Loftus-Hills, 1981; Cowden and Roberts, 1990 Stone and Masterman, 1998; Stone and Archibald, 2004) consists of lower basalt, komatiite, upper basalt, and felsic volcanic and sedimentary units, locally overlain by coarse clastic rock packages. This volcano-sedimentary sequence was intruded by felsic to intermediate intrusive rocks, underwent metamorphism (upper greenschist to lower amphibolite facies) and polyphase deformation. The dome is interpreted as a doubly plunging asymmetrical inclined D_3 anticline with a NNW-striking and steeply W-dipping axial surface.

Stratigraphic units that are spatially and genetically most closely associated with nickel sulphide mineralization at Kambalda are the Lunnon Basalt (footwall), and the Kambalda Komatiite Formation. The latter consists of the basal, locally mineralized Silver Lake Member (host sequence) overlain by the upper unmineralised Tripod Hill Member (hanging wall sequence). According to Gresham and Loftus-Hill (1981) and Stone and Archibald (2004), the immediate nickel sulphide mineralisation environment is characterized by: (i) embayments or trough structures in the upper surface of the Lunnon Basalt, (ii) lack of sedimentary rock in the trough structures, (iii) contact nickel sulphide ore completely or partially confined within the trough structures that are considered to represent primary volcanic topography (Ross and Hopkins, 1975; Gresham and Loftus-Hill, 1981; Lesher, 1989) or, alternatively, to have resulted from post volcanic deformation (Cowden, 1985, 1988; Cowden and Archibald, 1987; Stone and Archibald, 2004); (iv) hanging wall ore, usually stratiform, occurring at the base of the overlying flows or, rarely blebby sulphides within the basal unit, (v) offset ore displaced from contact or hanging wall positions and, (vi) thickened MgO enriched ultramafic rocks (channel facies komatiite) in the immediate hanging wall. The channel facies are thick (up to 100 m), high magnesian (up to 45 % MgO) komatiite flows flanked by sheet flow facies (non-ore environment). Sheet flow facies are gradational to the channel facies and are thinner (10-20 m), less magnesian (16-36 % MgO), and more texturally and chemically differentiated compared to the channel facies. Sheet flow facies commonly contain thin sedimentary units which are normally absent in the channel facies and in the gradation to the channel facies.

Each deposit in the Kambalda camp comprises one or more orebodies or ore shoots, which comprise ore surfaces or subshoots (Woolrich et al., 1981). Fisher and Otter-Juan deposits (Fig. 2.6) are termed complexes on account of the structural and spatial complexity of the distribution of their subshoots (Marston, 1984). Based on ore characteristics, Marston (1984) noted that nickel sulphide orebodies of the Kambalda camp consist of eastern and western subgroups divided by a straight NW-SE line that passes immediately east of the Wroth orebody, and immediately west of the Lunnon orebody (Fig. 2.7). The eastern group orebodies are larger, contain less hangingwall ore compared to the western group orebodies. Carbonaceous, slaty metasediments are more abundant in the western than eastern group. Non-chloritic metasediments in the eastern group orebodies contain more albite, tremolite and total sulphide than those in the western group orebodies (Bavinton, 1981). This dichotomy in ore characteristics between the eastern and western groups is consistent with observations that from east to west, the Kambalda komatiite formation thins, channel facies (ore environment) become less well-defined, and sheet flow facies (non-ore environment) become more dominant (Gresham, 1986; Cowden and Roberts, 1990; Williams et al., 1993; Beresford et al., 2002). Centrographic analyses by Mamuse et al. (2009) indicate that total nickel endowment is greater in the eastern side than in the western side of the Kambalda camp, in accord with the observed asymmetries in ore characteristics across the dome.

Readers are referred to Gresham and Loftus-Hill (1981) and Marston (1984) for detailed descriptions of individual orebodies and deposits of the Kambalda camp. Specific aspects of nickel mineralisation within the Kambalda camp covered in detail elsewhere include geochemistry (Woolrich et al., 1981; Brand et al., 1999; Arndt and Jenner, 2001; Lesher and Burnham, 2001), structural controls of mineralisation (Stone and Archibald, 2004; Stone et al., 2005), volcanology (Beresford and Cas, 2001; Cas and Beresford, 2001; Rice and Moore, 2001; Beresford et al. 2002, 2005).

2.5.2 The Tramways camp

The Tramways nickel deposit camp (Figs. 2.6, 2.8) lies within the Tramways complex of the Kambalda-Tramways corridor (Brilliant Mining Corp., 2007). The mafic-ultramafic stratigraphy of the Tramways complex is considered similar to that of the Kambalda area (Gresham and Loftus-Hill, 1981; Marston, 1984). In upward succession, the stratigraphy consists of lower basalt, komatiite, upper basalt and felsic volcanic and sedimentary

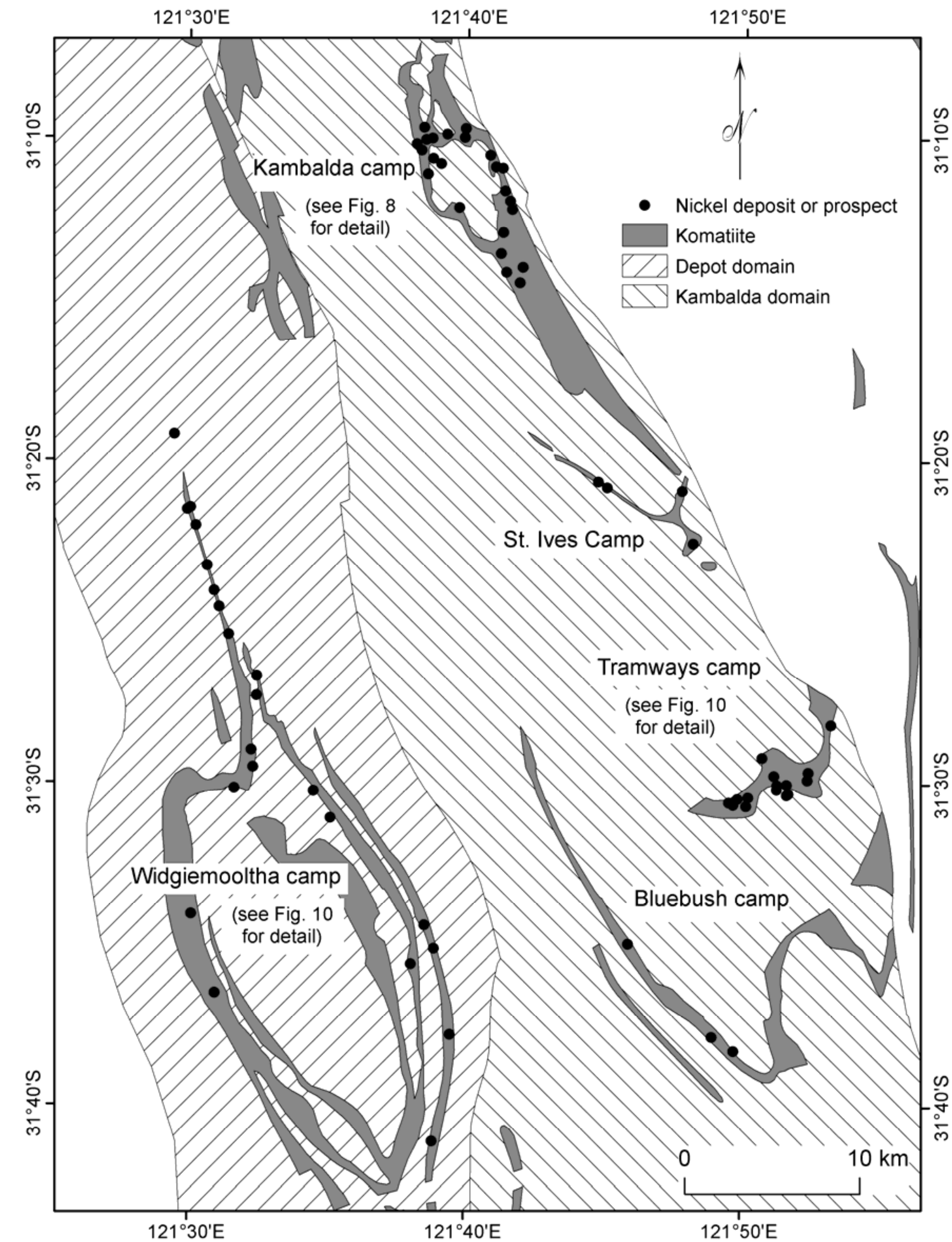

Fig. 2.6 Nickel sulphide deposit camps within the Kambalda and Depot Domains in the southern part of the Kalgoorlie Terrane (geology after GSWA, 2008).

units, that are in places unconformably overlain by coarse clastic rock packages. The information presented below is principally drawn from Gresham and Loftus-Hill (1981), Marston (1984), Brilliant Mining Corp. (2007), Onley et al. (2006) and Mapleson et al. (2007).

The Tramways deposit camp contains 16 deposits that dominantly consist of massive sulphides (pyrrhotite-pyrite-pentladite±chalcopyrite) occurring on the footwall basalt/ komatiite contact variably confined to trough structures in the footwall basalt. Subordinate mineralization occurs as hangingwall disseminated sulphides and remobilized sulphide orebodies in structural settings within the footwall basalt. The nickel sulphide orebodies are ribbon-like, ranging from 50 to 500 m long, 30 to 80 m wide and 0.5 to 30 m thick (Brilliant Mining Corp. 2007). The orebodies generally display antithetic associations with contact sediments although at Cruikshank and John deposits (Fig. 2.8) sediments overlap the ore zones (Marston, 1984).

The geological structure of the Tramways complex is dominated by two doubly plunging, upright anticlines with curvilinear SW-NE oriented axial surfaces that are separated by a complexly faulted N-S syncline truncated to the north by a SE-NE oriented fault (Marston, 1984). The fault, known as the Tramways thrust (Fig. 2.8), is structurally associated with overturning of the Tramways Complex (Brilliant Mining Corp., 2007). This is consistent with the deep drilling-based interpreted presence of southeast plunging recumbent folding at Cruikshank deposit (Fig. 2.8) reported by Marston (1984). A projected axis of the overturned fold subparallel to the Tramways thrust (Fig., 2.8; Brilliant Mining Corp., 2007) underpins the proposed 'overturned dome model' that enhances nickel prospectivity at Tramways. A possible extension of the presumed axis of the overturned fold through Cruikshank is envisaged in Figure 2.8. In 2007, an area two kilometres wide and straddling Joy prospect (Fig. 2.8), was earmarked for 17-20 drill-testing (8,000-9,000 drill metres) to test the overturned model (Brilliant Mining Corp., 2007).

The main deposits in the Tramways camp are described in Table 2.1.

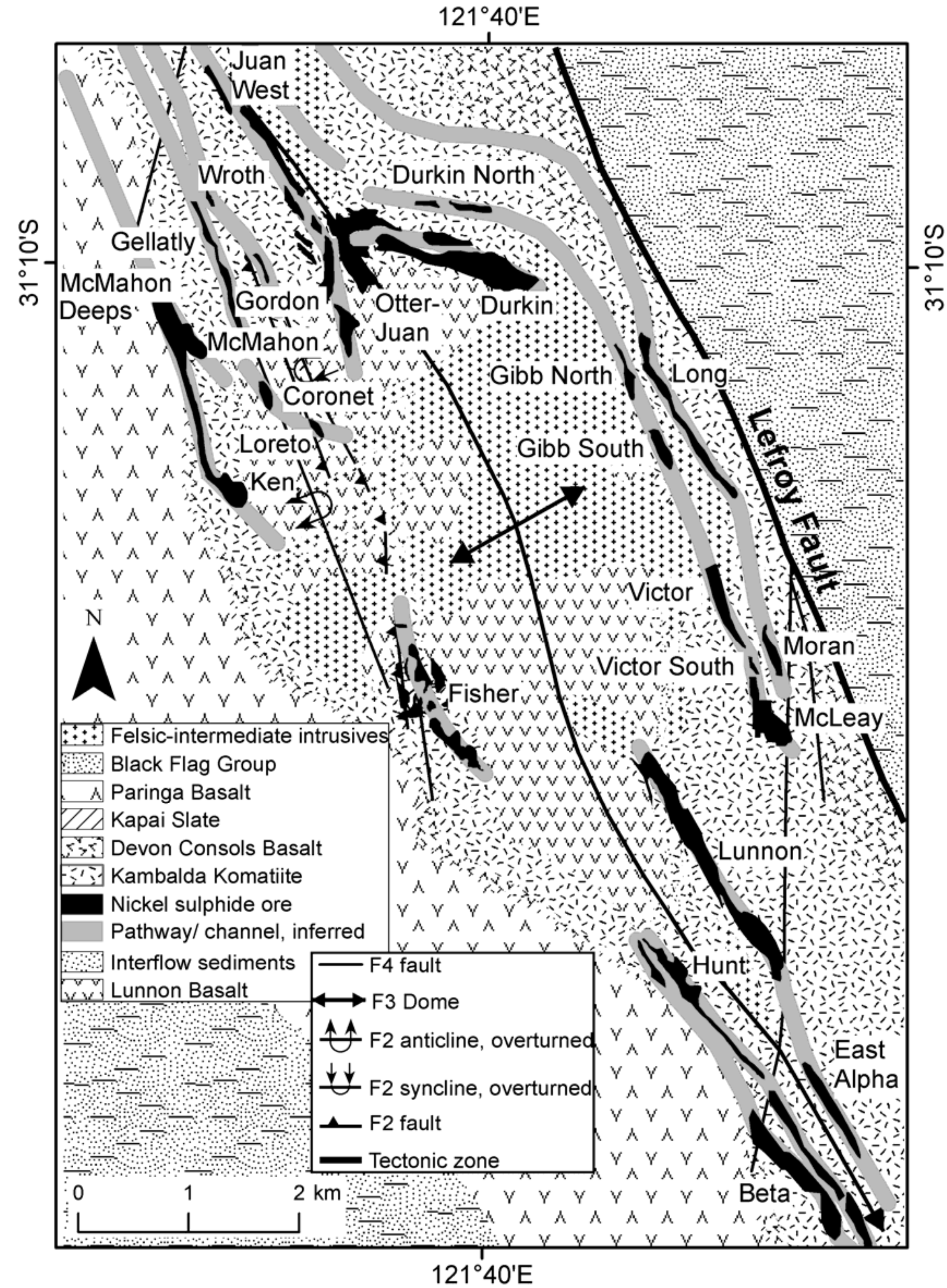

Fig. 2.7 Geology of the Kambalda camp and sketch of nickel sulphide magma pathways/ channels in the camp (geology after Gresham and Loftus-Hills, 1981; Cowden and Roberts; 1990; Stone and Archibald, 2004; channels after Reliance Mining Limited, 2004, 2005; Independence Mining Group N.L., 2009).

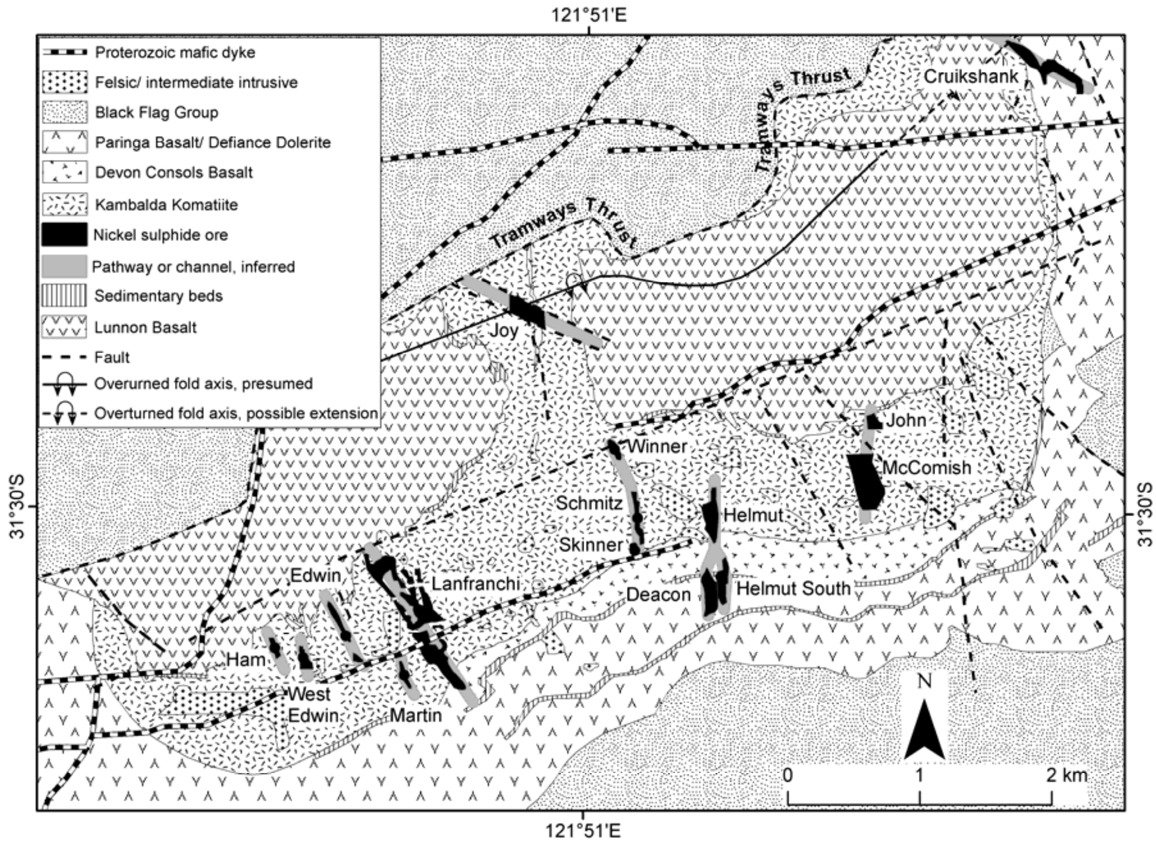

Fig. 2.8 Geology of the Tramways camp and sketch of nickel sulphide magma pathways/ channels in the camp (geology after Gresham and Loftus-Hill, 1981 and Onley et al., 2006; channels interpreted from Mincor Resources N.L. 2007; 2008).

2.5.3 The St. Ives camp

This section draws from Gresham and Loftus-Hill (1981) and Marston (1984). The St. Ives camp (Fig. 2.6) consists of four main Kambalda-style nickel sulphide deposits or prospects (Jan, Foster, NW Foster and East Coee) that occur in the same anticlinal zone of mafic to ultramafic metavolcanic rocks that contains the Kambalda camp. The Jan orebody, located near the southern extremity of the St. Ives camp, consists of a series of hanging-wall ore horizons with minor contact ore in small structurally complex positions. Channel facies of the host basal komatiite are 100- to150-m thick. The extensively carbonated sequence is dominated by talc-magnesite-chlorite rocks. The unmineralised upper member consists of thin komatiitic flows. The footwall metabasalt, which is thought to core the Kambalda-St. Ives anticline in the area, is fine- to medium-grained and undeformed except along contacts with ultramafic rocks where it is foliated.

TABLE 2.1[1] Descriptions of the main nickel sulphide deposits within the Tramways camp

Deposit	Geology	Mining/ Exploration activities
Lanfranchi	Lanfranchi deposit occurs within the Lanfrachi nickel sulphide channel (Fig. 2.8) and is the longest and widest collection of orebodies at Tramways camp.	Mining of the Lanfrachi orebody commenced in 1987 and was effectively completed in 1999, producing a total of 1.4 million tonnes at 2.32 % Ni over a down plunge length of 1.5 km. Underground hole resource delineation for a possible 200-metre immediate down-plunge extension of the Lanfranchi deposit, known as Lanfrachi West, located west of the southern part of the main deposit was being undertaken at the time of writing this thesis.
Schmitz	Schmitz orebody is located on the high grade Winner-Schmitz-Skinner channel (Fig. 2.8), and is split into four contact ore surfaces by felsic to intermediate intrusive rocks.	Schmitz was mined out after 11 years in 2004.
Winner	Mineralization at Winner consists of high arsenic (1,091 ppm As, uncut) massive and matrix contact sulphide ore, with minor disseminated ore in the overlying ultramafic rock.	Production commenced in November 2007, with a pre-mining probable mineral reserve of 144,000 tonnes ore at 4.26 % Ni, and an indicated mineral resource of 111,700 tonnes grading 6.16 % Ni. The high arsenic Winner ore is blended with low arsenic Helmut South, Deacon and Lanfranchi ores.
Skinner	The Skinner orebody, plunging 30° to the South, is interpreted as a structural offset from the original Winner-Schmitz channel. To the east the orebody is bounded by a footwall of sheared felsic to intermediate intrusive and to the west by a hanging wall consisting of ultramafic and felsic to intermediate intrusives.	Skinner was discovered in 1999, and mining of the orebody commenced the same year and was completed in 2001. A total of 298,781 tonnes of ore grading 4.87 % Ni for 14,505 tonnes of nickel metal was produced from the 140 m by 30 m by 30 m orebody during this period.

Notes

[1]Sources of information in Table 2.1 include: Gresham and Loftus-Hill (1981), Marston (1984), Onley et al. (2006), Mapleson et al. (2007), Brilliant Mining Corp. (2007) and Mapleson et al. (2007).

TABLE 2.1[1] **(continued)** Descriptions of the main nickel sulphide deposits within the Tramways camp

Deposit	Geology	Mining/ Exploration activities
Helmut	Helmut consists of disseminated and matrix mineralization that occupies intercumulus spaces of the host orthocumulate textured talc-magnesite unit. A barren 3 to 7 m thick ultramafic zone occurs between the ore and footwall basalt.	Helmut was mined between 1996 and 2002. The mineralized pod is 50-80 m wide, 10-30 m thick and 350 m long on plunge.
Helmut South	Mineralization at Helmut South is dominantly low tenor disseminated ore hosted in a talc carbonate altered rock at the basalt-ultramafic contact, where minor massive sulphide stringers may also occur.	First production from Helmut South was achieved in September 2005.
Edwin	The Edwin orebody is up to 50 m wide and 60 m long on plunge, hosting contact matrix and massive sulphide ore. In some places barren ultramafic separates interflow sediments from ore and in other places the sediments directly overlie the ore. The ore is of similar grade to that at Lanfranchi which is 600 m to the east.	Edwin was exhausted in 1979 after only three years of mining.
Deacon	Deacon consists of disseminated and matrix ore and significant lenses of massive sulphide mineralization. The mineralization occurs within a channel structure adjacent and parallel to the Helmut orebody to the east. Disseminated sulphides a blebby and are slightly more concentrated towards the footwall contact.	Deacon was discovered in October 2006, and production commenced in March 2008 with a pre-mining probable reserve of 1.7 Mt grading 2.54 % Ni for 43,000 t nickel metal.
Cruikshank	Cruikshank is a large low grade contact envelope of disseminated (and subordinate matrix) sulphide ore directly overlying carbonaceous or cherty metasediments. It is interpreted to occupy the upper limb of a recumbent anticline that plunges SE at 35°, cut by a high angle NW to SE reverse fault on the upper levels.	Cruikshank orebody was discovered by percussion drilling based on a soil geochemical anomaly in 1969.

Notes

[1]Sources of information in Table 2.1 include: Gresham and Loftus-Hill (1981), Marston (1984), Onley et al. (2006), Mapleson et al. (2007), Brilliant Mining Corp. (2007) and Mapleson et al. (2007).

The orebody is dissected by an easterly striking dolerite dyke. Foster orebody is located west-northwest of Jan orebody in an area where the ultramafic thickness rarely exceeds

150 m in the ore environment (channel facies) and 100 m in the flanking environment. The orebody is contained within a major trough structure which defines three structural ore domains: the southeast domain (ore in a clearly defined trough structure of variable morphology), central domain (open shallowly depressed contact orebody) and northwest domain (ore in a deeply incised tough structure). The northwest domain is underlain by a relatively undeformed, homoclinal sedimentary layer, interpreted as the site of a pre-existing topographic feature in the footwall basalt.

The komatiite associated with the East Cooee orebody is up to 250 m thick, and contains several basal lensoid olivine-peridotite units (altered to talc-magnesite-chlorite rocks) which are up to 50 m thick. The orebody consist entirely of hangingwall mineralization in two planar subshoots that are ovoidal and occur on flow unit boundaries at the base of talc-magnesite-chlorite units.

2.5.4 The Bluebush camp

The following description of the Bluebush nickel sulphide deposit camp (Fig. 2.9) is drawn from Marston (1984). The Bluebush komatiite sequence is separated from the Tramways komatiite sequence by poorly exposed metavolcanic and metasedimentary rocks. The stratigraphy of the Bluebush area is similar to that of the Kambalda-St. Ives-Tramways area in that the immediate ore environment consists of komatiites that are overlain and underlain by metabasalts, and contains thin horizons of sulphidic metasediments. This package is overlain by felsic volcanic and clastic rocks.

The Bluebush camp consists of several relatively small nickel sulphide orebodies and prospects in which nickel sulphides occur at or near the footwall contact of the komatiite sequence (Kambalda-style). The Cameroon orebody consists of disseminated or blebby sulphides in a basal 40-m thick weakly foliated talc-magnesite-chlorite rock. The Stockwell-Grimsby orebody consists of (i) three *en echelon* elongate lenses of massive breccia ore that plunge gently to the southeast over a strike length of 850 m, in weakly foliated medium-grained, granular talc-carbonate-chlorite assemblage, and (ii) disseminated or blebby sulphides in the basal few metres of the ultramafic sequence, grading 1.0 to 1.5 % nickel. Lesser known nickel sulphide prospects in the Bluebush area include Lawry, Duke and Republican Hill.

2.6 Geology and nickel sulphide mineralization of the Widgiemooltha Dome (Depot Domain)

All of the 22 nickel sulphide deposits in the Depot Domain are confined to the Widgiemooltha Dome (Fig. 2.6, 2.9). The deposits generally occur at the komatiite-basalt contacts within the periphery of the Widgiemooltha Dome, a doubly plunging anticlinal synkinematic granitoid intruded into the greenstones of the Kalgoorlie Terrane (McQueen, 1981; Marston, 1984). The flanking mafic-ultramafic layers dip outwards at between 45 and 85 degrees, but flatten to between 20 and 50 degrees close to the plunging anticlinal axis at the northern and southern fringes of the dome (Marston, 1984). Four phases of deformation recognized in the area are (Archibald, et al., 1978; McQueen, 1981): (i) early large-scale recumbent folding apparent in low strain areas (D_1), (ii) D_2 deformation that produced macroscopic and mesoscopic F_2 N to NNW-trending axial plane slaty cleavage, (iii) a synmetamorphic D_3 phase initiated with dome emplacement which produced steep layer-parallel metamorphic foliation parallel to F_3 northwesterly striking folds, most pronounced on the eastern flank and, (iv) a late D_4 deformation which crenulated F_3 surfaces.

The mafic-ultramafic sequences at Widgiemooltha are envisaged to young outwards from the dome (Marston, 1984). In particular, the upward stratigraphic succession, from the dome outwards (Fig. 2.9), of the ultramafic sequences consist of (McQueen, 1981): (i) an apparently barren lower (innermost) komatiite sequence, (ii) a central komatiite sequence, hosting Wannaway, Munda, Mount Edwards, Dordie Rocks and other deposits, and (iii) an outer sequence containing Redross, Mariners and other prospects or deposits. These ultramafic sequences, which contain thin intercalated horizons of carbonaceous cherty sulphidic metasediments (locally associated with contact nickel mineralization), are thinner (50 to 250 metres thick) but they generally resemble those at Kambalda (Gemuts and Theron, 1975; McQueen, 1981; Marston, 1984). A revised

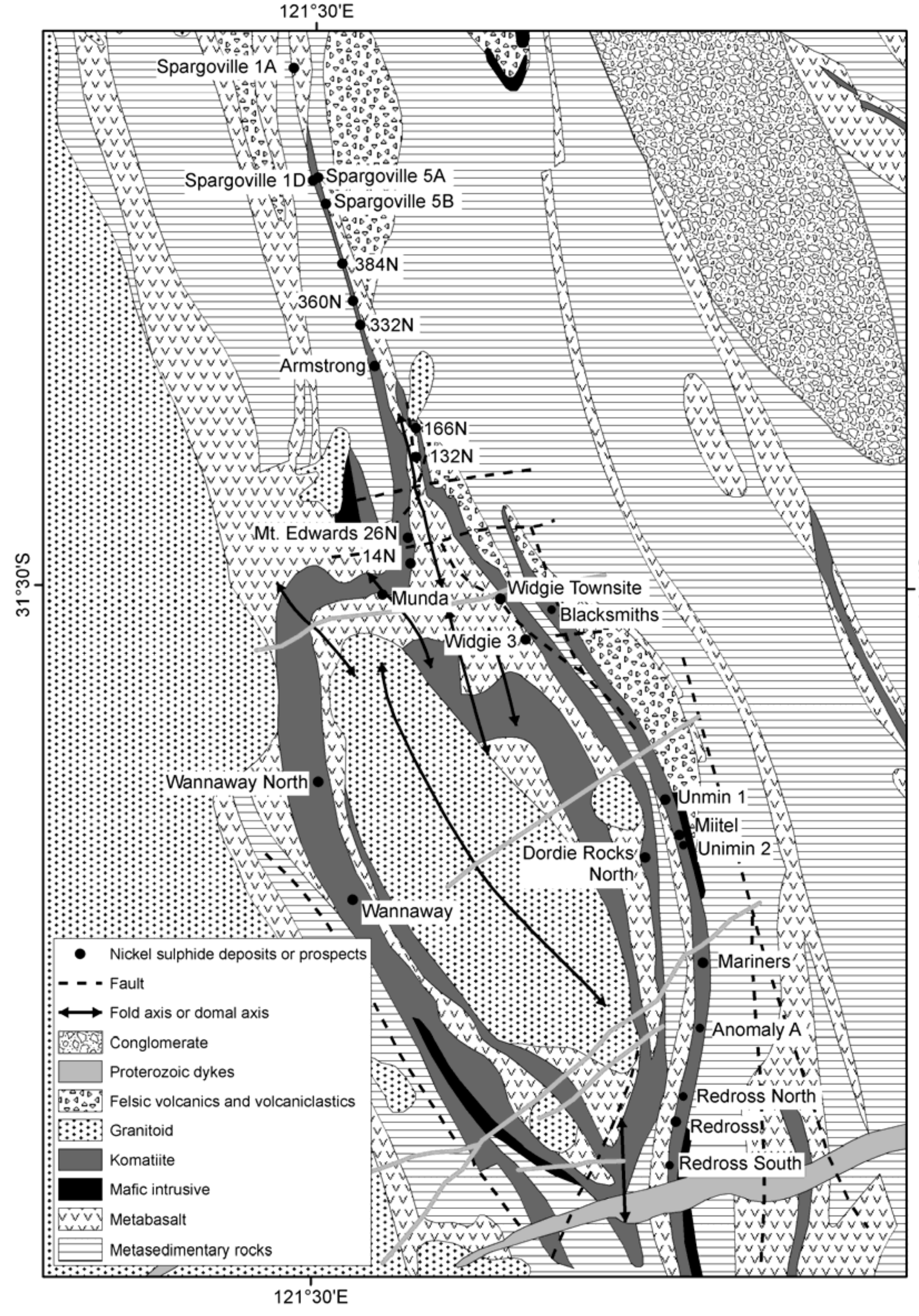

Fig. 2.9 Geology and nickel sulphide deposits and prospects of the Widgiemooltha Dome (after GSWA, 2008).

stratigraphic framework (Krapez et al., 2000) considers the mineralized central and outer komatiite sequences to be components of the Widgiemooltha komatiite whereas the unmineralised inner komatiite sequence constitutes the Mt. Morgan komatiite. It has also been suggested that the Mt. Morgan komatiite could, in fact, be a structural repetition of the Widgiemooltha komatiite, rendering the Mt. Morgan komatiite potentially prospective for nickel sulphide mineralization (Daddow et al., 2003).

Regional metamorphism at Widgiemooltha, which is higher grade than that at Kambalda (McQueen, 1981; Marston, 1984), has been described as follows by McQueen (1981). Ultramafic rocks along the eastern edge of the Widgiemooltha Dome have undergone serpentinisation, and extensive prograde talc-carbonate alteration. In the north, there has been serpentinisation, minor carbonate alteration, and prograde reconstitution to fosterite-talc rich assemblages. At the western periphery, dunitic units have been retrogressively serpentinised without significant prograde serpentinisation and talc-carbonate alteration. Diversity of these metamorphic and alteration environments are reflected in sulphide mineralogical composition.

Key characteristics of nickel sulphide mineralization within the Widgiemooltha Dome are (Gemuts and Theron, 1975; McQueen, 1981; Marston, 1984): (i) mineralization dominantly occurs at the basal contact of komatiite with basalt (Kambalda-style), although deformation along the komatiite-basalt contact has offset some orebodies (e.g. Redross, Widgie 3) by reverse faulting into the hanging wall ultramafic rocks or footwall metabasalt, (ii) though Kambalda style, the Widgiemooltha camp (~360 kt contained nickel metal) has, on average, much smaller deposits that those at Kambalda camp (~1.5 Mt contained nickel metal), (iii) although the nickel deposits are commonly associated with trough structures or embayments, these are much shallower and less confining compared to those at Kambalda, (iv) orebodies plunge parallel to the trough structures but may locally parallel fold axes, plunges of faulted wedges of metabasalt or mineral lineations in wallrocks, and (v) in decreasing abundance, the primary sulphide minerals at Widgemooltha are: pyrrhotite, pentlandite, pyrite and chalcopyrite.

TABLE 2.2[1] Descriptions of some nickel sulphide deposits within the Widgiemooltha camp

Deposit	Geology	Mining/ Exploration activities
Redross	Redross deposit is controlled structurally by a wedge of footwall metabasalt which projects up to 80 m into the base of the ultramafic unit. The main Redross vein lies to the west beneath the wedge whereas a smaller vein (Eastern vein) lies on the eastern surface of the wedge. The ultramafic unit is intensely talc-carbonated and contains accessory chlorite, anthophyllite and tremolite.	Redross was discovered in 1968 and initially mined between 1973 and 1978. Mining operations resumed in 2004.
Wannaway	Wannaway is located stratigraphically on the central ultramafic unit and geographically to the west of the Widgiemooltha Dome (Fig. 2.9) The orebody pitches 60 degrees to the north along a shallow trough structure in the footwall metabasalt, from which it is separated by barren serpentinite in the upper 250 m. At depth the orebody converges into the contact and enters the footwall in places. Most of the mineralization is disseminated sulphides, with massive sulphides occurring as veins below the disseminated sulphides.	Wannaway was mined from 1984 to 1998 and from 2001 and 2007 producing a total of 27,000 tonnes of nickel metal.
Mariners	Mariners is a high arsenic deposit, consisting of down-plunge *en echelon* pods, and hosted in an intensely talc-carbonated ultramafic sequence within a north plunging trough structure.	Mariners was discovered in the 1970s has been mined from 1991 to 1999, and from 2004 to present. It has an approximate total endowment of 67,000 tonnes of nickel metal.
Miitel	The Miitel orebody is an elongated, near vertical and gently plunging orebody situated on the intensely talc-carbonated eastern flank of the Widgiemooltha Dome.	Miitel was discovered from initial intercepts in the 1970s. and has a total nickel metal endowment of 87,000 tonnes, the highest within the Widgiemootha camp.

Notes

[1]Sources of information in Table 2.2 include are McQueen (1981) and Marston (1984), supplemented by stock exchange reports.

TABLE 2.2[1] **(continued)** Descriptions of some nickel sulphide deposits within the Widgiemooltha camp

Deposit	Geology	Mining/ Exploration activities
Dordie Rocks North	The Dordie Rocks North orebody consists of two small low grade orebodies (2,200 tonnes total contained nickel) occupying a trough structure at the mafic-ultramafic basal contact, with sulphide veinlets penetrating the footwall metabasalt.	The Dordie Rocks North orebody was discovered in 1969 with a pre-mining resource of 191,000 tonnes grading 2.37 % nickel.
Widgiemooltha 3	Widgiemooltha 3 is sigmoidal lesoid with arsenical sulphide mineralization located along the northern side of a footwall trough structure that pitches steeply to the north. Numerous small matrix ore shoots and ore stringers occur along the trough structure's edges and footwall fractures.	The total pre-mining contained nickel metal of the deposit is estimated at 10,500 tonnes.

Notes

[1]Sources of information in Table 2.2 include are McQueen (1981) and Marston (1984), supplemented by stock exchange reports.

The main nickel sulphide deposits and prospects within the Widgiemooltha Dome are described in Table 2.2.

2.7 Geology and nickel sulphide mineralization of the Coolgardie Domain

The following description of the most significant nickel sulphide deposits in the Coolgardie Domain namely, Nepean, Miriam and Bouchers, is drawn from Marston (1984). They are Kambalda-style Type 1 deposits found at or near the komatiitic basalt contact. Nepean nickel mine (1.1 million tonnes @ 3% Ni), the largest known deposit in the Coolgardie Domain, is located at the northern end of a large supracrustal remnant in granitoid rocks. The supracrustal remnant consists of amphibolite derived from basalt and gabbro. The amphibolite, consisting of thin conformable units of ultramafic rocks, metasediments and felsic country rocks, has a strike length of 8 km and is up to 2 km wide. The ultramafic units are numbered 1 to 4 from west to east in the mine area. The deposit consists of two overlapping orebodies in units 2 and 3. Most of the mineralization is contact ore on the basal (eastern) contacts with hanging-wall ore occurring on the top contact of unit 3. Matrix ore is the dominant type of ore in these zoned orebodies in which massive ore occurs at the base of and/ or in the matrix ore.

The lesser known Bouchers and Miriam prospects occur in a belt of cumulate-rich ultramafics to the northwest of, and on strike from, the Nepean deposit.

References

Archibald, N. J., Bettenay, L. F., Binns, R. A., Groves, D. I., Gunthorpe, R. J., 1978. The evolution of Archaean greenstone terrains, Eastern Goldfields province, Western Australia. Precambrian Research 6, 105-151.

Arndt, N.T., Jenner, G.A.,1986. Crustally contaminated komatiites and basalts from Kambalda, Western Australia. Chemical Geology 56, 229-255.

Australian Mines Limited. http://www.australianmines.com.au/operations.29.html (accessed September 20, 2009)

Barnes, S.J., 2006a. Komatiites: petrology, volcanology, metamorphism, and Geochemistry, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration: Society of Economic Geologists, Special Publication 13, 13-49.

Barnes, S.J., 2006b. Komatiite-hosted nickel sulphide deposits: geology, geochemistry,and genesis, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication13, 51-97.

Barnes, S.J., Perring, C.S., 2006. Appendix. Summary of geological features of nickelsulphide deposits of the Yilgarn craton, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, 99-118.

Barnes, S.J., Gole, M.J., Hill, R.E.T., 1988. The Agnew nickel deposit, Western Australia. Part I. Stratigraphy and structure. Economic Geology 83, 524-536.

Barley, M. E., Brown, S. J. A., Cas, R. A. F., Cassidy, K. F., Champion, D. C., Gardoll,S. J., Krapež, B., 2003. An integrated geological and metallogenic framework for the eastern Yilgarn Craton: developing geodynamic models of highly mineralized Archaean granite-greenstone terranes. Amira International Limited, AMIRA Project no. P624 (unpublished report).

Bavinton, O.A., 1981. The nature of sulfidic metasediments at Kambalda and their broadrelationships with associated ultramafic rocks and nickel ores. Economic Geology 76, 1606-1628.

Beresford, S.W., Cas, R.A.F., 2001. Komatiitic invasive flows, Kambalda, Western Australia. Canadian Mineralogist 39, 525-535.

Beresford, S.W., Cas, R., Lahaye, Y., Jane, M., 2002. Facies architecture of an Achaean komatiite-hosted Ni-sulphide ore deposit, Victor, Kambalda, Western Australia: implications for komatiite lava emplacement. Journal of Volcanology and Geothermal Research 118, 57-75.

Beresford, S.W., Stone, W.E., Cas, R.A.F., Lahaye, Y, Jane, M., 2005. Volcanological controls on the localisation of a komatiite-hosted Ni-Cu-(PGE) deposit, Coronet, Kambalda, Western Australia. Economic Geology 100, 1457-1467.

Beresford, S, During, P., Florentine, M., Rosengren, N., Bleaker, W., Barley, M., CAS, R., Tait, M., Wallace, H., 2004. The Structural and Stratigraphic Architecture of the Agnew/Wiluna Belt, WA, Project P710 Project Final Report. AMIRA International Limited (unpublished report), 511 pp.

Beresford, S.W., Fiorentini, M., Hronsky, J.M.A., Rosengren, N., Bertuch, D.I., Saleem, A., Cas, R.A.F., Stone, W.E., Duuring, P., Bekker, A., Barley, M., 2007. Komatiite-hosted Ni-Cu-(PGE) deposits: understanding deposit and camp footprints, in: Bierlein F.P. and Knox-Robinson C.M., (eds.), 2007. Proceedings of Geoconferences (WA) Inc. Kalgoorlie ’07 Conference, 25-27 September 2007, Kalgoorlie, Western Australia. Geoscience Australia Record 2007/14, 249 pp.

Brand, N.W., 1999. Element ratios in nickel sulphide exploration: vectoring towards ore environments. Journal of Geochemical Exploration 67, 145-165.

Brilliant Mining Corp, 2007. 5.4% Ni delivered from winner during first month production, Lanfranchi Nickel Mine, Kambalda District of Western Australia. News releases, November 29, 2007, TSX Venture Exchange, Vancouver.

Brilliant Mining Corp, 2008. Production commences 18 months after discovery at high-grade Deacon orebody, Lanfranchi Nickel Mine, Kambalda District of Western News releases, Australia March 31, 2008, TSX Venture Exchange, Vancouver.

Brilliant Mining Corp, 2008. Tramways Dome Drill Program to Commence Lanfranchi Nickel Mine, Kambalda District of Western Australia. News releases, March 13 2008, TSX Venture Exchange, Vancouver.

Cas, R.A.F., Self, S., Beresford, S.W., 1999. The behaviour of the fronts of komatiite lavas in medial to distal settings. Earth and Planetary Science Letters 172, 127-139.

Cassidy, K.F., Champion, D.C., Krapez, B., Barley, M.E., Brown, S.J.A., Blewett, R.S., Groenewald, P.B., Tyler, I.M., 2006. A revised tectonic framework for the Yilgarn craton, Western Australia. Geological Survey of Western Australia, Record 2006/ 8, 8 pp.

Cowden, A.C., Roberts, D.E., 1990. Komatiite-hosted nickel sulphide deposits, Kambalda, in: Hughes, F.E. (Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 14, Melbourne, pp. 567-581.

Daddow, B., McCuaig, T., C., Mappleson, D.B., 2003. Structural controls of the Wannaway nickel-sulfide deposit, Widgiemooltha, Western Australia. 5th International Mining Geology Conference, Bendigo, Victoria, Australia, 17-19 November, 2003, pp. 101-112.

De Vitry, C., Libby, J. W., Langworthy, P. J., 1998, Rocky's Reward nickel deposit, in: Berkman, D.A., and Mackenzie, D.H. (Eds.), Geology of Australian and Papua New Guinean mineral deposits. The Australasian Institute of Mining and Metallurgy Monograph 22, Melbourne, pp. 315-319.

Donaldson, M.J., Lesher, C.M., Groves, D.I., Gresham, J.J., 1986. Comparison of Archaean dunites and komatiites associated with nickel mineralisation in Western Australia: implications for dunite genesis. Mineralium Deposita 21, 296-305.

Duuring P., Bleeker, W., Beresford S.W., 2004. Major folding and remobilization of nickel sulphides at Perseverance, Leinster, Western Australia, in: Beresford, S.W., Duuring, P., Fiorentini, M., Rosengren, N., Bleeker, W., Barley, M., Cas, R., Tait, M., Wallace, H. 2004. The Structural and Stratigraphic Architecture of the Agnew/Wiluna Belt, WA AMIRA Project P710. AMIRA International Limited (unpublished report), pp. 317-346.

Duuring P., Bleeker, W. and Beresford S.W., 2008. Structural Modification of the Komatiite-Associated Harmony Nickel Sulfide Deposit, Leinster, Western Australia. Economic Geology 102, 277-297.

Duuring, P., Bleeker, W., Beresford, S.W. and Hayward, N., 2010. Towards a volcanic-structural balance: relative importance of volcanism, folding, and remobilisation of nickel sulphides at the Perseverance Ni–Cu–(PGE) deposit, Western Australia. Mineralium Deposita 45, 281-311.

Eisenlohr, B.N., 1988. The structural development and controls on mineralisation of thenorthern sector of the Norseman-Wiluna Belt, Western Australia. PhD thesis, University of Western Australia, Perth, 187 pp.

Fiorentini, M.L., Rosengren, N., Beresford, S.W., Grguric, B., Barley, M.E. 2007. Controls on the emplacement and genesis of the MKD5 and Sarah's Find Ni–Cu–PGE deposits, Mount Keith, Agnew–Wiluna Greenstone Belt, Western Australia. Mineralium Deposita 42, 847-877.

Gemuts, I., Theron, A. C., 1975. The Archaean between Coolgardie and Norseman-Stratigraphy and mineralization, in: Knight, C.L. (Ed.), Economic Geology of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 5, Melbourne, pp. 66-74.

Gresham, J.J., 1986. Depositional environments of volcanic peridotite-associated nickelsulfide deposits with special reference to the Kambalda Dome, in: Friedrich, G.H., Genkin, A.D., Naldrett, A.J., Ridge, J.D., Sillitoe, R.H., Vokes, F.M. (Eds.), Geology and Metallogeny of Copper Deposits. Springer-Verlag, Berlin, pp. 63-89.

Gresham, J.J., Loftus-Hills, G.D., 1981. The geology of the Kambalda nickel field, Western Australia. Economic Geology 76, 1373-1416.

Grguric, B.A., Rosengren, N.M., Fletcher, C.M., and Hronsky, J.M.A. 2006. Type 2 deposits: geology, mineralogy, processing of the Mount Keith and Yakabindie orebodies, Western Australia, in: Barnes, S.J. (Ed.), Nickel deposits of the

Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, 119-138.

Groenewald, P.B., Riganti, A., 2004. East Yilgarn 1:100,000 geological information series-an explanatory note. Geological Society of Western Australia Report 95, 58 pp.

GSWA (Geological Survey of Western Australia), 2008. 1:500 000 Interpreted bedrock geology of Western Australia, 2008 update. http://mapserver.doir.wa.gov.au/datacentre/ (accessed April 24, 2009).

Hill, R.E.T., Gole, M.J., 1990. Nickel sulphide deposits of the Yilgarn Block, in: Hughes, F.E. (Ed.), Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 14, Melbourne, pp.557-559.

Hill, R.E.T., Barnes S.J., Gole M.J., Dowling, S.E. 1990. Physical volcanology of komatiites. A field guide to the komatiites of the Norseman-Wiluna Greenstone Belt, Eastern Goldfields Province, Yilgarn Block, Western Australia. Excursion guide book no. 1. Geological Survey of Western Australia, Perth, 100 pp.

Hill, R.E.T., Barnes, S.J., Gole, M.J., Dowling, S.E., 1995. The volcanology of komatiites as deduced from field relationships in the Norseman-Wiluna greenstone belt, Western Australia. Lithos 34, 159-188.

Hill R.E.T., Barnes S.J., Dowling, S.E., Thordarson, T. 2004. Komatiites and Nickel sulfide orebodies of the Black Swan area, Yilgarn Craton, Western Australia. Part 1. Petrology and volcanology of host rocks. Mineralium Deposita 39, 684-706.

Hoatson, D.M., Jaireth, S., Jaques, A.L., 2006. Nickel sulphide deposits in Australia: characteristics, resources and potential. Ore Geology Reviews 29, 177-241.

Independence Group N.L., 2009. Growing a great company, Annual General Meeting, 25November, 2009. http://www.independencegroup.com.au/IRM/content/investor/presentations.htm (accessed December 18, 2009).

Jubilee Mines N.L., 2007a. Bannockburn Project-new nickel discovery and exploration update. Announcement, April 18 2007. Australian Stock Exchange, Sydney, 3 pp.

Jubilee Mines N.L., 2007b. Significant increase to Sinclair resource. Announcement, September 24, 2007. Australian Stock Exchange, Sydney, 2 pp.

Keays, R.R., 1995. The role of komatiitic and picritic magmatism and S-saturation in the formation of ore deposits. Lithos 34, 1-18.

Krapez, B., Brown, S.J.A., Hand, J., Berley, M.E., Cas, R.A.F., 2000. Age constraints on recycled crustal and supracrustal sources of Archaean metasedimentary sequences, Eastern Goldfields Province, Western Australia: evidence from SHRIMP zircon dating. Tectonophysics 322, 89-133.

Langworthy, P. 2004. Cosmos nickel project, Kathleen Valley, in: Neumayr, P., Harris, M., Beresford, S.W (Eds.), Gold and Nickel Deposits in the Archean Norseman-Wiluna Greenstone Belt, Yilgarn Craton, Western Australia – a field guide. Geological Survey of Western Australia, Perth, pp.109-116.

Lesher, C.M., 1989. Komatiite-associated nickel sulphide deposits, in: Whitney, J.A., and Naldrett, A.J. (Eds.), Ore deposition associated with magmas. Reviews in Economic Geology 4, 44-101.

Lesher, C.M.; Burnham, O.M., Keys, R.R., 2001. Trace element geochemistry and petrogenesis of barren and ore-associated komatiites. Canadian Mineralogist 39, 673-696.

Lesher, C.M.and Keys, R.R., 2002. Komatiite-associated Ni-Cu-PGE deposits: geology, mineralogy, geochemistry and genesis, in: Cabri L.J. (Ed.), The geology, geochemistry mineralogy and mineral beneficiation of platinum group elements. Canadian Institute of Mining Metallurgy and Petroleum Special Publication 54, 579-617

Mamuse, A., Powal, A., Kreuzer, O.P., and Beresford, S., 2009. A new method for centrographic analysis of mineral deposit clusters. Ore Geology Reviews 36, 293-305.

Mamuse, A., Porwal, A., Kreuzer, O., Beresford, S.W., 2010a. Spatial statistical analysis of the distribution of komatiite-hosted nickel sulfide deposits of the Kalgoorlie Terrane, Western Australia: clustered or not? Economic Geology 105, 129-142.

Mapleson, D.B, Bewsher, A.W., Bayley, J. 2007. Technical report on the Lanfrachi nickel project, Kambalda, Western Australia. BM Geological Services Pty Ltd., Perth, 137 pp.

Marston, R.J., 1984. Nickel mineralization in Western Australia. Mineral Resources Bulletin 14. Geological Survey of Western Australia, Perth, 271 pp.

Marston, R.J., Groves, D.I., Hudson, D.R., Ross, J.R., 1981. Nickel sulphide mineralisation of Western Australia: a review. Economic Geology 76, 1330-1363.

Martin, J. E., Allchurch, P. D., 1975. Perseverance nickel deposit, Agnew. Economic

Geology of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 5, Melbourne, pp.149-155.

McCall, L.M., Dentith, M.C., Li, Z.X., Trench, A., 1995. The magnetic signature of komatiitic peridotie-hosted nickel sulphide deposits in the Widgiemooltha area, Western Australia. Exploration Geophysics 26, 66-77.

McQueen, K.G., 1981. Volcanic-associated nickel deposits from around the Widgiemooltha dome, Western Australia. Economic Geology 76, 1417-1448.

MINEDEX database. Western Australia Department of Mines and Petroleum http://mapserver.doir.wa.gov.au/meta/arcMetaPage.asp?Id=532 (accessed January 14, 2009).

MINMET database, Intierra Pty Ltd. http://www.intierra.com/ (accessed January 14, 2009).

Myers, J. S., 1990. Precambrian tectonic evolution of part of Gondwana, southwestern Australia. Geology 18, 537-540.

Myers, J. S., 1995. The generation and assembly of an Archaean supercontinent: evidence from the Yilgarn Craton, Western Australia, in: Coward, M.P., Ries, A.C. (Eds.), Early Precambrian processes, The Geological Society Special Publication 95, 143-154.

Myers, J. S., 1997. Preface: Archaean geology of the Eastern Goldfields of Western Australia-a regional overview. Precambrian Research 83, 1-10.

Myers, J.S. and Hickman, A.H., 1990. Pilbara and Yilgarn cratons-regional geology and Mineralization, in: Hughes, F.E. (Ed.), Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 14, Melbourne, pp. 129-133.

Naldrett, A.J., 2004. Magmatic Ore Deposits. Geology, Geochemistry and Exploration. Springer-Verlag, Berlin, 727 p.

Naldrett, A.J., Turner, A.R., 1977. The geology and petrogenesis of a greenstone belt and related nickel sulfide mineralization at Yakabindie, Western Australia, Precambrian Research 5, 43-103.

Nelson, D.R., 1998. Granite-greenstone crust formation on the Archaean earth-a consequence of two superimposed processes. Earth and Planetary Science Letters 158, 109-119.

Onley, P., Stephenson, W., Miller, A., Payne, P., Mappleson, D., Woodward, G., 2006. Technical Report: Lanfranchi Nickel Project, Western Australia. Golder Associates, Perth, 88 pp.

Page, M.L., Schmulian, M.L., 1981. The proximal volcanic environment of the Scotia nickel deposit. Economic Geology 76, 1981-1479. Panoramic Resources Limited, undated. Geology. http://www.panoramicresources.com/go/operations/lanfranchi/geology (accessed September 22, 2009)

Panoramic Resources Limited, 2009. Site visit Review, 29 June 2009. http://www.panoramicresources.com/files/090625_Stonebridge.pdf (accessed September 22, 2009).

Reliance Mining Limited, 2004. Quarterly report for the period ended 31 March 2004. Reliance Mining Limited, Perth, 11 pp.

Reliance Mining Limited, 2005. Beta Hunt Project Update. Company Announcements, 12 January 2005. Australian Stock Exchange, Sydney, 3 pp.

Rice, A., Moore, J., 2001. Physical modelling of the formation of komatiite-hosted nickel deposits and a review of the thermal erosion paradigm. Canadian Mineralogist 39, 491-503.

Rosengren, N.M., Beresford, S.W., Grguric, B.A., Cas, R.A.F., 2004. Flow focusing in a large komatiite sill: implications for the assembly and genesis of the Mt. Keith Ultramafic and associated NiS mineralization, in: Rosengren, N.C. 2004. Architecture and emplacement origin of an Archaean komatiitic dunite and associated NiS mineralization: Mt. Keith, Agnew-Wiluna Greenstone Belt, Yilgarn craton, Western Australia. PhD thesis, Monash University, Australia, pp. 155-194.

Rosengren, N.M., Grguric, B.A., Beresford, S.W., Fiorentini, M.L., Cas, R.A.F. 2007. Internal stratigraphic architecture of the komatiitic dunite-hosted MKD5 disseminated nickel sulfide deposit, Mount Keith Domain, Agnew-Wiluna Greenstone Belt, Western Australia. Mineralium Deposita 42, 821-845.

Rosengren NM, Beresford SW, Grguric BA, Cas RAF, 2005. An intrusive origin for the komatiitic dunite-hosted Mount Keith nickel sulfide deposit, Western Australia: Economic Geology 100, 149-156.

Ross, J.R.H., Hopkins, G.M.F., 1975. Kambalda nickel sulphide deposits, in: Knight, C.L. (Ed.), Economic Geology of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 5, Melbourne, 100-121.

Ross, J. R., Travis, G. A., 1981. The nickel sulfide deposits of Western Australia in global perspective: Economic Geology 76, 1291-1329.

Stolz, G. W., Nesbitt, R. W., 1981. The komatiite nickel sulfide association at Scotia: a petrochemical investigation of the ore environment. Economic Geology 76, 1480-1502.

Stone, W.E. and Masterman, E.E., 1998. Kambalda nickel deposits, in: Berkman, D.A., Mackenzie, D.H. (Eds.), Australian and Papa New Guinean Mineral Deposits. The Australasian Institute of Mining and Metallurgy Monograph 22, Melbourne, pp. 347-356.

Stone, W.E., Archibald, N.J., 2004. Structural controls on nickel sulphide oreshoots in Archaean komatiite, Kambalda, WA: the volcanic trough controversy revisited. Journal of Structural Geology 26, 1173-1194

Stone, W.E., Beresford, S.W., Archibald, N.J., 2005. Structural setting and shape analysis of nickel sulfide shoots at the Kambalda Dome, Western Australia: implications for deformation and remobilization. Economic Geology 100, 1441-1455.

Sulway, R.M., Glacken, A.M., Earl, A. 2005. LionOre Mining International Ltd: Independent Technical Report, Black Swan Nickel Project 4966. Snowden, Perth, 57 pp.

Swager, C. P., 1995. Geology of the greenstone terranes in the Kurnalpi-Edjudina region, southeastern Yilgarn Craton. Geological Survey of Western Australia Report 47, Perth, 31 pp.

Swager, C.P., 1997. Tectono-stratigraphy of late Archaean greenstone terranes in the southern Eastern Goldfields, Western Australia. Precambrian Research 83, 11-42.

Swager, C. P., Griffin, T. J., 1990. An early thrust duplex in the Kalgoorlie-

Kambalda greenstone belt, Eastern Goldfields Province, Western Australia: Precambrian Research 48, 63-73.

Swager, C.P., Griffin, T.J., Witt, W.K., Wyche, S., Ahmat, A.L., Hunter, W.M., McGoldrick, P.J., 1995. Geology of the Archaean Kalgoorlie Terrane-an explanatory note. Geological Survey of Western Australia Report 48 (reprint of Record 1990/12), Perth, 26 pp.

Trofimovs, J., 1999. Facies architecture of the tri-modal volcanic succession of the southern portion of the Archaean Agnew-Wiluna greenstone belt, Leinster, Western Australia. Bsc Honours Thesis, Monash University, Melbourne, 121 pp.

Trofimovs, J., Tait, M. A., Cas, R. A. F., McArthur, A., Beresford, S. W., 2003. Can the role of thermal erosion in strongly deformed komatiite-Ni-Cu-(PGE) deposits be determined? Perseverance, Agnew-Wiluna Belt, Western Australia: Australian Journal of Earth Sciences 50, 199-214.

Williams, R.I., Archibald, N.J., Miller, D.R., 1993. Nickel sulphide deposits of the Kambalda dome - a 3-dimensional perspective. Australian Geological Survey Organisation Geoscience Record 1993/54, pp. 171-173.

Woolrich, P., Cowden, A., Giorgetta, N.E., 1981. The chemical and mineralogical variations in the nickel mineralization associated with the Kambalda Dome, Western Australia. Economic Geology 76, 1629-1644.

CHAPTER 3

SPATIAL STATISTICAL ANALYSIS OF THE DISTRIBUTION OF KOMATIITE-HOSTED NICKEL SULPHIDE DEPOSITS OF THE KALGOORLIE TERRANE, WESTERN AUSTRALIA: CLUSTERED OR NOT?

Mineral resources assessments can be confounded by false perceptions of mineral deposit clustering. The false perceptions are ubiquitous because the clustering of mineralized geological settings, which is more prevalent, is commonly mistaken for the clustering of mineral deposits. In this chapter, published in *Economic Geology* (Mamuse et al[1,2]., 2010a), distance-based point pattern analysis techniques are used to analyse the spatial distribution of nickel sulphide deposits vis-à-vis that of mineralised komatiite bodies in the Kalgoorlie Terrane. The main outcomes of the analysis are: (i) komatiite bodies are preferable spatial analysis for nickel sulphide resources assessment in the Kalgoorlie Terrane, and (ii) within komatiite bodies nickel sulphide deposits are not clustered; the perceived clustering reflects clustering of host komatiite bodies. These results have significant implications for nickel sulphide resource assessments in the Kalgoorlie Terrane described in the subsequent chapters

Abstract

The spatial distribution of mineral deposits is a critical component of predictive estimation of undiscovered mineral resources. Nickel sulphide deposits in the Kalgoorlie Terrane of Western Australia, the world's premier province for komatiite-hosted nickel sulphide deposits, are generally perceived to be clustered. In order to verify this assertion, the spatial distribution pattern of these deposits is analysed using distance-based spatial analysis methods (nearest neighbour and *K* function). Results of these spatial analyses indicate that komatiite bodies that contain the nickel sulphide deposits in the terrane are clustered. In contrast, nickel sulphide deposits within komatiite bodies are either randomly distributed or dispersed, and not clustered. Therefore the apparent clustering of nickel sulphide deposits within the Kalgoorlie Terrane may be a mere expression of the underlying clustering of the host komatiite bodies. These findings have two main implications: (i) nickel exploration models implemented through area

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[1]Mamuse, A., Porwal, A., Kreuzer, O., Beresford, S.W., 2010a. Spatial statistical analysis of the distribution of komatiite-hosted nickel sulphide deposits of the Kalgoorlie Terrane, Western Australia: clustered or not? Economic Geology 105, 129 – 142.

[2]The lead author (PhD candidate) contributed more than 90% of the origination, content and preparation of this chapter and the published paper.

selection based on localization controls of favourable komatiite bodies, followed by direct detection of deposits within komatiite bodies have spatio-statistical validity, (ii) a Poisson distribution could be a plausible initial model for predicting the number of nickel sulphide deposits within a komatiite body.

3.1 Introduction

The spatial distribution of mineral deposits is a critical component of predictive estimation of undiscovered mineral resources (Singer and Menzie, 2008). Based on point pattern theory (Cliff et al., 1975, Getis and Boots, 1978; Ripley, 1977; 1981), mineral deposits may be characterized as randomly distributed, clustered or dispersed. The mean inter-deposit distance in a random distribution (expected mean random distance), calculated on the basis of the size of the study area and the number of deposits, provides the benchmark for describing deposit spatial patterns. If the average distance between deposits is not statistically different from the expected mean random distance, the deposit pattern is random. The deposits are clustered if, on average, they are closer together than the expected mean random distance. Deposits are dispersed if, on average, they are further apart than the expected mean random distance.

According to Singer and Menzie (2008), economic geologists tend to falsely perceive mineral deposit clustering on maps because of: (a) inflation of study areas by inclusion of non-permissive or covered geologic settings, (b) inclusion of different deposit types, (c) ambiguity in the definition of 'deposit' and (d) uneven exploration maturity, even within permissive settings. Such false positive determinations of clustering are defined as 'Type 1' errors. 'Type 2' errors occur where clustered deposits are incorrectly passed as being not clustered.

To eliminate these errors which can adversely affect mineral resources assessments, mineral deposit clustering must be sensitively assessed (Singer and Menzie, 2008; Ford and Blenkinsop, 2008). In this chapter, an approach that minimizes errors in determination of deposit spatial patterns is illustrated using nickel-sulphide deposits in the Kalgoorlie Terrane, Western Australia. These deposits are traditionally considered to occur in 'groups' or 'camps' (Marston, 1984; Barnes and Perring, 2006). This study seeks to establish whether the deposit groups or camps are genuine deposit clusters or they merely represent clustering of the underlying geological controls on mineralization (Singer and Menzie, 2008). Understanding deposit clustering in this key nickel province, which contains more that 60% (~11 Mt Ni) of the world's known komatiite-hosted nickel sulphide resources (Hoatson et al. 2006), could enhance efforts in exploration and nickel resources assessments in similar nickel provinces elsewhere. Komatiite-hosted nickel sulphide deposits are well suited for the proposed analysis because they constitute a relatively well understood deposit type whose permissive geological settings are well defined by the distribution of komatiites. Because of this, clustering of this deposit type can be reliably assessed, making it possible to distinguish genuine deposit clustering from clustering of geological settings.

3.2 Spatial analysis methods used in this chapter

3.2.1 Background to point pattern analysis

Given that mineral deposits may be regarded as realizations of stochastic mineralization processes (Sahu, 1982; Knoring and Dech, 1993; Porwal, 2006; Singer and Menzie, 2008; Zuo et al., 2008), their spatial distribution patterns may be analysed by point pattern analysis. Point pattern spatial analysis methods have well founded theory (Clark and Evans, 1954; Cliff et al., 1975; Getis and Boots, 1978; Ripley, 1977; 1981; Cliff and Ord, 1981; Cressie, 1993; Bailey and Gatrell, 1995) and have been applied in social sciences (e.g. epidemiology, human geography, and criminology), physical sciences (e.g. ecology, chemistry and geosciences) and astronomy, among other disciplines.

In the context of point pattern theory, each mineral deposit in a study area where 'mineralization events' have occurred may be regarded as a point defined by a unique pair of geographical coordinates. Several methods could be applied to analyse point patterns of mineral deposits, including: (i) area-based or density-based methods, such as quadrat counts and kernel estimation, (ii) distance-based methods, such as nearest neighbour, and *G*, *F* and *K* functions (Haggett et al., 1977; O'Sullivan and Unwin, 2003; Lloyd, 2007), and (iii) fractal analysis methods, such as box counting (Mandelbrot, 1983; Carlson, 1991; Turcotte 1986, 1992; Blenkinsop, 2004). Dale et al. (2002) showed that many of these methods, unified and underpinned by the mathematical cross-product concept and the analogous moving window concept, are conceptually similar. The major advantages of distance-based methods are that they preserve data continuity and provide a direct description of the second order properties of the point pattern (O'Sullivan and Unwin, 2003; Gatrell et al., 1996). This study utilizes nearest neighbour and *K* function distance-based methods, thus permitting spatial analysis for the full range of scales and data density. The *K* function enables comprehensive analysis at all scales of the pattern, but is more meaningful for a relatively large number of data points. In this study, *K* function analysis is performed only on datasets containing at least nine deposit points. Nearest neighbour methods permit spatial analysis of fewer deposit points and, in this study, nearest neighbour methods are performed on datasets containing at least four nickel sulphide deposits.

3.2.2 Nearest neighbour methods

Nearest neighbour analysis methods are attributed to Clark and Evans (1954). In a mineral deposit pattern the distance between any deposit and its closest neighbour is known as the nearest neighbour distance and is denoted $d_{\min}$. The mean nearest neighbour distance, $\bar{d}_{\min}$, is the average of the all values of $d_{\min}$ in the pattern. The expected nearest neighbour distance for the deposit pattern, $E(d)$, is given by $E(d) = 0.5 \times \sqrt{(A/N)}$, where A is the area of the study area, and N the number of deposits. The nearest neighbour index is calculated as the ratio $\bar{d}_{\min} / E(d)$ or the difference $\bar{d}_{\min} - E(d)$. A deposit pattern is clustered if the ratio is less than one or the difference is negative, indicating that the deposits are closer together than would be expected if they were randomly distributed. The pattern is dispersed if the ratio is greater than one or the difference is positive and random if the ratio is one or the difference is zero.

Clark and Evans (1954) developed a *Z*-test to determine whether the observed mean nearest neighbour distance is significantly different from the mean random distance. The test is given by,

$$Z = \frac{\overline{d}_{\min} - E(d)}{SE}, \tag{3.1}$$

where SE is the standard error, given by

$$SE = \frac{0.26136}{\sqrt{n^2 / A}}. \tag{3.2}$$

At the 95 % confidence level, for example, the magnitude of Z must be greater than 1.96 to be statistically significant.

Nearest neighbour distances can be extended beyond the first nearest neighbour to include the second, third, up to the k^{th} nearest neighbours to cover a wider range of spatial scales (Wong and Lee, 2005; Mitchell, 2005; Levine, 2007). In calculation of the k-order index, the mean random distance to the k^{th} neighbour, $E\ (d_k)$ is calculated as:

$$E(d_k) = \frac{k(2k)!/(2^k k!)^2}{\sqrt{n/A}}. \tag{3.3}$$

On a plot of the k-order against the k-order index, a point pattern is clustered if it plots below the straight line $E\ (d_k) = 1$ and dispersed if it plots above the line.

3.2.3 *K* and *L* functions

In K function analysis (Ripley, 1977; 1981) all distance thresholds (and not just the 1st order, or 2nd order or kth order distances) are analysed cumulatively for each mineral deposit point, up to a specified radial distance. The observed number of deposits within the radial distance is compared to the number that would be expected if the deposits within the radial distance were randomly distributed according to a theoretical random distribution known as complete spatial randomness (CSR). The deposits are clustered if the observed number of deposits within the radial distance is greater than those expected under CSR, dispersed if the reverse is true or random if the observed number of deposits equals that expected under CSR.

The K function is defined as (Bailey and Gatrell, 1995; O'Sullivan and Unwin, 2003; Lloyd, 2007; Levine, 2007):

$$\hat{K}(r) = \frac{A}{N^2} \sum_i \sum_{i \neq j} \frac{I_r(r_{ij})}{w_{ij}}, \tag{3.4}$$

where N is the number of mineral deposits a study area $\Re$ with area A, r_{ij} is the distance between the i^{th} and j^{th} deposits in $\Re$, and $I_r\ (r_{ij})$ is the number of other points j found within distance r summed over all points I, and w_{ij} the edge correction factor. A variation of the K function known as the L function is a square root transformation, given by:

$$\hat{L}(r) = \sqrt{\frac{\hat{K}(r)}{\pi}}. \tag{3.5}$$

The pattern is considered clustered if the observed $\hat{L}(r)$ lies above the theoretical curve for CSR; the reverse is true for a dispersed pattern. To determine whether the clustering or dispersion is statistically significant, simulations of the theoretical CSR are run and the resulting $L(r)$ functions are compared to the $\hat{L}(r)$ function of the observed deposit pattern (Bailey and Gatrell, 1995; Levine, 2007; Baddeley, 2008). The observed deposit pattern is significantly clustered if its $\hat{L}(r)$ function lies above the upper envelope of the $L(r)$ functions of the simulated CSR patterns. Conversely, the deposit pattern is significantly dispersed if its $\hat{L}(r)$ function lies below the lower envelope of the simulated CSR patterns. Advantages of using $\hat{L}(r)$ over $\hat{K}(r)$ are that the square root transformation renders $\hat{L}(r)$ graphs easier to read and helps stabilize variance of the estimator, making the analysis more powerful (Baddeley, 2008). Zuo et al. (2009) and Mamuse et al. (2009) have applied the K function to analyse the spatial distribution of mineral deposits. In this thesis the more common term '*K* function' is generally used but the reader should be aware that it is the L function as defined in Eq. 3.5 that is actually applied here.

3.2.4 Software

In this study, nearest neighbour and *K* function analyses were performed using the software program Spatstat (Baddeley and Turner, 2005), an add-on point pattern analysis library that runs within the public domain *R* statistical package. The *k*-order nearest neighbour analysis was performed using CrimeStat statistical software of Levine (2007).

3.3 Description of the nickel deposits dataset

The nickel deposit dataset utilized in this study (Table 3.1) was compiled mainly from the MINEDEX (Western Australian Department of Mines and Petroleum) and MINMET (Intierra Resources Pty Ltd.) databases and technical reports of exploration companies. In this study, the term 'deposit' includes the following: (i) currently or previously mined nickel-sulphide deposits (ii) unmined deposits with reported historic or current nickel sulphide resources and, (iii) prospects with significant drill-intersected nickel sulphides. Although prospects may not currently constitute economic deposits they may become economic deposits in the future. However, inclusion of prospects in analyses in this study may exaggerate the number of deposits and promote a tendency towards deposit clustering.

For point pattern analysis, mineral deposits, which have areas and volumes, need to be represented as points. In general the deposit coordinates used in this analysis (Table 3.1) represent deposit centroids. However, some clarification is necessary because some deposits have complex patterns of orebody geometry. The main situations encountered are:

1. A deposit is mapped as one orebody. In this simplest case, the deposit's point location is represented by the coordinates of the centroid of the orebody. This is the case for most komatiitic dunite-associated deposits and many komatiitic peridodite-associated deposits in the Kalgoorlie Terrane.

2. A deposit consists of more than one ore surface or sub-shoot (Woolrich et al., 1981). In this case, the deposit location is represented by the common centroid of the ore surfaces. This situation is exemplified by komatiitic peridotite-associated deposits at Kambalda (Fisher and Otter-Juan deposits, Fig. 3.1) and Tramways (Lanfranchi and Edwin deposits, Fig. 3.2).

3. Deposits initially delineated independently but subsequently inferred to be on the same magma pathway and, therefore inferred to be closely related or even to be parts of one deposit. Examples include the Gibb-Gibb South-Victor-McLeay-Victor South pathway and the McMahon-Ken pathway (Fig. 3.1). Such deposits have not been combined and each retains its own centroid represented by unique coordinates (Table 3.1).

4. Deposits mapped as points. For some prospects and undeveloped deposits, available maps display only point locations of deposits, and not deposit outlines. In these cases the assumption is that each point represents a specific location on the deposit, such as a centroid.

5. Tectonically remobilised deposits that are genetically associated with komatiites but are hosted in non-komatiite rocks not included in this analysis because, strictly, they are not komatiite-hosted. Three deposits, Coronet, concealed beneath a metalbasaltic wedge within Kambalda Dome (Fig. 3.1), and Helmut South and Deacon (both of which lie south of the mapped limits of the host komatiite in the Tramways camp; Fig. 3.2) have been excluded this way. The Spatstat statistical package used in analyses in this study ensures that only deposits that are fully contained within an analysis unit (komatiite) partake in the analysis.

3.4 Delineation of geological units for spatial analysis

Delineation of geologic analysis units is a critical part in the analysis of the spatial distribution pattern of mineral deposits because whether or not the deposits are clustered in part depends on the size of the analysis unit. A clustered deposit point pattern may

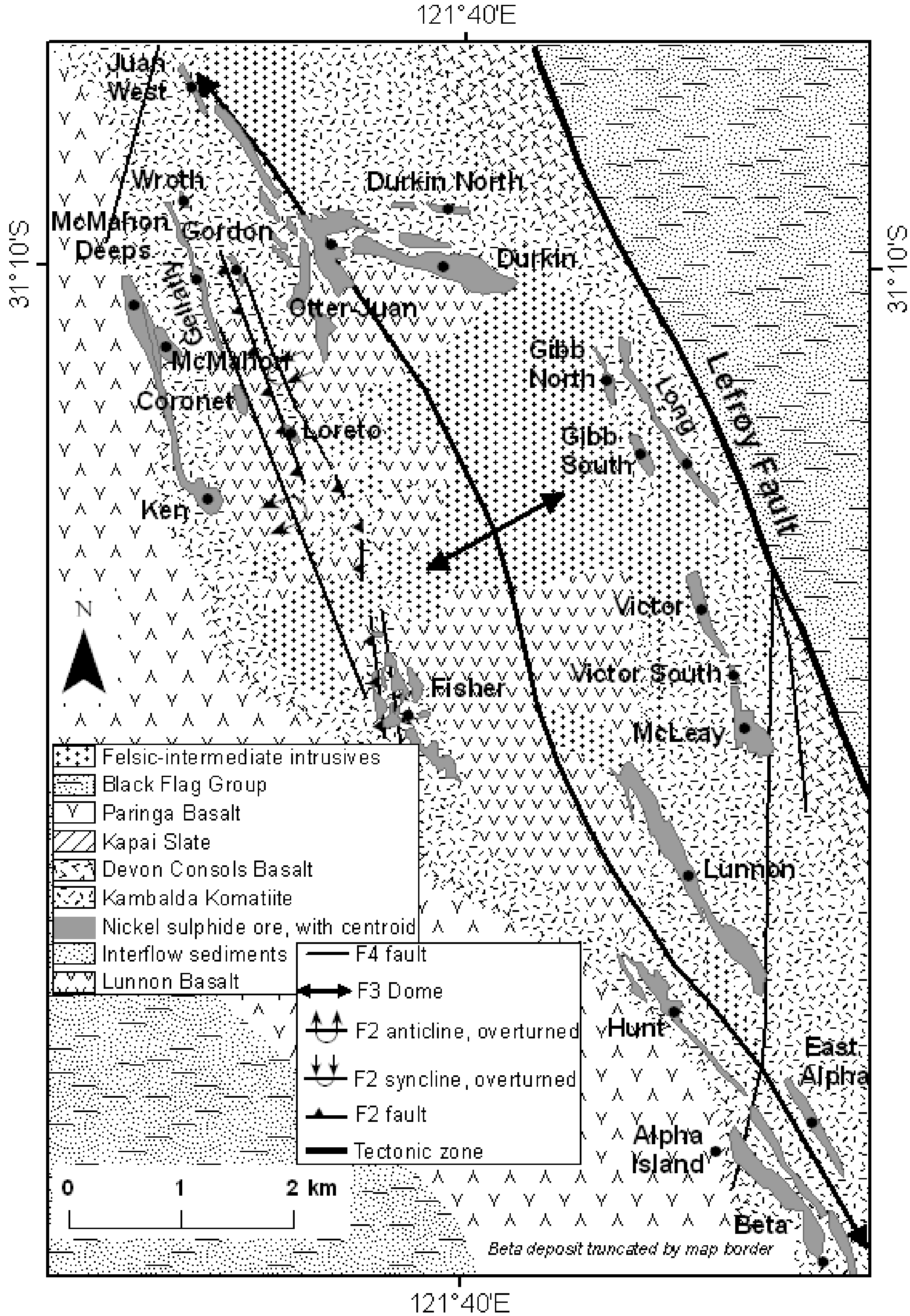

Fig. 3.1 Nickel deposits and deposit centroids of the Kambalda group as utilized in spatial analyses in this study. Geology is after Gresham and Loftus-Hills (1981), Cowden and Roberts (1990), and Stone and Archibald (2004).

turn out to be dispersed if a smaller analysis unit is used for analysing the pattern. In the same way, inclusion of non-permissive geologic settings may falsely enlarge the analysis unit resulting in false appearance of deposit clustering (Singer and Menzie, 2008).

The base geology for this study is derived from the 1:500,000 bedrock geological map of Western Australia (GSWA, 2008). Komatiites constitute the sample space or permissive tract (Singer, 1993; Fig. 1.1) with respect to nickel sulphide deposits in the Kalgoorlie Terrane. The geology of the Kalgoorlie Terrane is described in detail in Chapter 2 of this thesis. At the present day erosion level, the komatiites are not a continuous mass, but occur as discrete entities separated by non-komatiite rocks (Fig. 2.1b, c). In this chapter, each contiguous segment of komatiite rocks depicted on the bedrock geological map of Western Australia (GSWA, 2008) is termed a 'komatiite body' (see definition in Table 3.2). Using komatiite bodies as analysis units in this chapter permits one to narrow down from the overall permissive geological setting by distinguishing between komatiite bodies that contain nickel sulphide deposits and those that do not. One could in theory narrow down even further by using favourable subfacies, namely pathway subfacies in komatiitic peridotites or dunite lens subfacies in komatiitic dunites (Barnes 2006a, b; see definitions in Table 3.2) as analysis units instead using entire komatiitic peridotite bodies or dunite bodies. However, the lack of complete and uniform mapping coverage of the favourable komatiite subfacies for the entire Kalgoorlie Terrane render the subfacies inappropriate analysis units for this study.

Thus komatiite bodies may represent the best available spatial analysis unit in this study. Figure 1.1 in Chapter 1 is a schematic illustration of the spatial analysis framework adopted in this study. In adopting komatiite bodies as spatial analysis units, it is worth noting that their definition is a function of geological mapping scale. The 1: 500,000 scale bedrock geological map of Western Australia (GSWA, 2008; Figs. 2.1b, c) provides full and uniform, but considerably generalized, mapping coverage of komatiites within the Kalgoorlie Terrane. For example, the Mt. Keith komatiite body on the GSWA (2008) map includes the Mt. Keith (Eastern), Cliffs (Central) and Monument

(Western) ultramafic units which can be mapped as stratigraphically distinct units as in Barnes (2006a, p. 23), or Rosengren et al. (2007). In addition, intervening non-komatiite rocks may be included within the confines of the generalized komatiite bodies. Therefore although komatiite bodies may be reasonable spatial analysis units for this

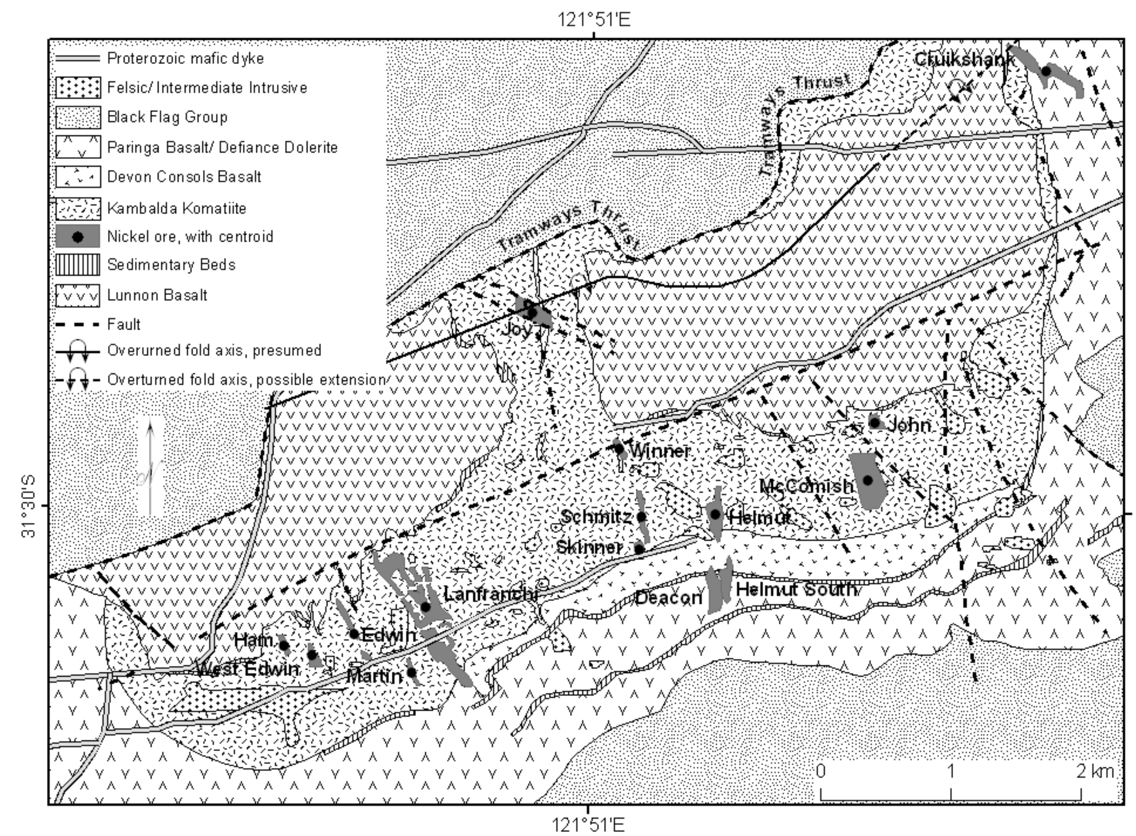

Fig. 3.2 Nickel deposits and deposit centroids of the Tramways deposit group as utilised in spatial analyses in this study. Geology is after Gresham and Loftus-Hill (1981) and Onley et al. (2006).

study, they are somewhat inflated because of unavoidable generalization at the 1:500,000 scale.

The following aspects relating to komatiite bodies as spatial analysis units should be borne in mind when interpreting results of this study. Komatiite bodies (peridotite or dunite bodies) may or may not contain currently known nickel sulphide deposits. It is theoretically possible that in future nickel sulphide deposits may be discovered in komatiite bodies that presently do not contain known deposits, or in komatiite bodies that are not yet mapped or known. Komatiite bodies that contain known nickel sulphide deposits (Table 3.1) and those that potentially can, but currently do not, contain known nickel sulphide deposits are collectively 'favourable' to hosting nickel sulphide deposits. In general, komatiites are considered 'favourable' or 'unfavourable' to hosting nickel sulphide deposits based on volcanological and geochemical criteria (Lesher et al., 2001; Barnes et al., 2004; Barnes, 2006a; b; Fiorentini et al., 2008). The presence of pathway subfacies in komatiite bodies is a useful geological proxy to this favourability (sections 1.5.1, 2.3, 2.5), but favourable komatiites do not necessarily contain known or unknown nickel sulphide deposits.

Therefore in this study, deposit-hosting komatiite bodies (Table 3.1) are the demonstrably mineralized subset of favourable komatiite bodies (Fig. 1.1).

3.5 Framework for spatial analyses in this chapter

The main research question that the present point pattern analysis seeks to answer is: are nickel sulfide deposits in the Kalgoorlie Terrane genuinely clustered, or is the perceived clustering just a manifestation of the clustering of the underlying geological control, namely, the distribution of mineralized komatiites? As pointed out by Singer and Menzie (2008), it is critical to avoid confusion between the clustering of favourable geological settings and the clustering of mineral deposits. In order achieve this, the following spatial patterns are separately analysed in this study: (i) the distribution of nickel sulphide deposits within each demonstrably mineralized komatiite body, and (ii) the distribution of demonstrably mineralized komatiite bodies with respect to all komatiite bodies in the Kalgoorlie Terrane.

Out of the 222 komatiite bodies in the Kalgoorlie Terrane, 57 are demonstrably mineralized (contain at least one of the deposits in Table 3.1) and the rest do not contain known nickel sulphide deposits (GSWA, 2008; Table 3.3). Out of the 57 demonstrably mineralized komatiite bodies, 14 contain at least four deposits, and five contain at least nine deposits. Various subsets of these komatiite bodies are utilized in the following ways in this study.

1. Nearest neighbour and *k*-order neighbour statistics are used to examine clustering of nickel sulphide deposits within each komatiite body that contains at least four nickel sulphide deposits.

2. *K* function analysis is used to examine clustering of nickel sulphide deposits within each komatiite body that contains at least nine nickel sulphide deposits.

3. Clustering of demonstrably mineralized komatiite bodies in each tectonic domain of the Kalgoorlie Terrane is tested with respect to the total population of komatiite bodies in that tectonic domain. This test proceeds by first extracting a random sample of points from demonstrably mineralized komatiite bodies in each tectonic domain. Although the actual number of points generated does not matter, a sampling density of two points per square kilometre was applied so that the number of the random points is close to the number of actual deposits in each tectonic domain. Then the spatial distribution of the sampled points with respect to all komatiite bodies in that domain is analysed using the *K* function.

3.6 Results and interpretation of the spatial analyses

K function analyses of the spatial distribution of nickel sulphide deposits in each komatiite body that contains more than nine nickel sulphide deposits are shown in Figure 3.3. The figure suggests that none of the komatiite bodies contains significantly clustered nickel sulphide deposits. Kambalda (Fig. 3.3a) and inner Widgiemooltha (Fig. 3.3d) komatiite bodies contain deposits that exhibit weak, statistically insignificant clustering, whereas deposits in each of the remaining komatiite bodies exhibit spatial dispersion.

Mean nearest neighbour statistics for each komatiite body that hosts at least four nickel sulphide deposits are summarized in Table 3.4. The difference between the observed (O) and expected (E) mean nearest neighbour distances, O-E, is positive for all komatiite bodies. This suggests that, relative to an expected random distribution, nickel sulphide

TABLE 3.1. List of nickel sulphide deposits utilised in spatial analyses in this chapter

		Decimal degrees				[3]Decimal degrees				[3]Decimal degrees	
[1]Deposit Name	[2]Komatiite Body	Longitude	Latitude	[1]Deposit Name	[2]Komatiite Body	Longitude	Latitude	[1]Deposit Name	[2]Komatiite Body	Longitude	Latitude
20 SW	Blair	121.74	-30.97	Anomaly 1	Cosmos	120.58	-27.61	Alpha East	Kambalda	121.70	-31.24
Anomaly 11		121.72	-30.96	Anomaly 3		120.58	-27.65	Alpha Island		121.69	-31.24
Blair		121.72	-30.91	Anomaly 6		120.58	-27.61	Beta		121.70	-31.25
Blair South		121.71	-30.95	Anomaly 9		120.58	-27.63	Durkin		121.66	-31.17
Channel		121.69	-30.90	Cosmos		120.58	-27.60	Durkin North		121.67	-31.16
47000S	Bluebush	121.79	-31.61	Mercury		120.58	-27.57	Fisher		121.66	-31.20
Cameron		121.83	-31.64	North Cosmos		120.57	-27.59	Gellatly		121.64	-31.17
East Bluebush		121.85	-31.63	Prospero		120.58	-27.64	Gibb		121.68	-31.18
Lawry		121.82	-31.63	Tapinos		120.58	-27.64	Gibb South		121.68	-31.18
Stockwell-Grimsby		121.77	-31.58	Venus		120.57	-27.58	Gordon		121.65	-31.17
Carnilya East	Carnilya Hill	121.86	-31.05	West Cosmos		120.58	-27.60	Hunt		121.69	-31.23
Dunlop		121.80	-31.04	Corella	Honeymoon Well	120.39	-26.89	Juan West		121.64	-31.15
Goodyear		121.80	-31.04	Harakka		120.38	-26.92	Ken		121.64	-31.19
Locality 7		121.75	-31.06	Hannibals		120.38	-26.92	Ken Far North		121.64	-31.17
Southern		121.85	-31.06	Harrier		120.40	-26.95	Long		121.69	-31.18
Wren		121.74	-31.03	Jericho		120.45	-27.04	Loreto		121.65	-31.18
Zone 29		121.81	-31.05	Kingston		120.41	-26.97	Lunnon		121.69	-31.22
Alec Mairs	Cosmos	120.58	-27.60	Wedgetail		120.36	-26.88	McLeay		121.69	-31.20

Notes

[1]'Deposit' is used in this table as in explained in the text.

[2]'Komatiite body' is used in this table as in explained in the text and in Table 3.2.

[3]Decimal degrees (GDA 1994 datum) are reported in this table although the spatial analyses were based on an Azimuthal projection using the units of metres.

TABLE 3.1. *Cont…*

		Decimal degrees[3]				Decimal degrees[3]				Decimal degrees[3]	
Deposit Name[1]	Komatiite Body[2]	Longitude	Latitude	Deposit Name[1]	Komatiite Body[2]	Longitude	Latitude	Deposit Name[1]	Komatiite Body[2]	Longitude	Latitude
McMahon	Kambalda	121.64	-31.17	Salute		121.03	-28.46	McComish	Tramways	121.87	-31.50
Otter-Juan		121.65	-31.16	Skipper		120.98	-28.42	Schmitz		121.85	-31.50
Victor		121.69	-31.19	Cliffs	Mt. Keith	120.55	-27.30	West Edwin		121.83	-31.51
Victor South		121.69	-31.20	Mt Keith		120.54	-27.23	Winner		121.85	-31.50
Wroth		121.64	-31.16	Sarah's Find		120.54	-27.20	132N	Widgiemooltha (inner)	121.54	-31.46
11 Mile Well	Perseverance	120.74	-27.88	Spinifex Park		120.56	-27.32	14N		121.54	-31.49
Harmony		120.69	-27.77	East Cooee	St. Ives	121.80	-31.35	26N-Mt Edwards		121.54	-31.48
Perseverance		120.70	-27.82	Foster		121.75	-31.35	332N		121.52	-31.41
Perseverance East		120.71	-27.82	Jan		121.80	-31.38	Andrews		121.50	-31.36
Progress		120.71	-27.81	NW Foster		121.75	-31.34	Armstrong		121.52	-31.42
Rocky's Reward		120.70	-27.79	Cruikshank	Tramways	121.88	-31.47	Cooke-166N		121.54	-31.45
Sir Samuel		120.66	-27.70	Edwin		121.83	-31.51	Dordie Rocks North		121.63	-31.59
Water Tank		120.72	-27.85	Ham		121.83	-31.51	Inco Boundary		121.53	-31.50
Babylon	Mt. Clifford	121.06	-28.48	Helmut		121.86	-31.50	Locality 3		121.50	-31.56
Kent		120.98	-28.39	John		121.87	-31.49	McEwen-360N		121.52	-31.40
Mariott's		120.99	-28.45	Joy		121.85	-31.49	Orchard		121.52	-31.50
Randal's Find		120.99	-28.47	Lanfranchi		121.84	-31.51	Rhona		121.60	-31.53
Rattler		120.97	-28.35	Martin		121.84	-31.51	Spargoville 5A		121.50	-31.36

Notes

[1]'Deposit' is used in this table as in explained in the text.

[2]'Komatiite body' is used in this table as in explained in the text and in Table 3.2.

[3]Decimal degrees are reported in this table although the spatial analyses were based on an Azimuthal projection using the units of metres.

TABLE 3.1. *Cont…*

Deposit Name[1]	Komatiite Body[2]	Decimal degrees[3] Longitude	Latitude
Spargoville 1A		121.49	-31.32
Spargoville 2 or 5B		121.50	-31.37
Wannaway		121.52	-31.61
Wannaway B		121.51	-31.58
Wannaway North		121.50	-31.57
Widgie 3		121.59	-31.52
Widgie Townsite		121.58	-31.50
Zabel-384N		121.51	-31.39
Anomaly A	Widgiemooltha (outer)	121.66	-31.65
Blacksmiths		121.60	-31.51
Dordie Trend		121.62	-31.55
Mariners		121.66	-31.63
Miitel		121.65	-31.59
Redross		121.65	-31.69
Redross North		121.65	-31.68
Redross South		121.65	-31.70
Unmin 1		121.64	-31.57
Unmin 2		121.65	-31.59
Betheno	Yakabindie	120.58	-27.42
David		120.58	-27.44
Goliath		120.59	-27.45
Goliath Central		120.59	-27.45
Goliath South		120.59	-27.47
Six Mile		120.58	-27.43

Notes

[1]'Deposit' is used in this table as in explained in the text.

[2]'Komatiite body' is used in this table as in explained in the text and in Table 3.2.

[3]Decimal degrees are reported in this table although the spatial analyses were based on an Azimuthal projection using the units of metres.

deposits in all komatiite bodies are dispersed rather than clustered. The *Z*-score suggests that at 95 % level of significance the average nearest neighbour distances between deposits in all komatiite bodies, except Kambalda, are significantly longer (i.e. dispersed) relative to a random distribution. These results imply that nickel sulphide deposits within komatiites at Kambalda exhibit a random distribution, whereas those hosted by other komatiite bodies may be dispersed.

The *k*-order neighbour analysis (Fig. 3.4) illustrates that nickel sulphide deposits within komatiite bodies are dispersed with respect to the theoretical *k*-order spatial

TABLE 3.2. Komatiite terminology used in this chapter

Term	Definition
Disseminated ore	'Olivine-rich cumulate containing few percent interstitial magmatic sulphides' (Barnes, 2006a: 15).
Dunite lens sub-facies	Lenticular dunites, primarily consisting of olivine adcumulate with or without lower orthocumulate zones, that occupy magma pathways and may host type 1 or 2 nickel sulphide ores (Barnes 2006a)
Komatiite body	Any discrete komatiite entity as depicted on the GSWA (2008) 1:500,000 bedrock geological map of Western Australia (usage proposed for this chapter).
Komatiite sequence	'A correlatable, stratigraphically coherent package of komatiitic rocks believed to have formed in a single eruptive episode' (Barnes, 2006a: 15).
Massive ore	'Ore consisting of 80 % or more magmatic sulphide' (Barnes, 2006a: 15).
Pathway	'The locus of prolonged, focused magma flow within a flow filed or subvolcanic plumbing system' (Barnes, 2006a: 15).
Pathway subfacies	Flow units, typically 50m or more thick and primarily consisting of olivine orthocumulate to mesocumulate textures with minor spinifex textures, that occupy pathways and may host Type 1 nickel sulphide ores (Barnes, 2006a).
Type 1 deposit	Nickel sulphide ores consisting of massive and net-textured or matrix ores at the base of komatiite lava flows (Hill and Gole, 1990; Barnes, 2006b).
Type 2 deposit	Disseminated low-grade nickel sulphide ores centrally disposed within thick olivine cumulate bodies (Hill and Gole, 1990; Barnes, 2006b).

randomness at all orders of nearest neighbour distances. However, insignificant clustering is detectable at lower *k* orders within the Kambalda komatiite body.

The above results suggest that nickel sulphide deposits within individual komatiite bodies in the Kalgoorlie Terrane are not clustered. However, this does not rule out the clustering of the host komatiite bodies themselves. An explicit test of whether or not the host komatiite bodies are clustered was performed over a set of randomly generated points restricted to lie only within the demonstrably mineralized komatiite bodies. The test returned a positive result of clustering (Fig. 3.5). This result implies that for each tectonic domain of the Kalgoorlie Terrane, clustering is a property of the host komatiite bodies, not of the deposits within them.

TABLE 3.3. Mineralized[1] and unmineralized[2] komatiite bodies within the Kalgoorlie Terrane

		Mineralized domains					Unmineralized	
		Boorara	Depot	Kambalda	Ora Banda	Coolgardie	Domains	Total
Komatiite bodies	Total count	87	25	29	21	40	20	222
	Mineralized	28	2	4	20	3	0	57
	Unmineralized	59	23	25	1	37	20	165
	% Mineralized	32.2	8.0	13.8	95.2	7.5	0.0	25.7
	% Unmineralized	67.8	92.0	86.2	4.8	92.5	100.0	74.3
Area of komatiite bodies (km^2)	Total	622.8	317.8	342.5	586.3	485.6	46.8	2401.8
	Mineralized	349.2	88.1	95.2	3.4	35.8	0.0	571.8
	Unmineralized	273.6	229.7	247.4	582.9	449.7	46.8	1830.0
	% Mineralized	56.1	27.7	27.8	0.6	7.4	0.0	23.8
	% Unmineralized	43.9	72.3	72.2	99.4	92.6	100.0	76.2

Notes: In this table, a mineralized[1] komatiite is one that contains at least one of the deposits in Table 3.1. Those komatiites that do not contain any of the deposits in Table 3.1 are denoted unmineralized[2]. Similar usage is applied with respect to mineralized and unmineralized domains. Areas were calculated from GSWA (2008) bedrock geological map.

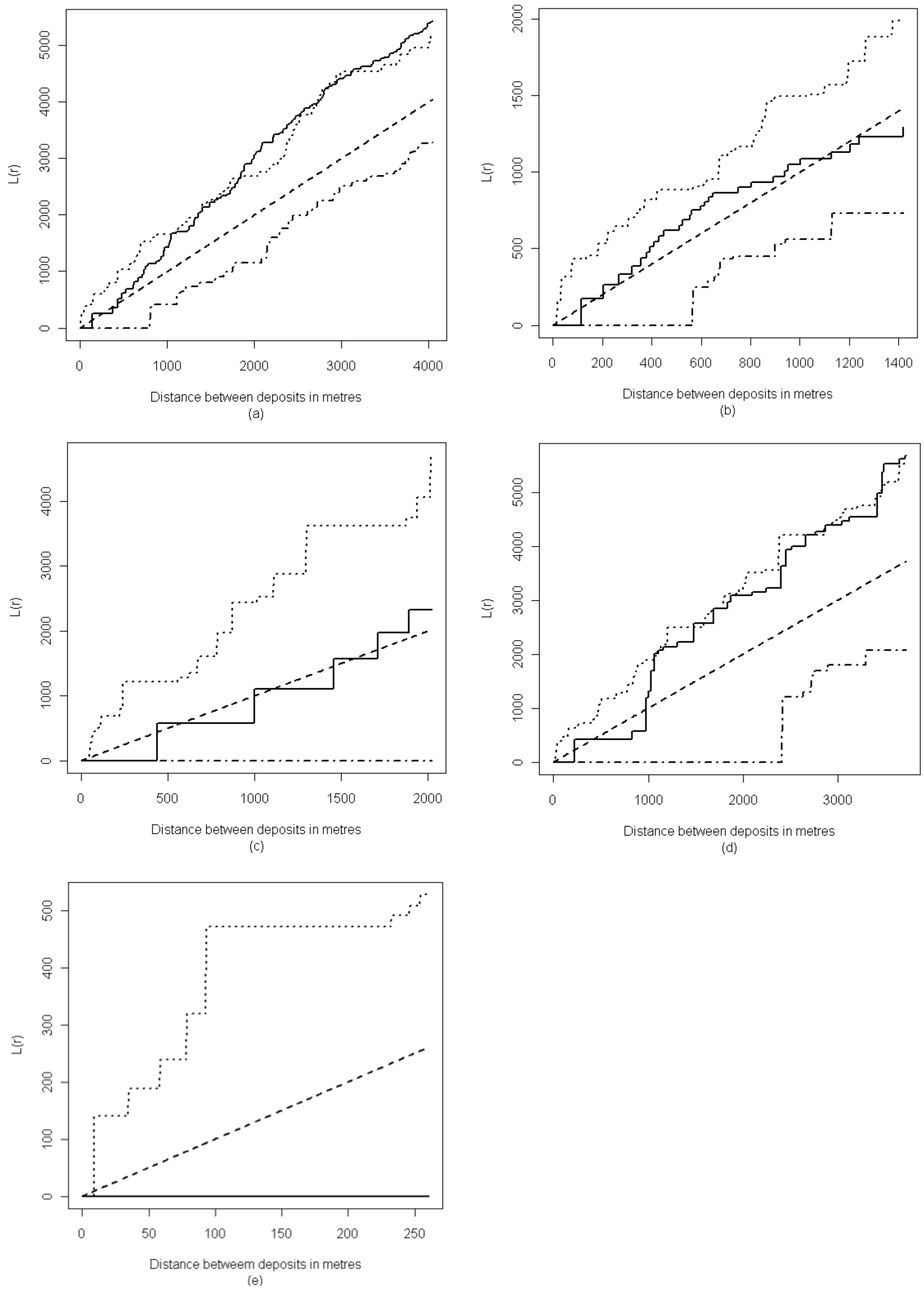

Fig. 3.3 *K* function analyses of nickel sulphide deposits within different komatiite bodies, (a) Kambalda, (b) Tramways, (c) Widgiemooltha (outer), (d) Widgiemooltha (inner) and (e) Cosmos.

3.7 Discussion

There are two key results from the point pattern analyses in this chapter. The first result is that, based on the distribution of currently known deposits (Table 3.1), no komatiite body in the Kalgoorlie Terrane contains nickel sulphide deposits that are clustered. This is despite three factors that would have artificially enhanced the likelihood of an outcome depicting clustering. First, several prospects, some of which may never become deposits, were included in this analysis which could have exaggerated the number and concentration of analysis points thereby increasing the likelihood of an outcome depicting clustering. Second, by not grouping closely associated deposits (section 3.3), the number of deposits partaking in the analysis was similarly maximised. Third, the size of the analysis units (komatiite bodies), based on a 1:500,000 map (GSWA, 2008), may have been exaggerated due to the inevitable inclusion of non-komatiite rocks and lumping together of separate

TABLE 3.4. Nearest neighbour indices for deposit patterns in individual komatiite bodies

Domain	Komatiite Body	Komatiite Area (km^2)	No. of Deposits	Mean nearest neighbour distances (km)				
				Observed (O)	Expected (E)	O-E	Standard error	Z- Score
Boorara	Honeymoon	38.60	7	2.48	1.17	1.30	0.23	5.61
	Mt Keith	10.72	4	3.16	0.82	2.34	0.21	10.95
	Yakabindie	2.67	6	0.94	0.33	0.60	0.07	8.48
	Perseverance	13.48	8	2.81	0.65	2.16	0.12	17.99
	Mt. Clifford	33.38	7	3.29	1.09	2.20	0.22	10.21
	Carnilya Hill	14.51	7	1.61	0.72	0.90	0.14	6.29
	Blair	19.88	5	2.23	1.00	1.23	0.23	5.30
Ora Banda	Cosmos[1]	3.42	12	0.65	0.27	0.38	0.04	9.42
Depot	Widgie2	71.00	22	1.62	0.88	0.75	0.10	7.79
	Widgie3	17.15	9	2.18	0.69	1.49	0.12	12.40
Kambalda	Kambalda	49.18	23	0.77	0.73	0.04	0.08	0.53
	St Ives	3.92	4	1.85	0.49	1.35	0.13	10.45
	Tramways	8.82	12	0.63	0.40	0.23	0.06	4.16
	Bluebush	27.14	5	2.48	1.16	1.31	0.27	4.81

Notes: The tectonic framework proposed for the Yilgarn Craton by Cassidy et al. (2006) controversially places the Cosmos komatiite body within the Ora Banda Domain (see Chapter 2). The Cosmos komatiite body is widely considered to belong to the Boorara Domain (S. Beresford, personal communication June, 2009).

komatiite units at that scale. Attempting to maximise chances of a clustering result this way follows a general approach of handling uncertainty known as worst case uncertainty handling as applied in geology and other disciplines (Bardossy and Fodor, 2001).

The second result of this study is that demonstrably mineralized komatiite bodies (i.e. containing one ore more deposits listed in Table 3.1) in the Kalgoorlie Terrane are clustered with respect to the total population of komatiite bodies in the terrane. This result, shown in Figure 3.5, was obtained by analysing the spatial pattern of sample points randomly generated (therefore not clustered) within each komatiite body with respect to the total population of komatiite bodies in each tectonic domain.

The two findings stated above, strictly, relate to the distribution of known nickel sulphide deposits in known komatiite bodies in the Kalgoorlie Terrane. By making some additional assumptions, it is possible to broaden the interpretation of these findings. For example if one assumes that the terrane is relatively mature in terms of nickel sulphide exploration (Hronsky and Schodde, 2006), the observed spatial distributions of deposits and komatiite bodies may be taken as approximations of their geologic spatial distributions. Another assumption commonly made is that the known deposits (and komatiite bodies) are a representative sample of the actual deposits (Blenkinsop and Sanderson, 1999; Blenkinsop, 2004), permitting inferences regarding the spatial distribution of the natural population of deposits and komatiite bodies. If this is correct, then the clustering of demonstrably mineralized komatiite bodies may reflect clustering of the true population of favourable komatiite bodies. Similarly, like the spatial distribution of known deposits, the true population of deposits in each komatiite body may not be clustered.

Results of this study support the observation of Singer and Menzie (2008) that the clustering of mineralized geological settings is probably more prevalent than, and is commonly mistaken for, the clustering of mineral deposits. In this study, this has been successfully resolved by identifying and separately assessing the deposit component and geological settings component of clustering.

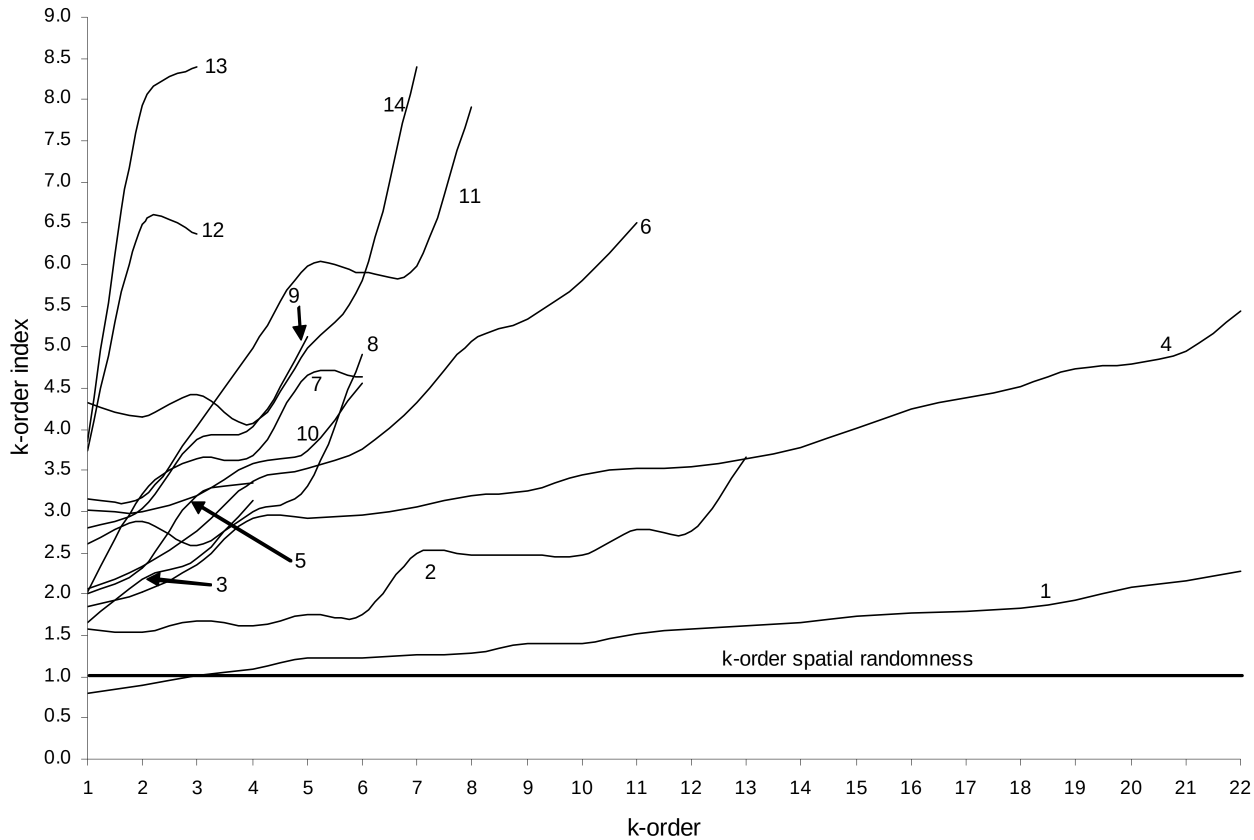

Fig. 3.4 K-order indices for nickel sulphide deposits within komatiites of the study area: (1) Kambalda, (2) Tramways, (3) Bluebush (4) Widgiemooltha (inner), (5) Blair, (6) Cosmos, (7) Carnilya Hill, (8) Honeymoon, (9) Yakabindie, (10) Mt. Clifford, (11) Widgiemooltha (outer), (12) St. Ives (13) Mt. Keith, (14) Perseverance.

Although this study used komatiite bodies as the analysis units, it can be argued that favourable komatiite subfacies, namely pathway subfacies and dunite lens subfacies (see definitions in Table 3.1) are more preferable spatial analysis units. However, maps showing favourable subfacies of komatiites with consistent coverage of the entire Kalgoorlie Terrane are not available. Nevertheless, given that there is no deposit clustering at the level of komatiite bodies, it is unlikely that deposits would be clustered at the level of the favourable subfacies. As pointed out by Singer and Menzie (2008), the appearance of deposit clustering generally diminishes as mapping becomes more detailed.

The foregoing discussion indicates that nickel sulphide deposits are not clustered within komatiite bodies in the Kalgoorlie Terrane. Based on the rationale of Singer and Menzie (2008) as explained above, it follows that the deposits are unlikely to be clustered at the lower level of favourable subfacies. Another candidate in the selection of an appropriate spatial analysis unit is the full sample space consisting of all komatiites (Fig. 1.1) in the Kalgoorlie Terrane. Using this analysis unit, *K* function analysis depicts clustering (Fig. 3.6). However, this result is invalidated by its close resemblance to Figure 3.5 in which even a set of randomly distributed points depicted 'clustering'. In other words, the analysis unit consisting of all komatiites in the Kalgoorlie Terrane is inappropriate in the context of the present analysis because a false positive clustering result ('type 1 error') is obtained even where the point pattern is random.

This study has two main implications. Firstly, initial exploration targeting (prediction) should start to give way to direct detection methods (Hronsky and Groves, 2008) when the exploration space has been reduced to the level of a favourable komatiite body because, as demonstrated in this study, deposits are randomly distributed or dispersed within a komatiite body. Secondly if the nickel sulphide deposits are randomly distributed within komatiite bodies, a Poisson distribution with mean (and standard deviation) based on, say, deposit density (Root et al., 1992; Singer et al., 2001) may provide a plausible upper estimate for the number of contained deposits. This assumption of randomness may be valid in the case of komatiitic peridotite-associated deposits such (e.g. Kambalda or Tramways camps; Figs. 3.1, 3.2, 3.3, 3.4). However, the Poisson model would tend to overestimate the number of undiscovered deposits in komatiitic dunite bodies (e.g. Mt. Keith or Cosmos) which contain spatially dispersed nickel sulphide deposits (Figs. 2.2, 2.3a, 3.3, 3.4).

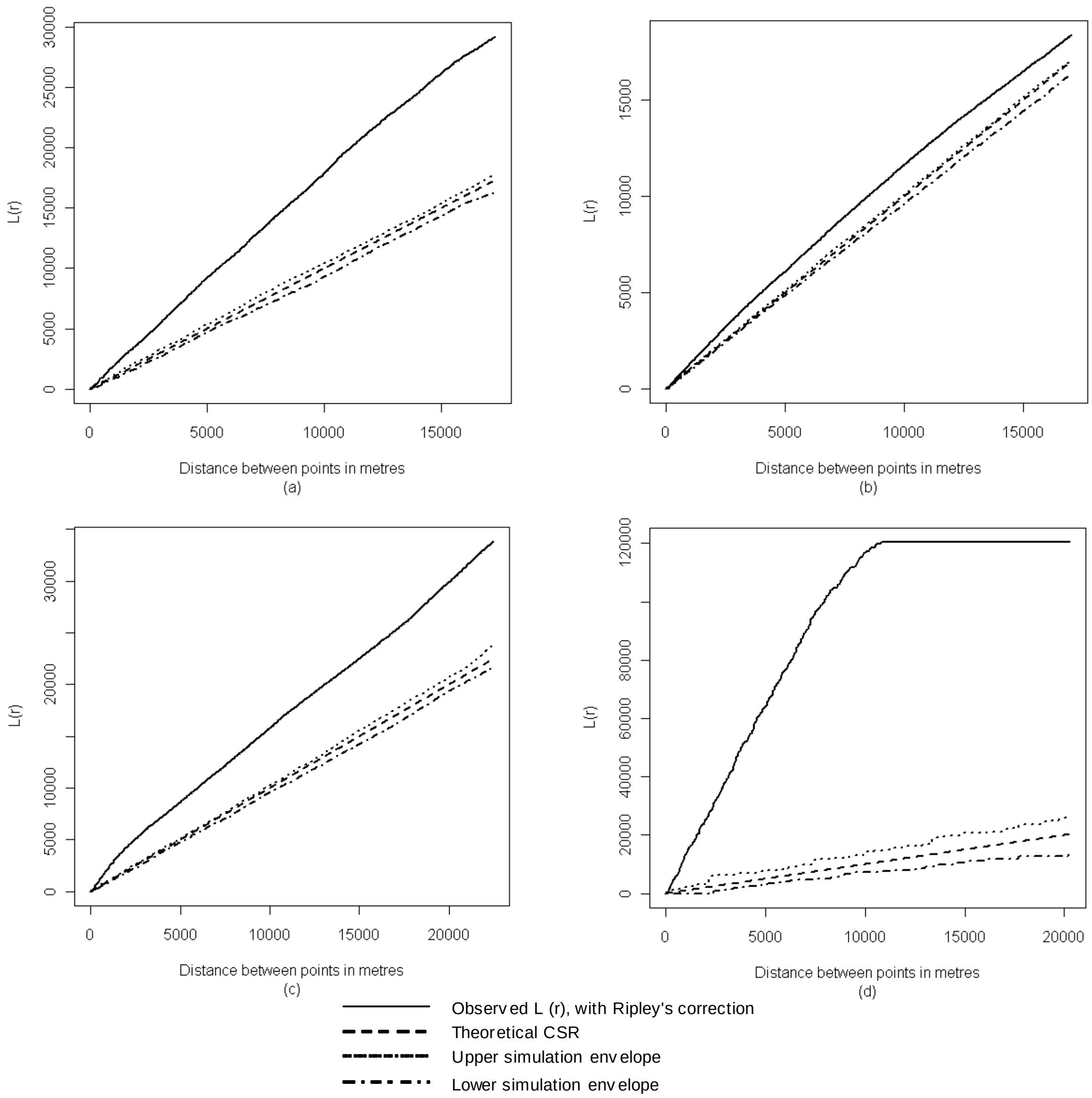

Fig. 3.5 *K* function and simulation envelopes for the distribution demonstrably mineralized komatiites within (a) Kambalda Domain, (b) Boorara Domain, (c) Depot Domain and (d) Ora Banda Domain.

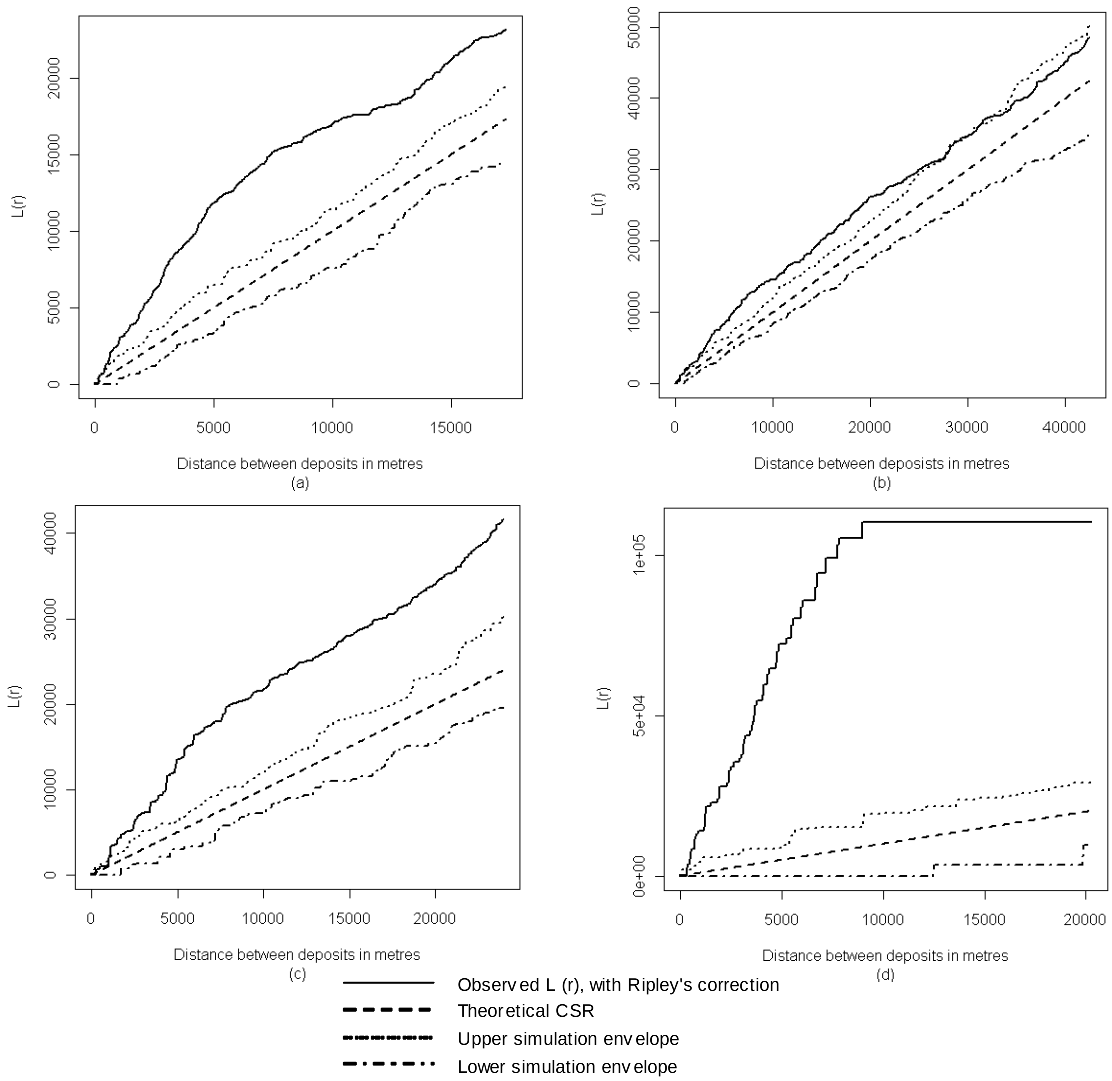

Fig. 3.6 *K* function and simulation envelope for the distribution of nickel sulphide deposits with respect to the total komatiite population in (a) Kambalda Domain, (b) Boorara Domain, (c) Depot Domain and (d) Ora Banda Domain.

3.8 Conclusions

Results of this study lead to the following conclusions:

1. Nickel sulphide deposits in komatiite bodies in the Kalgoorlie Terrane are randomly distributed or dispersed and not clustered.

2. Demonstrably mineralized komatiite bodies in each tectonic domain of the Kalgoorlie Terrane are clustered with respect to the distribution of all komatiite bodies in that tectonic domain.

3. Nickel exploration models which apply conceptual targeting to locate mineralised komatiite targets followed by direct detection of deposits within komatiite bodies are consistent with spatial analysis results in the chapter. This is because the location of mineralised komatiites can be predicted but that of deposits within them is difficult to predict because they are randomly distributed.

4. A Poisson distribution could be a plausible initial model for estimating the number of nickel deposits within komatiite bodies in the Kalgoorlie Terrane.

References

Baddeley, A., 2008, Analysing spatial point patterns in R. Workshop Notes, version 3. Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, 199 pp. http://www.csiro.au/resources/pf16h.html

Baddeley, A. and Turner, R., 2005. Spatstat: an R package for analysing spatial point patterns. Journal of Statistical Software, 12(6):1–42, URL: www.jstatsoft.org, ISSN: 1548-7660.

Bailey, C.T. and Gatrell, A.C., 1995. Interactive spatial data analysis. Longman, Harlow, 413 pp.

Bardossy, G., Fodor, J., 2001. Traditional and new ways to handle uncertainty in geology. Natural Resources Research 10, 179-187.

Barnes, S.J., 2006a. Komatiites: petrology, volcanology, metamorphism, and Geochemistry, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration: Society of Economic Geologists, Special Publication 13, 13-49.

Barnes, S.J., 2006b. Komatiite-hosted nickel sulphide deposits: geology, geochemistry, and genesis, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication13, 51-97.

Barnes, S.J., Hill, R.E.T., Perring, C.S., and Dowling, S.E., 2004. Lithogeochemical exploration for komatiite associated Ni-sulphide deposits: strategies and limitations: Mineralogy and Petrology 82, 259-293.

Barnes, S.J., Perring, C.S., 2006. Appendix. Summary of geological features of nickel sulphide deposits of the Yilgarn craton, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, 99-118.

Beresford, S, During, P., Florentine, M., Rosengren, N., Bleaker, W., Barley, M., CAS, R., Tait, M., Wallace, H., 2004. The Structural and Stratigraphic Architecture of the Agnew/Wiluna Belt, WA, Project P710 Project Final Report. AMIRA International Limited (unpublished report), 511 pp.

Beresford, S., Stone, W.E., Cas, R.A.F., Lahaye, Y, Jane, M., 2005. Volcanological controls on the localisation of a komatiite-hosted Ni-Cu-(PGE) deposit, Coronet, Kambalda, Western Australia, Economic Geology 100, 1457-1467.

Blenkinsop, T.G., 2004, Applications of fractal geometry to mineral exploration, in: Muhling, J., Goldfarb, R., Vielreicher, N., Bierlein, F., Stumpfl, E., Groves, D., Kenworthy, S. (Eds.), Predictive Mineral Discovery Under Cover, Extended Abstracts. SEG 2004 Conference, 27 September-1 October 2004 Perth, Western Australia, p. 158-161.

Blenkinsop, T.G., Sanderson, D.J., 1999, Are gold deposits in the crust fractals? A study of gold mines in the Zimbabwean craton, in: McCaffrey, K.J.W., Lonergan, L.,Wilkinson, J.J. (Eds.), Fractures, Fluid Flow and Mineralization. Geological Society Special Publication 155, 141-151.

Carlson, C.A., 1991. Spatial distribution of mineral deposits. Geology 19, 111- 114.

Cassidy, K.F., Champion, D.C., Krapez, B., Barley, M.E., Brown, S.J.A., Blewett, R.S., Groenewald, P.B. and Tyler, I.M., 2006. A revised tectonic framework for the Yilgarn craton, Western Australia. Geological Survey of Western Australia Record 2006/ 8, 8 pp.

Clark, P.J. and Evans, F.C., 1954. Distance to nearest neighbour as a measure of spatial relationships in populations. Ecology 35, 445-453.

Cliff, A.D. and Ord, J.K., 1981. Spatial processes-models and applications. Pion, London, 266 pp.

Cliff, A.D., Ord, P., Bassett, K., Davies, R., 1975. Elements of spatial structure: a quantitative approach. Cambridge University Press, Cambridge, UK, 258 pp.

Cowden, A.C., Roberts, D.E., 1990. Komatiite-hosted nickel sulphide deposits, Kambalda, in: Hughes, F.E. (Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 14, Melbourne, pp. 567-581.

Cressie, N.A.C., 1993, Statistics for spatial data, John Willey & Sons, New York, 900 pp.

Dale, M. R. T., Dixon, P., Fortin, M. J., Legendre, P., Myers, D. E. and Rosenberg, M. S. 2002. Conceptual and mathematical relationships among methods for spatial analysis. Ecography 25, 558-577.

Donaldson, M.J., Lesher, C.M., Groves, D.I., and Gresham, J.J., 1986. Comparison of Archaean dunites and komatiites associated with nickel mineralisation in Western Australia: implications for dunite genesis. Mineralium Deposita 21, 296-305.

Fiorentini, M.L., Beresford, S.W. and M.E. Barley, 2008. Ruthenium-chromium variation: a new lithogeochemical tool in the exploration for komatiite-hosted Ni-Cu-(PGE) deposits. Society of Economic Geologists 103, 431-477.

Ford, A., Blenkinsop, T.G., 2008. Combining fractal analysis of mineral deposit clustering with weights of evidence to evaluate patterns of mineralisation: application to copper deposits of the Mt. Isa inlier, NW Queensland, Australia. Ore Geology Reviews 33, 435-450.

Gatrell, Bailey, T.C., Diggle, P.J., Rowlinson, B.S., 1996. Spatial point pattern analysis and its application in geographical epidemiology: Transactions of the Institute of British Geographers NS 21, 256-274.

Getis, A. and Boots, B., 1978. Models of spatial processes. An approach to the study of point, line and area patterns. Cambridge University Press, London, 198 pp.

Gresham, J.J., Loftus-Hills, G.D., 1981. The geology of the Kambalda nickel field, Western Australia: Economic Geology 76,1373-1416.

Groenewald, P.B. and Riganti, A., 2004. East Yilgarn 1:100,000 geological information series-an explanatory note: Geological Society of Western Australia Report 95, 58 pp.

GSWA (Geological Survey of Western Australia), 2008. 1:500 000 Interpreted bedrock geology of Western Australia, 2008 update. http://mapserver.doir.wa.gov.au/datacentre/ (accessed April 24, 2009).

Haggett, P., Cliff, A.D. and Frey, A. 1977. Locational methods. Edward Arnold, London, 605 pp.

Hill, R.E.T., Gole, M.J., 1990. Nickel sulphide deposits of the Yilgarn Block, in: Hughes, F.E. (Ed.), Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 14, Melbourne, pp.557-559.

Hill, R.E.T., Barnes S.J., Gole M.J., Dowling, S.E. 1990. Physical volcanology of komatiites. A field guide to the komatiites of the Norseman-Wiluna Greenstone Belt, Eastern Goldfields Province, Yilgarn Block, Western Australia. Excursion guide book no. 1. Geological Survey of Western Australia, Perth, 100 pp.

Hill, R.E.T., Barnes, S.J., Gole, M.J., Dowling, S.E., 1995. The volcanology of komatiites as deduced from field relationships in the Norseman-Wiluna greenstone belt, Western Australia. Lithos 34, 159-188.

Hoatson, D.M., Jaireth, S., Jaques, A.L., 2006, Nickel sulphide deposits in Australia: characteristics, resources and potential. Ore Geology Reviews 29, 177-241.

Hronsky, J.M.A.,Groves, D.I., 2008. Science of targeting: definitions, strategies, targeting and performance measurement. Australian Journal of Earth Sciences 55, 3-12.

Hronsky, J.M.A., and Schodde, R.C., 2006. Nickel exploration history of the Yilgarn carton: from the nickel boom to today, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, 1-11.

Knoring, L.D. and Dech, V.N., 1993, Mathematics for geologists, in: Zeidler, R.B. (Ed.), Geotechnika 10: Netherlands, A.A. Balkema, 200 pp.

Lesher, C.M.; Burnham, O.M., and Keys, R.R., 2001. Trace element geochemistry and petrogenesis of barren and ore-associated komatiites. Canadian Mineralogist 39, 673-696.

Lesher, C.M., Keays, R.R. 2002. Komatiite-associated Ni-Cu-PGE deposits: geology, mineralogy, geochemistry and genesis, in: Cabri, L.J. (Ed.), The geology, geochemistry mineralogy and mineral beneficiation of platinum group elements, Canadian Institute of Mining Metallurgy and Petroleum Special 54, 579-617.

Levine, N., 2007. CrimeStat® III. A spatial statistics program for the analysis of crime incident locations (version 3). Ned Levine & Associates and the National Institute of Justice.

Lloyd, C.D., 2007. Local models for spatial analysis. CRC/ Taylor and Francis, Boca Raton, USA, 260 pp.

Mamuse, A., Powal, A., Kreuzer, O.P., and Beresford, S., 2009. A new method for centrographic analysis of mineral deposit clusters. Ore Geology Reviews 36, 293-305.

Mandelbrot B.B., 1983. The fractal geometry of nature. W.H. Freeman and Company, New York, 468 pp.

Marston, R.J., 1984. Nickel mineralization in Western Australia. Geological Survey of Western Australia Mineral Resources Bulletin 14, 271 pp.

Marston, R.J., Groves, D.I., Hudson, D.R. and Ross, J.R., 1981. Nickel sulphide mineralisation of Western Australia: a review. Economic Geology 76, 1330-1363.

MINEDEX database. Western Australia Department of Mines and Petroleum http://mapserver.doir.wa.gov.au/meta/arcMetaPage.asp?Id=532 (accessed January 14, 2009)

MINMET database, Intierra Pty Ltd. http://www.intierra.com/ (accessed January 14, 2009).

Mitchell, A., 2005. The Esri guide to GIS analysis (volume 2: spatial measurements and statistics). ESRI Press, California, 238 pp.

Myers, J.S. and Hickman, A.H., 1990, Pilbara and Yilgarn cratons-regional geology and Mineralization, in: F.E. Hughes, (Ed.), Geology of the Mineral deposits of Australia and Papua New Guinea. The Australian Institute of Mining and Metallurgy, p129-133.

Naldrett, A.J., 2004. Magmatic Ore Deposits. Geology, Geochemistry and Exploration. Springer-Verlag, Berlin, 727 pp.

Nelson, D.R., 1998. Granite-greenstone crust formation on the Archaean earth-a consequence of two superimposed processes. Earth and Planetary Science Letters 158, 109-119.

Onley, P., Stephenson, W., Miller, A., Payne, P., Mappleson, D., Woodward, G., 2006. Technical Report: Lanfranchi Nickel Project, Western Australia. Golder Associates, Perth, 88 pp.

O'Sullivan, D and Unwin, D. J, 2003. Geographic information analysis. John Willey and Sons, New Jersey, 436 pp.

Porwal, A., 2006, Mineral potential mapping with mathematical geological models. PhD dissertation, ITC , The Netherlands, 289 pp.

Ripley, B.D., 1977. Modeling spatial patterns: Journal of the Royal Statistical Society B, 39, 172-192.

Ripley, B.D.,1981. Spatial statistics. John, Willey and Sons, New York, 252 pp.

Root, D.H., Menzie, W.D. and Scott, W.A., 1992. Computer Monte Carlo simulation in quantitative resources estimation. Natural Resources Research 1, 125-138.

Rosengren, N.M., Beresford, S,W., Grguric, B.A., Cas, R.A.F., 2005. An intrusive origin for the komatiitic dunite-hosted Mount Keith nickel sulfide deposit, Western Australia. Economic Geology 100, 149-156.

Rosengren, N.M., Grguric, B.A., Beresford, S.W., Fiorentini, M.L., and Cas, R.A.F., 2007. Internal stratigraphic architecture of the komatiitic dunite-hosted MKD5 disseminated nickel sulfide deposit, Mount Keith Domain, Agnew-Wiluna Greenstone Belt, Western Australia. Mineralium Deposita 42, 821-845.

Sahu, B.K., 1982. Stochastic Modeling of Mineral Deposits. Mineralium Deposita. 17, 99-105.

Singer, D.A., Menzie, W.D., Sutphin, D.M., Mosier, D.L., and Bliss., J.D., 2001. Mineral Deposit Density: an update, in: Schulz, K.J. (Ed.), Contributions to Global Mineral Resource Assessment Research. U.S. Geological Survey Professional Paper 1640-A, pp. A1-A13. http://pubs.usgs.gov/pp/p1640a/p1640a.pdf (accessed January 13, 2008).

Singer, D.A. and Menzie, W.D., 2008. Map scale effects on estimating the number of undiscovered mineral deposits: Natural Resources Research 17, 79-86.

Stone, W.E. and Masterman, E.E., 1998. Kambalda nickel deposits, in: Berkman, D.A., Mackenzie, D.H. (Eds.), Australian and Papa New Guinean Mineral Deposits. The Australasian Institute of Mining and Metallurgy Monograph 22, Melbourne, pp. 347-356.

Stone, W.E., Archibald, N.J., 2004. Structural controls on nickel sulphide oreshoots in Archaean komatiite, Kambalda, WA: the volcanic trough controversy revisited. Journal of Structural Geology 26, 1173–1194.

Swager, C. P., 1995. Geology of the greenstone terranes in the Kurnalpi-Edjudina region, southeastern Yilgarn Craton. Geological Survey of Western Australia Report 47, Perth, 31 pp.

Swager, C.P., 1997. Tectono-stratigraphy of late Archaean greenstone terranes in the southern Eastern Goldfields, Western Australia. Precambrian Research 83, 11-42.

Turcotte D.L., 1986. A fractal approach to the relationship between ore grade and Tonnage. Economic Geology 81, 1528-1532.

Turcotte D.L., 1992. Fractals and chaos in geology and geophysics. Cambridge University Press, 221 pp.

Woolrich, P., Cowden, A., Giorgetta, N.E., 1981. The chemical and mineralogical variations in the nickel mineralization associated with the Kambalda Dome, Western Australia. Economic Geology 76, 1629-1644.

Wong, D.W.S. and Lee, J., 2005. Statistical analysis of geographic information with ArcView and ArcGIS. John Willey & Sons, New Jersey, 441 pp.

Zuo, R., Cheng, Q, Agterberg, F.P., Xia, Q., 2009. Evaluation of the uncertainty in estimation of skarn tin in Southern China. Ore Geology Reviews 35, 415-422.

CHAPTER 4

ASSESSMENT OF UNDISCOVERED NICKEL SULPHIDE RESOURCES, KALGOORLIE TERRANE, WESTERN AUSTRALIA

Chapter 3 established that komatiite bodies are appropriate units for spatial analysis of nickel sulphide resources in the Kalgoorlie Terrane and that clustering models are inappropriate for these assessments because the deposits are not clustered. Although the Poisson distribution model based on, say, the mean number of deposits per square kilometre of komatiite body may provide some initial estimates, the model is limited by its disregard of the well established relationship between the size of mineralised area and deposit density.

This chapter employs two methods to estimate undiscovered komatiite-associated nickel sulphide resources in the Kalgoorlie Terrane. In the first part of this chapter, resources within demonstrably mineralised, less explored komatiites in the terrane are estimated using deposit density and endowment density regression models. The density models were originally published in *Ore Geology Reviews* (Mamuse et al.[1,4]., 2010b), and the resource estimates were presented separately in a manuscript submitted to *Ore Geology Reviews* (Mamuse et al.[2,4]., submitted). The other part of this chapter draws from a manuscript currently being reviewed by *Mineralium Deposita* (Mamuse & Guj[3,4], in review) which utilises Zipf's law to estimate the total undiscovered komatiite-associated nickel endowment within the Kalgoorlie Terrane. A collective interpretation of the resources estimated using the two methods is presented and discussed.

[1]Mamuse, A., Beresford, S.W., Porwal, A., Kreuzer, O., 2010b. Assessment of undiscovered nickel sulphide resources, Kalgoorlie Terrane, Western Australia. Part 2. Deposit and endowment density models. Ore Geology Reviews 37, 41 – 57.

[2]Mamuse, A., Beresford, S.W., Porwal, A., Kreuzer, O., submitted. Assessment of undiscovered nickel sulphide resources, Kalgoorlie Terrane, Western Australia. Part 2. Estimates from local deposit and endowment density models. Ore Geology Reviews.

[3]Mamuse, A., Guj, P., in review. Rank statistical analysis of nickel sulphide resources of the Norseman-Wiluna Greenstone Belt, Western Australia. Mineralium Deposita.

[4]The lead author (PhD candidate) contributed more than 90% of the origination, content and preparation of this chapter and the published or submitted papers.

Abstract. Deposit and endowment density regression models and Zipf's law are applied separately to estimate undiscovered nickel resources in the Kalgoorlie Terrane, Western Australia. The regression models are based on the well established power law relationship between mineral deposit density and the size of host geological units, and that between mineral endowment density and the area of host geological units, which were corroborated in this study for 12 relatively more explored komatiites (control areas) in the Kalgoorlie Terrane. The models are applied to estimate the number of undiscovered nickel sulphide deposits and amount of undiscovered nickel endowment in less explored demonstrably mineralised komatiites in the terrane. In contrast, Zipf's law, according to which the size of the largest deposit is twice the size of the second, thrice the size of the third, four times the fourth, and so on, is used to estimate the terrane's total undiscovered nickel endowment. The regression models indicate that demonstrably mineralised, less explored komatiites in the Kalgoorlie Terrane contain 3.0 to 10.0 Mt (mean 5.5 Mt) undiscovered nickel metal in 59 to 210 (mean 114) deposits. On the other hand, Zipf's law predicts that the total amount of undiscovered nickel metal in the Kalgoorlie Terrane is about 3.0 Mt nickel metal, assuming that the largest deposit (Mt. Keith) is fully delineated or 10.0 nickel metal assuming that Mt. Keith partially delineated. The difference between Zipf's law and regression estimates are approximately indicative of the amount of undiscovered nickel endowment in komatiite bodies in the Kalgoorlie Terrane that are presently unexplored. Collectively, the two methods suggest that there may not be significant nickel sulphide resources outside the known demonstrably mineralised komatiite bodies in the Kalgoorlie Terrane.

4.1 Introduction

Mineral resource assessments are primarily concerned with estimating the number deposits and the amount of contained metal within an area. Mineral deposit density regression models based on regression analysis of the relationship between mineral deposit density (number of mineral deposits per unit area) and the area of host geological units, constitute one of the most robust methods for estimating the number of undiscovered mineral deposits (Singer et al., 2001; Singer, et al., 2005; Mosier et al., 2007; Singer, 2008). Typically, mineral deposit density regression models are based on the number of mineral deposits of a particular type in well explored regions (control areas) distributed worldwide. The work of D.A. Singer and others (Mosier et al., 2007; Singer, 1994, 2008; Singer et al., 2001, 2005), has availed global deposit density models for estimating mineral resources for several mineral deposit types. This has led Singer (2008) to formulate generalized equations for global estimation of the numbers of undiscovered mineral deposits and undiscovered mineral endowment (see also Singer, 2010). The function of these general or global mineral deposit density regression models is to estimate the number of undiscovered deposits in geologically similar areas worldwide. For example, the global porphyry copper deposit density regression model of Singer et al. (2005), based on 19 control areas in the Philippines, Peru, China, Central Europe, Kazakhstan, Australia, the USA, Canada, Mexico, Chile and Argentina and other places, was applied to estimate the number of undiscovered porphyry copper deposits in Antarctica.

Although estimates from the global or general deposit density models are useful, more locally specific estimates are obtainable if local deposit density models can be used instead of general or global deposit density models (Singer, 2008). In this chapter local deposit density models complemented by local endowment density models (Mamuse et al., 2010b), are utilised to estimate the number of undiscovered nickel sulphide deposits and amount of undiscovered nickel endowment in the Kalgoorlie Terrane, Western Australia. The models are constructed from deposit or endowment densities from 12 well explored komatiites (control areas) within the Kalgoorlie Terrane.

To reduce uncertainty in the estimates, areas that are not locally favourable to hosting nickel sulphide deposits are excluded from analyses in this study. Analyses are therefore restricted to komatiites that are less explored than control areas but which are demonstrably mineralised. In this study demonstrably mineralised komatiites are those komatiites that contain nickel sulphide deposits or, at least, those that contain prospects with drill-intersected nickel sulphides. Furthermore a distinction is clearly made between estimates in areas containing deposits and those containing only prospects. Higher confidence is placed on estimates in areas that contain known deposits compared to areas that contain only prospects. Estimates for areas that contain neither deposits nor prospects are not presented.

To provide an estimate of nickel sulphide resources that may be contained in outside the demonstrably mineralised, estimates from local deposit density and endowment models are compared with estimates based on Zipf's law. The application of Zipf's law in

Mininera resources assessments uses concepts of natural and residual endowment (McCuaig and Guj, 2006). Natural endowment is the total, generally unknown, mineral endowment of a terrane. The known mineral endowment of a terrane is the sum of cumulative production and current resources. The difference between natural endowment and known endowment constitutes the residual endowment. In this chapter, Zipf's law is applied to estimate a single value of total amount of metal left to be discovered in the Kalgoorlie Terrane. The difference between the Zipf's law estimate and the estimate from local density models mentioned above, provides an indication of the amount of undiscovered nickel endowment outside presently known, demonstrably mineralised komatiites in the terrane. Inferences about the possible number of deposits and apportioning the global endowment estimate from Zipf's analysis to individual deposits is not attempted in this chapter because of uncertainties stemming from inadequate and non-uniform deposit delineation.

4.2. Construction of nickel deposit and endowment density models, Kalgoorlie Terrane

4.2.1 Delineation of permissive areas

The geology of the Kalgoorlie Terrane, described in detail in Chapter 2, provides a general context to delineation procedures described in this section. The permissive area (Singer, 1993a) for komatiite-associated deposits in the Kalgoorlie Terrane is defined by the distribution of komatiites in the terrane (Fig. 2.2 b, c). The komatiites are not continuous rock masses, but occur as discrete komatiite bodies separated by non-komatiite rocks (see sections 1.4.2 and 3.4)

Spatial analyses are sensitive to the accuracy with which analysis units or analysis windows are drawn (Baddeley, 2008) which in part is a function of the mapping scale (Mosier et al., 2007; Singer and Menzie, 2008). Mamuse et al. (2010a) showed that analysing the spatial distribution of nickel sulphide deposits in the Kalgoorlie Terrane within an analysis window represented by the full sample space made up of all komatiite bodies (section 1.4.2) in the terrane is conceptually different from spatial analysis of nickel sulphide deposits within each komatiite body. The former analysis depicts the spatial distribution of host komatiite bodies whereas the latter represents the spatial distribution of the deposits themselves. Thus komatiite bodies are the appropriate spatial analysis units for area based calculations involving mineral deposits, such as deposit density (number of deposits per unit area).

Ideally, the most detailed map available must be used in the delineation of permissive areas (Mosier et al., 2007; Singer and Menzie, 2008) that are represented in this study by komatiite bodies (Figs. 4.1-4.7). To delineate komatiite bodies in the northern part of the Kalgoorlie Terrane (which are predominantly komatiitic dunites) the map of Beresford et al. (2004) was used because it is presently one of the most detailed compilations. To delineate komatiitic peridotite bodies in the southern part of the Kalgoorlie Terrane, the GSWA (2008) 1:500,000 bedrock geological map of Western Australia was utilised because of its uniform and sufficiently detailed coverage over this southern part of the terrane. In order to capture new detailed geological information in specific areas such as the area around Mt. Clifford (Fig. 4.5), maps from exploration companies were used to locally update the GSWA (2008) map.

4.2.2 Selection of control areas

Based on the map compiled from GSWA (2008), Beresford et al. (2004) and company reports, as described in section 3.1, the number of komatiite bodies that contain one or more nickel sulphide deposits in the Kalgoorlie Terrane is 48 (Appendix 1). The exploration intensity over the 48 demonstrably mineralised komatiite bodies is not uniform. If the 48 demonstrably mineralized komatiite bodies are ranked in terms of their exploration maturity, the top ranks may denote those komatiite bodies in

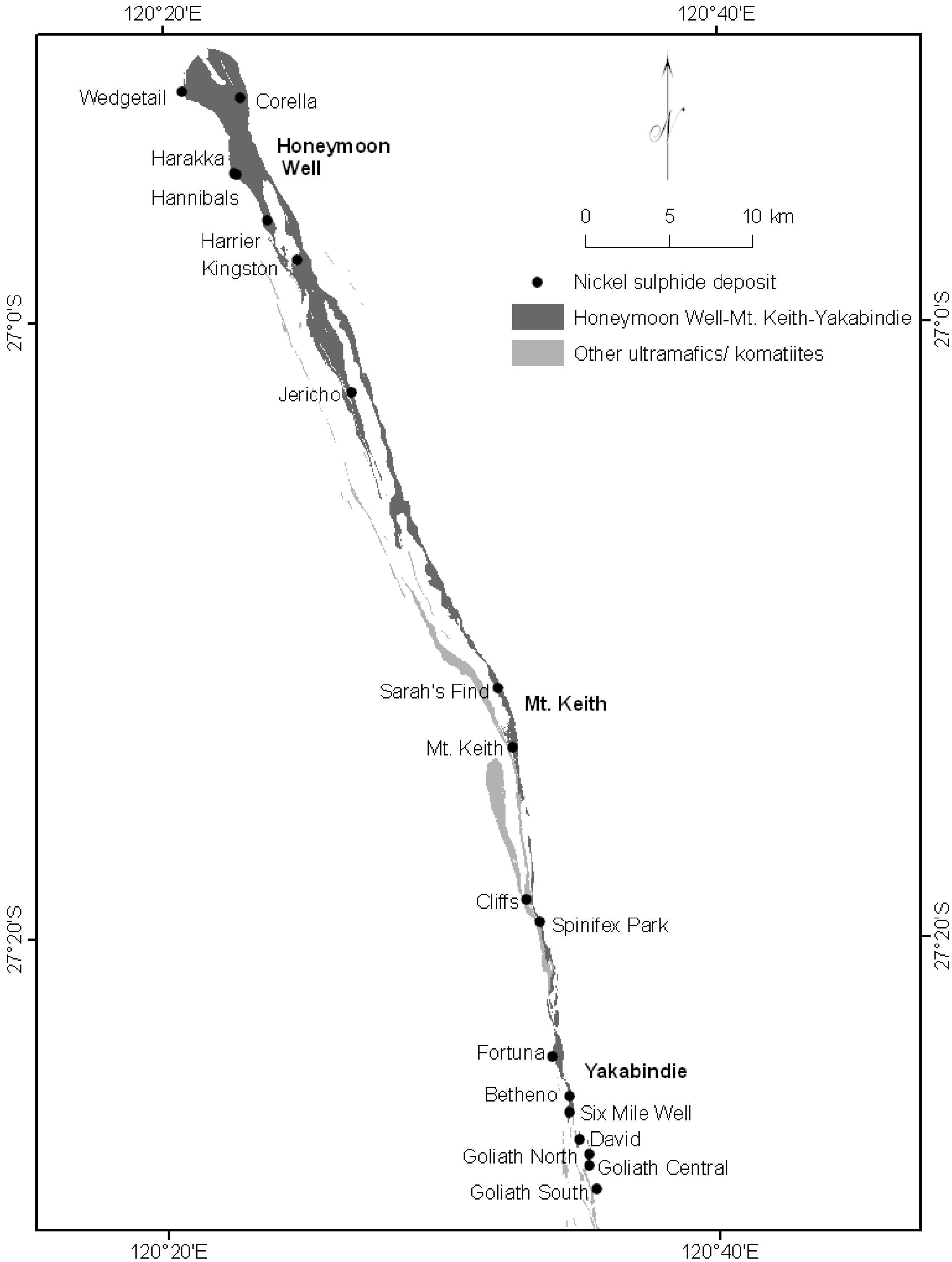

Fig. 4.1 Honeymoon Well-Mt. Keith-Yakabindie control area komatiite body (geology after Beresford et al., 2004)

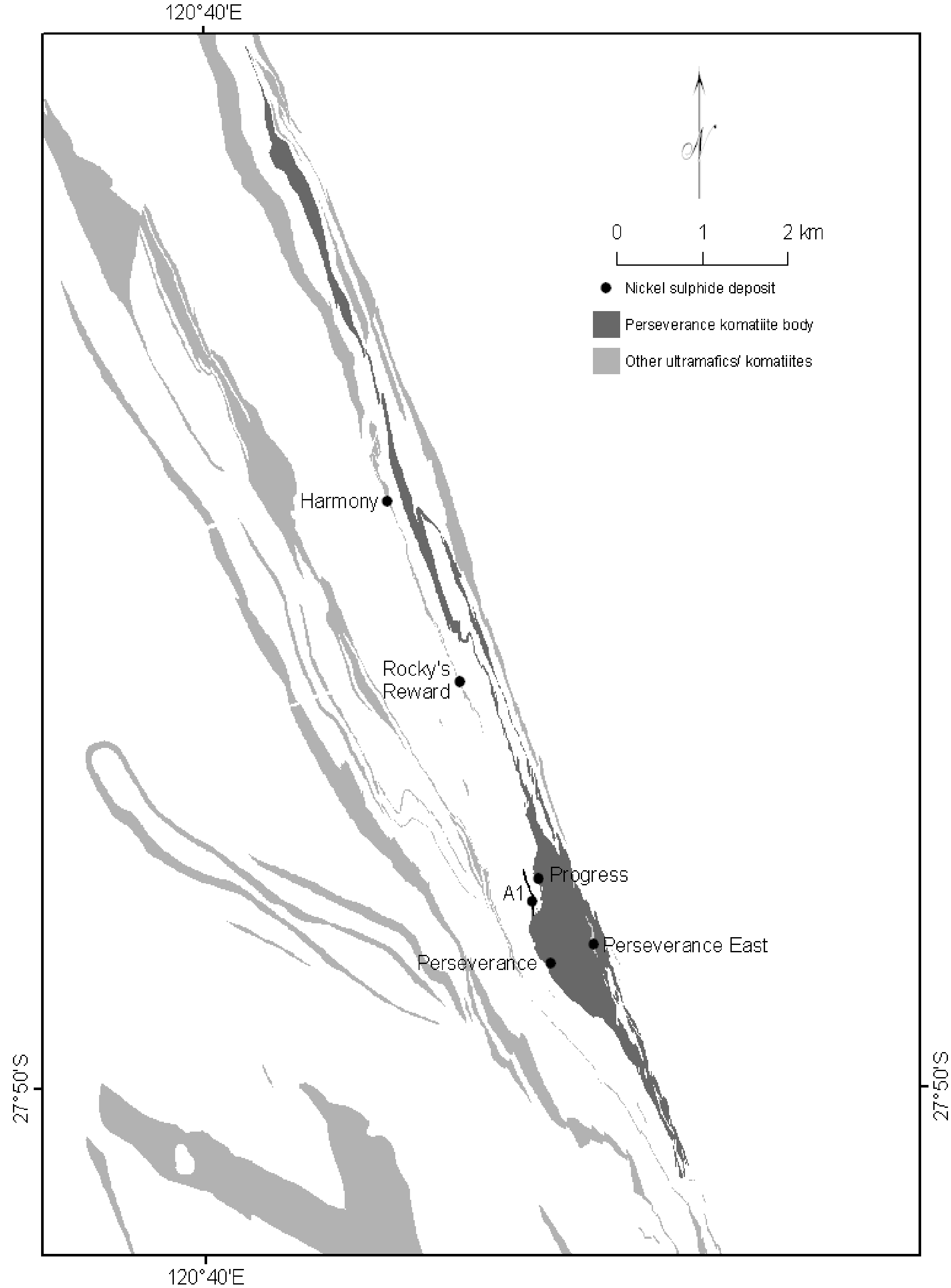

Fig. 4.2 Perseverance control area komatiite body (geology after Beresford et al., 2004)

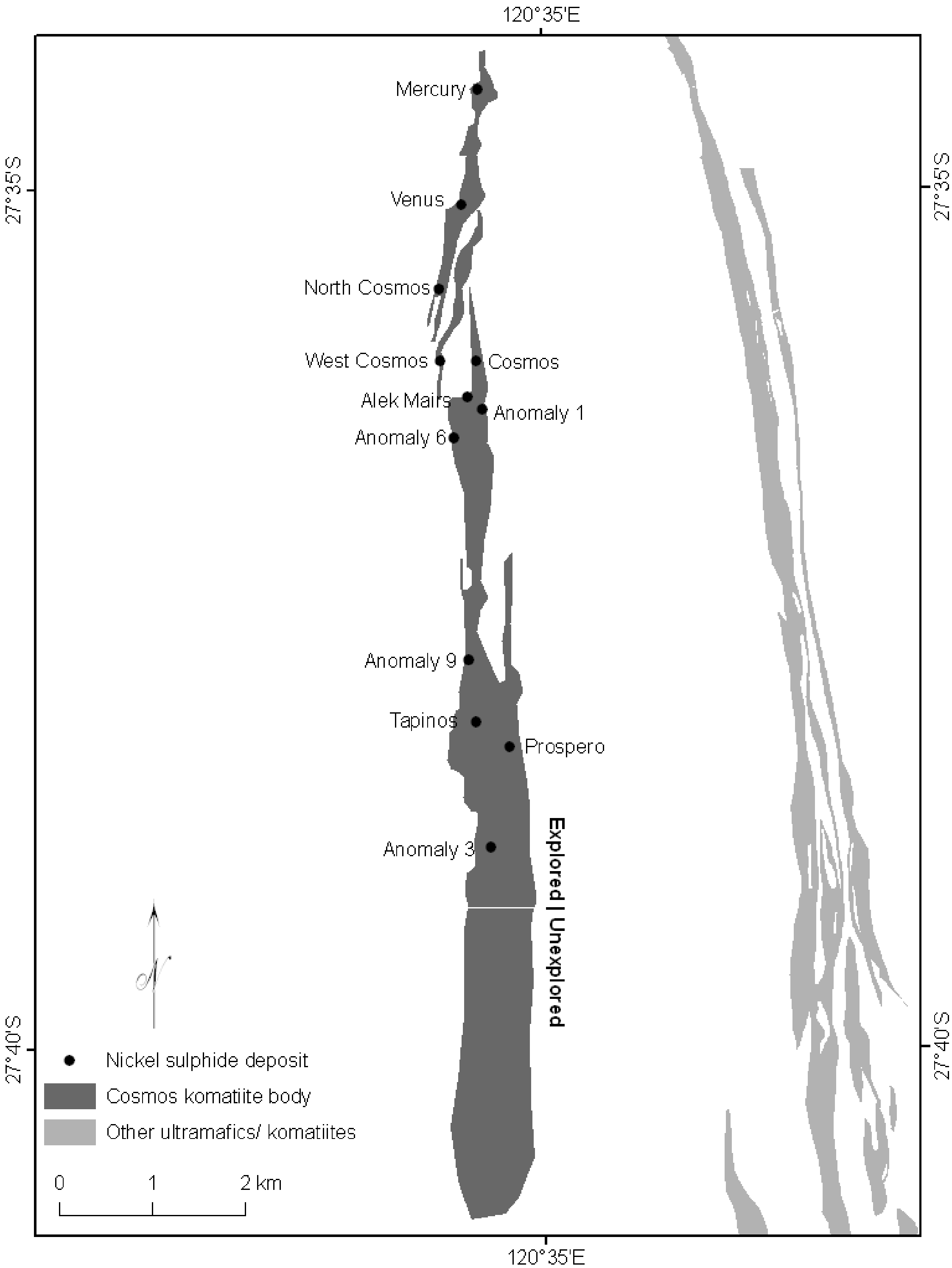

Fig. 4.3 Cosmos control area komatiite body (geology after Jubilee Mines N.L., 2005 and GSWA, 2008).

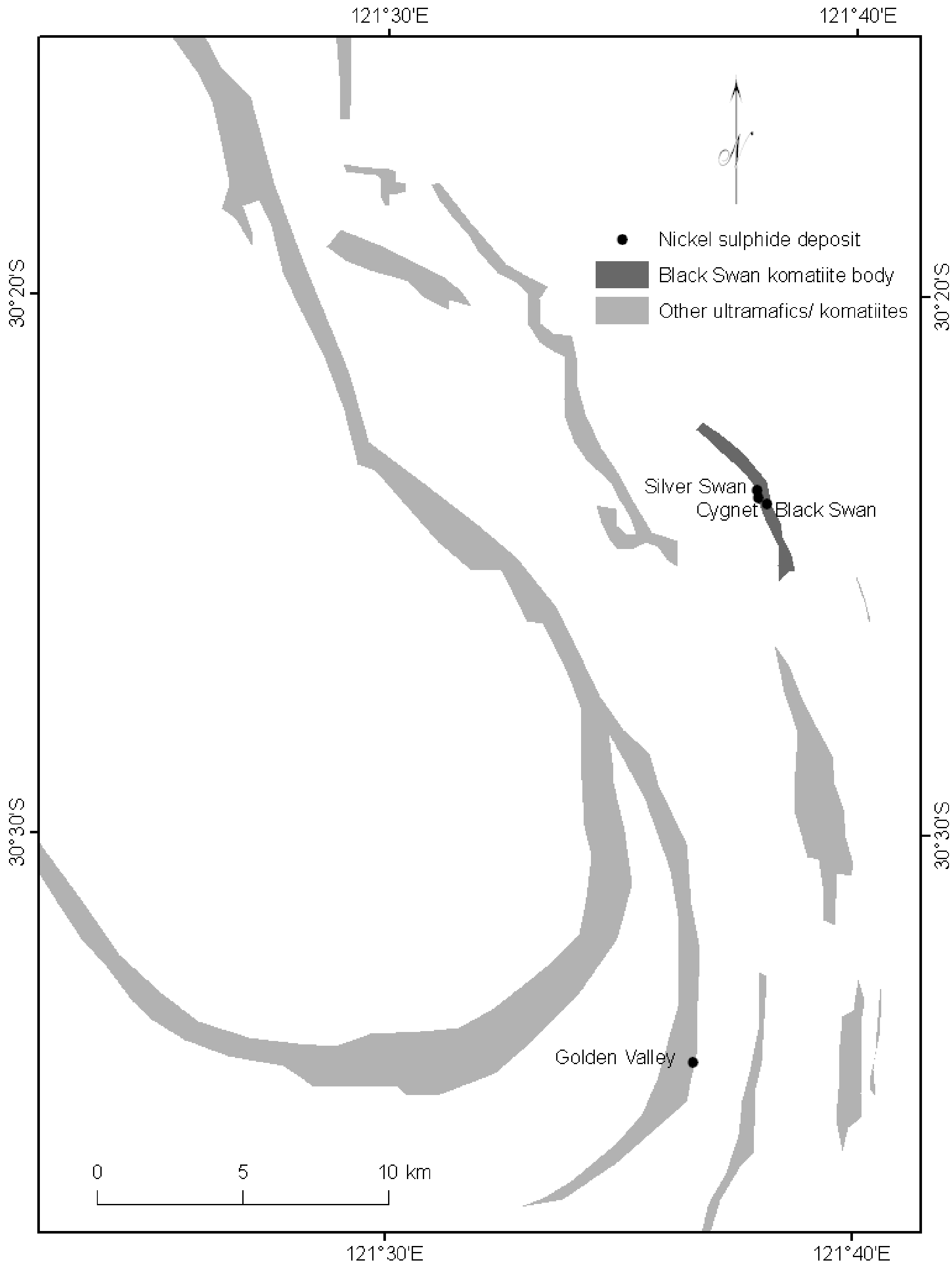

Fig. 4.4 Black Swan control area komatiite body (geology after Sulway et al. 2005 and GSWA, 2008).

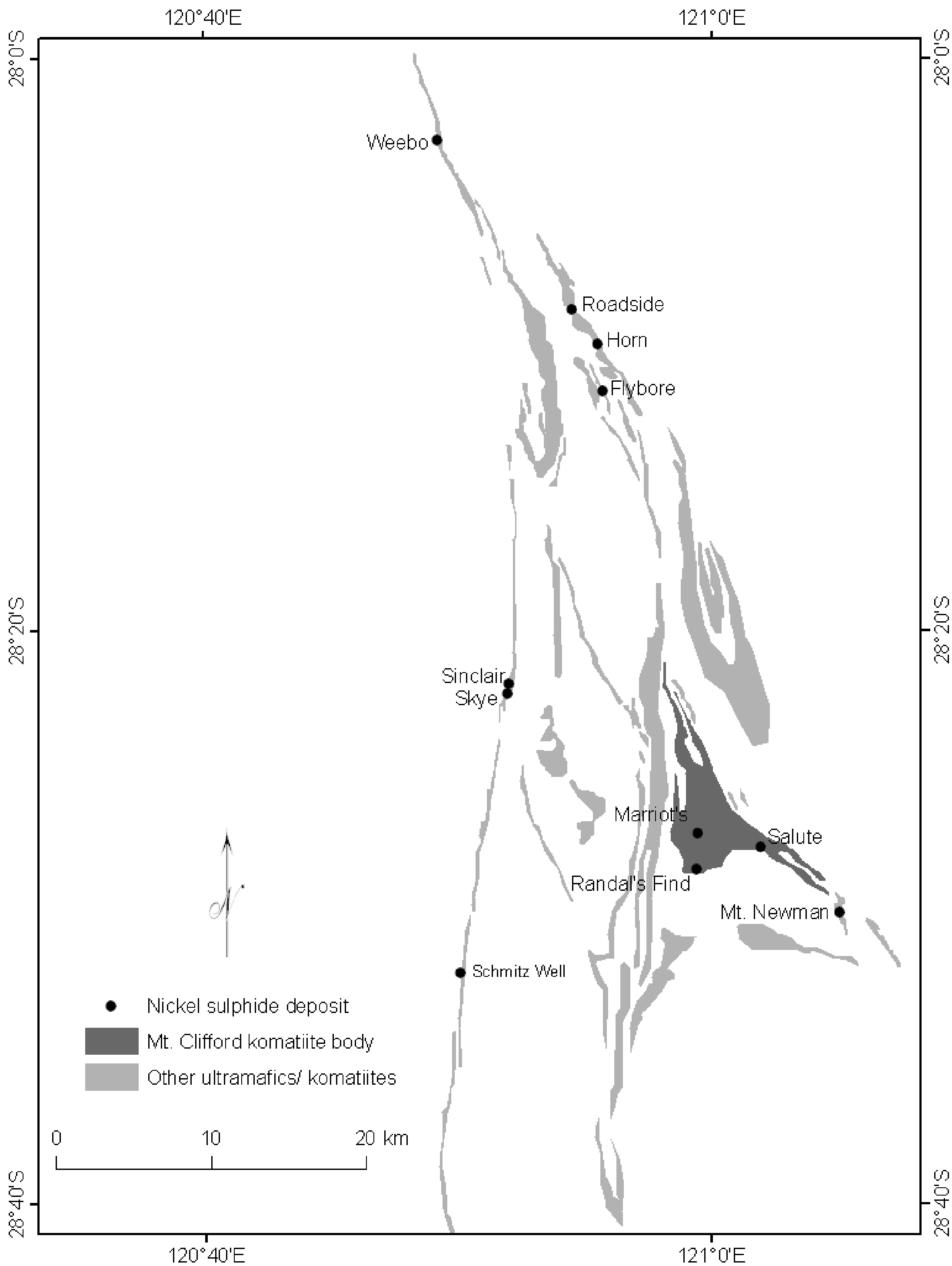

Fig. 4.5 Mt. Clifford Control area komatiite bodies (geology after Jubilee Mines N.L., 2007 and GSWA, 2008)

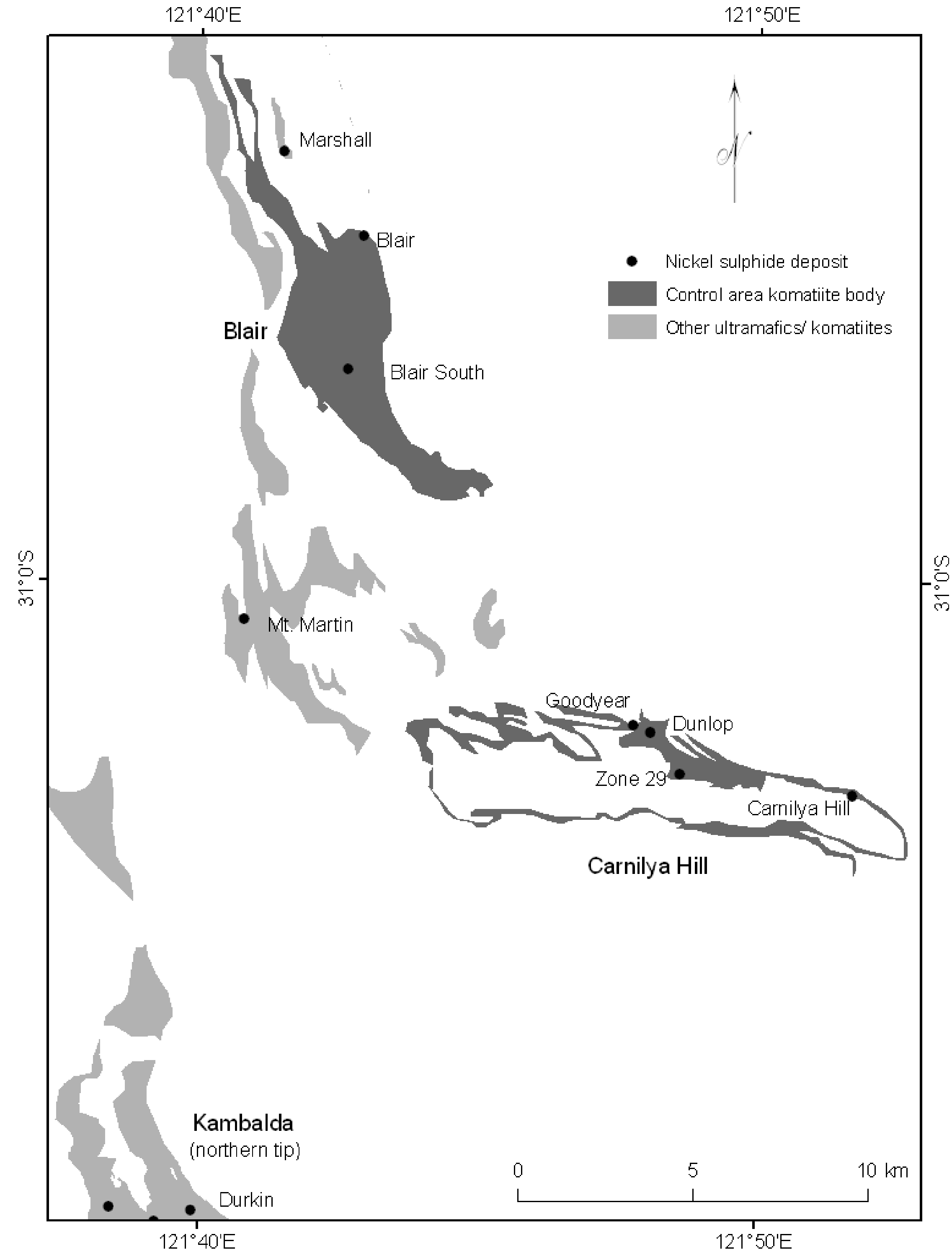

Fig. 4.6 Blair and Carnilya Hill control area komatiite bodies (geology after Australian Mines Limited, 2007 and GSWA, 2008)

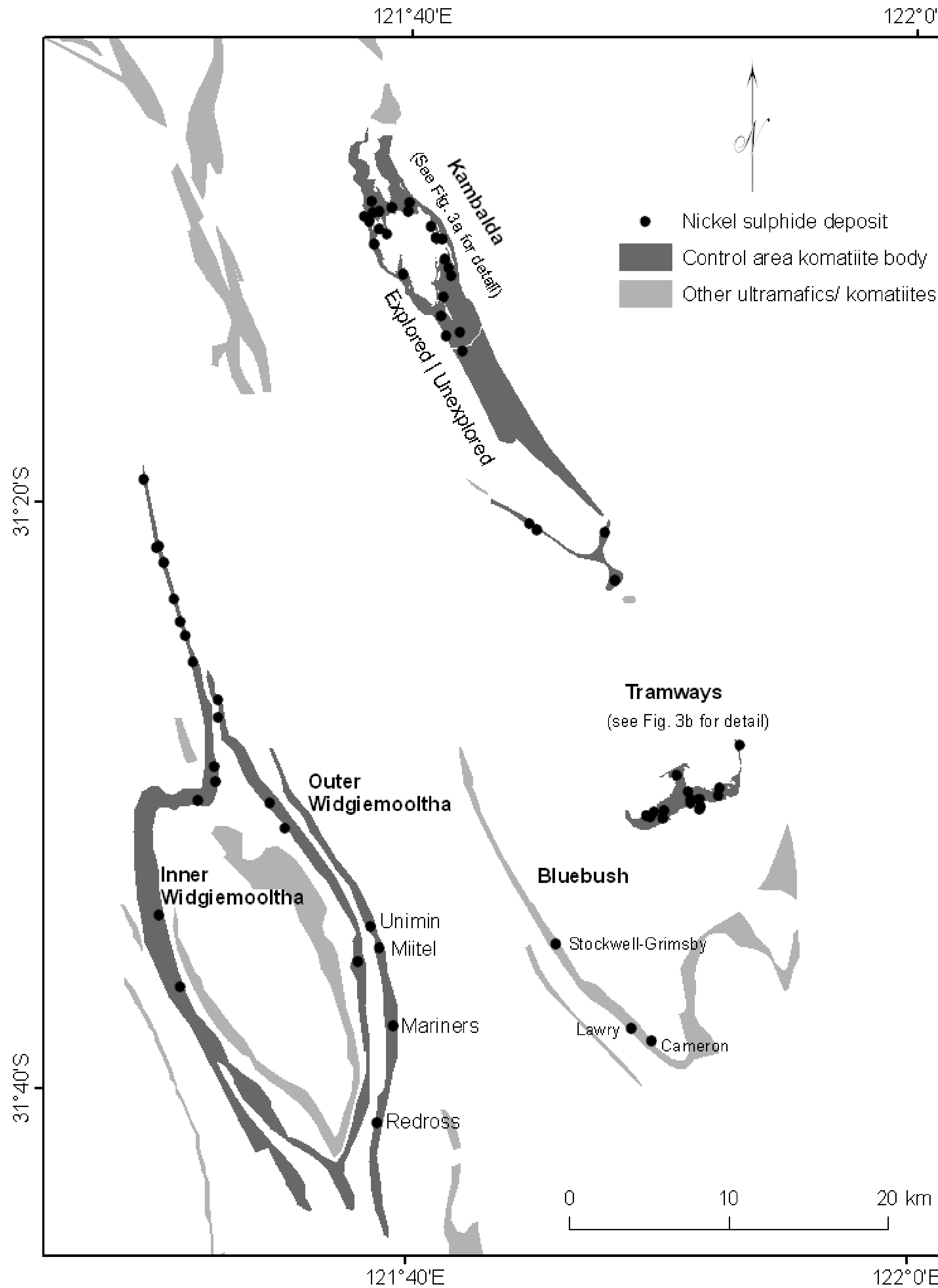

Fig. 4.7 Kambalda, St. Ives, Tramways and inner and outer Widgiemooltha Control area komatiite bodies (geology after Gresham and Loftus-Hill, 1981 and Onley et al., 2006 and GSWA, 2008)

which the spatial distribution of deposits most closely resembles their true geologic spatial distribution.

Expert knowledge, or calculations based on variables such as drilling depths and densities, tenement history and discovery rates may be applied for determining the ranks. In the present study, expert knowledge of the nickel exploration history of the Kalgoorlie Terrane was used to rank the 48 komatiite bodies according to their relative exploration maturity. The top 12 (one quarter) most explored komatiite bodies were selected as control areas (Table 4.1, Fig. 4.1-4.7). The 12 control area komatiite bodies (Table 4.1; Fig. 4.1-4.7; Appendix 1) were considered to exhibit deposit densities that closely approximate the true deposit densities. Further, one could reasonably expect that the control areas (2.4 to 71.0 km^2 in size; Table 4.1) exhibit deposit density variability (0.1 to 3.6 deposits/ km^2) that closely resembles the true variability of deposit densities across the range of sizes (areas) of komatiite bodies in the Kalgoorlie Terrane. Each control area komatiite body contains a minimum of two nickel sulphide deposits, at least one of which has a reported contained nickel metal resource. Four of the control areas are komatiitic dunites, and the remaining eight are komatiitic peridotites (Table 4.1; Appendix 1). Out of the 156 deposits and about 10.8 Mt contained nickel metal in the 48 komatiite bodies (Appendix 1), the 12 control areas account for 109 (70%) of the deposits and approximately 10 Mt (93 %) of nickel metal.

4.2.3 Deposit dataset and deposit grouping

The nickel deposit dataset for this study (Appendix 1) was compiled mainly from the MINEDEX (Western Australian Department of Mines and Petroleum) and MINMET (Intierra Resources Pty Ltd.) databases and technical reports of exploration companies. Included in the deposits dataset are: (i) currently or previously mined nickel sulphide deposits (ii) unmined deposits with reported historic or current nickel sulphide resources and, (iii) prospects with significant drill-intersected nickel sulphides. In total, the data base (Appendix 1) contains 142 individual deposits defined this way.

TABLE 4.1 Komatiite bodies selected as control areas[1] in this study

Komatiite body	Type[2]	Area (km^2)	No. of Nickel Sulphide deposits	No. of Deposits per km^2	Contained Ni (kt)	Ni metal (kt/ km^2)	Map	Description
Honeymoon Well_ Mt. Keith-Yakabindie	D	57.9	18	0.31	5,912	102.2	Fig. 4.1	This control area consists of about 70 km strike length of nearly continuous komatiite stratigraphy between Yakabinde in the south and Honeymoon Well in the North. Three komatiite belts, known as Mt. Keith, Cliffs and Monument ultramafic units, are correlated over this strike length. Both type 1 and type 2 nickel sulphide deposits are known in this control area.
Perseverance	D	2.4	3	1.27	1,055	447.2	Fig. 4.2	Perseverance, the world's largest type 1 nickel sulphide deposit, is associated with the 700-m thick Perseverance dunite lens. Also associated with the dunite lens are the A1 massive sulphide deposit, considered to have been tectonically remobilized from the main orebody, and the Progress deposit which occupies a secondary channel of the main Perseverance channel.
Cosmos	D	3.4	12	3.56	650	193.0	Fig. 4.3	Relatively high grade nickel sulphide deposits associated with Mt. Goode dunite lenses.
Black Swan	D	2.6	3	1.16	374	145.1	Fig. 4.4	The Black Swan nickel sulphide deposit camp is hosted in three magma pathways within the bimodal felsic-ultramafic Black Swan succession. Cygnet deposit (and its satellite White Swan deposit) is within the Cygnet major pathway. The Black Swan pathway which hosts the Black Swan deposit is also a major pathway. The Silver Swan (and its satellite Black Duck deposit) occurs within a secondary pathway or lava tube.
Mt. Clifford	P	33.4	3	0.09	9.4	0.3	Fig. 4.5	Disseminated ores in serpentinised peridotites at three locations.
Blair	P	19.9	2	0.10	23	1.2	Fig. 4.6	Kambalda style nickel sulphide mineralization, currently known at two deposits and several less advanced prospects.
Carnilya Hill	P	14.5	4	0.28	89	6.1	Fig. 4.6	Mineralization within the Carnilya Hill komatiite sequence consists of small lenses of massive and matrix sulphides, of which two have been mined.
Kambalda	P	24.1	11	0.91	1,135	47.0	Fig. 4.7	The world's type area for type 1 nickel sulphide deposits. A total of 22 nickel sulphide deposits are hosted by the Silver Lake Member of the Kambalda Komatiite
St. Ives	P	3.9	4	1.02	144	36.8	Fig. 4.7	Part of the world-class Kambalda-St. Ives-Tramways nickel sulphide district, containing four currently known type 1 nickel sulphide deposits.
Tramways	P	8.8	10	1.13	263	29.8	Fig. 4.7	Part of the world-class Kambalda-St. Ives-Tramways nickel sulphide district, containing at least 15 nickel sulphide deposits distributed within 10 magma pathways or channels.
Widgiemooltha (inner)	P	71.0	18	0.25	171	2.4	Fig. 4.7	The inner (stratigraphically lower) of two mineralized komatiite sequences at the Widgiemooltha Dome containing 18 nickel sulphide deposits
Widgiemooltha (outer)	P	17.1	4	0.23	137	8.0	Fig. 4.7	The outer (stratigraphically higher) of two mineralized komatiite sequences at the Widgiemooltha Dome containing 4 nickel sulphide deposits

Notes
[1]The 12 control areas in Table 4.1are the most explored komatiite bodies in Appendix 1.
[2]D stands for komatiitic dunite and P stands for komatiitic peridotite.

To facilitate spatial analyses, deposits need not only be defined in economic terms but also in spatial terms. Spatial proximity rules for combining deposits, usually based on some arbitrary radial distance within which deposits are combined, are applied to avoid confounding analyses due to ambiguity in deposit definition (Bliss and Menzie, 1993; Singer, 1993a, 2008; Singer et al., 2001). Deposits in all komatiitic dunite control areas in the Kalgoorlie Terrane, except Perseverance, are clearly defined by the host dunite lenses such that spatial definition rules are not required. However some deposit grouping scheme is required for komatiitic peridotite control areas in areas where potential ambiguity in deposit definition exists. One case in point is that of deposits within the Kambalda komatiite body where deposits may be volcanological or structural segments of the same lenticular orebody (Fig. 4.8). Given the large aspect ratios of the deposits and their presumed deposition along lava channels, radial spatial rules may not be ideal for deposit grouping. Another consideration is that any grouping of the komatiitic peridotite-associated deposits should ideally bear some conceptual resemblance to komatiitic dunite associated deposits defined by dunite lenses.

Based on the above considerations the Kambalda deposits were grouped according to their magma pathways (Fig. 4.8). According to Barnes et al. (1995) and Barnes (2006b), magma pathways (see Chapter 2) in komatiitic dunites (dunite lenses) are the equivalent of magma pathways in komatiitic peridotites (commonly known as channels). Currently, eleven channels are envisaged to exist at Kambalda (Gresham, 1986; Reliance Mining Limited, 2004; 2005; Independence Mining Group N.L., 2009; Fig. 4.8). For purposes of this study, all orebodies within a channel constitute one deposit (Appendix 1, Fig. 4.8). Similarly, it is currently estimated that ten nickel sulphide deposit channels exist within the Tramways camp (Panoramic Resources Limited undated and 2009) as depicted in Figure 4.9 and Appendix 1.

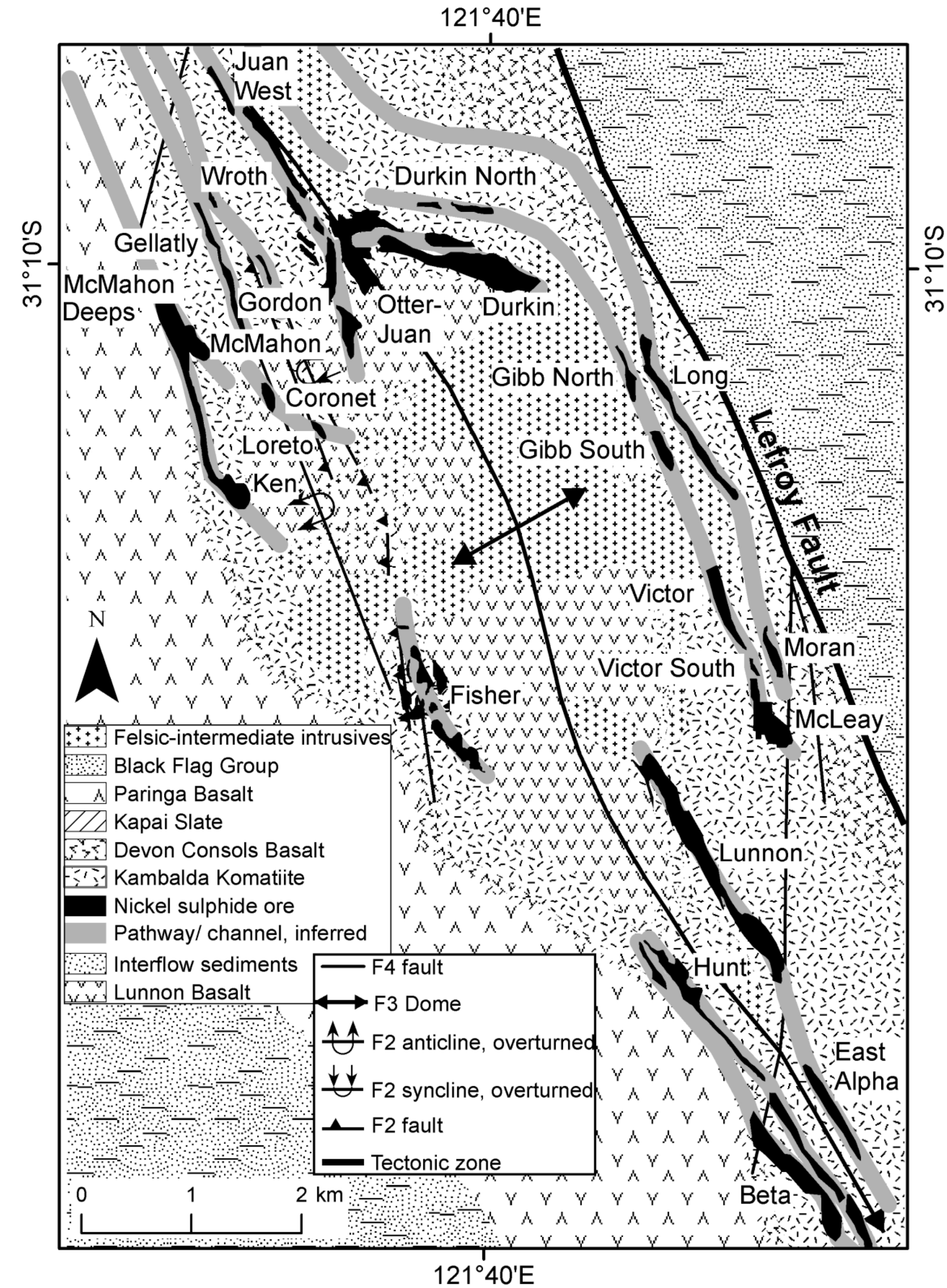

Fig. 4.8 Sketch of nickel sulphide magma pathways (channels) for the Kambalda camp (after Gresham, 1986; Reliance Mining Limited, 2004, 2005; Independence Mining Group N.L., 2009). Geology is after Gresham and Loftus-Hills (1981) and Cowden and Roberts (1990) and Stone and Archibald (2004).

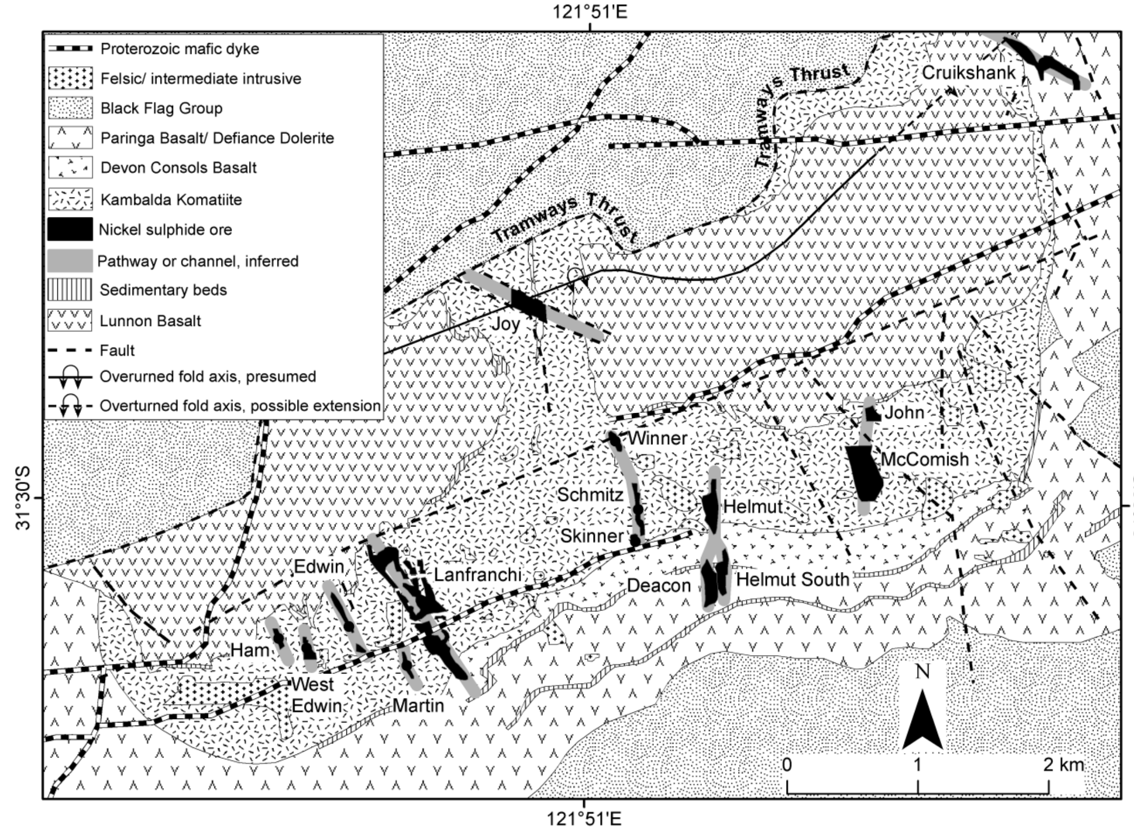

Fig. 4.9 Sketch of nickel sulphide magma pathways (channels) for the Tramways camp (after Mincor Resources N.L. 2007, 2008). Geology is after Gresham and Loftus-Hill (1981) and Onley et al. (2006).

In the Black Swan komatiite body, Silver Swan and Cygnet deposits are within 10 metres of each other and would probably constitute one deposit if some standard spatial rule was to be applied. However, based on the geological interpretation of Hill et al. (2004), Silver Swan (together with a satellite deposit known as Black Duck) occurs in a secondary pathway separate from the major pathway that hosts Cygnet and its satellite White Swan deposit. The disseminated Black Swan deposit occurs within another major pathway, bringing to three the number of known mineralized pathways. Based on this interpretation one can distinguish Silver Swan, Cygnet and Black Swan as three separate deposits within the Black Swan komatiite body (Table 4.1; Appendix 1).

Deposits in the remaining control areas (Blair, Carnilya Hill, Mt. Clifford, Inner Widgiemooltha, Outer Widgiemooltha and St. Ives) have not been grouped by magma pathways because of insufficient data and the individual deposits are used for the present analysis (Appendix 1).

Three deposits considered in this study to be genetically associated with the Perseverance dunite body are Perseverance, A1 shoot and Progress (Table 4.1; Appendix 1). Perseverance is the main disseminated deposit within a major magma pathway in the 700 m thick Perseverance lens. The A1 deposit is a massive nickel sulphide deposit that is interpreted to have been tectonically remobilised from the main deposit and the Progress deposit occupies a magma pathway secondary to the main pathway.

The above deposit grouping scheme avails to this study 92 entries (containing 109 individual deposits) for analysis (Appendix 1). Although these 92 entries are referred to as deposits in this study, the reader should be aware of the grouping described above.

4.2.4 Mineral deposit density

Mineral deposit density is the number of mineral deposits per unit area (Bliss et al., 1987; Bliss and Menzie, 1993; Singer, 1993a; Cox, 1993; Singer et al., 2001) which may be stated as:

$$\text{Deposit density} = \frac{\text{number of deposits}}{\text{area of permissive host rock (km}^2\text{)}} \tag{4.1}$$

Mineral deposit densities represent the base rate or probability of mineral occurrence (Bliss and Menzie, 1993). For example, in weights-of-evidence model for mineral potential analysis (Bonham-Carter, 1994), mineral deposit densities constitute the prior probability of deposit occurrence required to calculate the posterior probability based on the presence or absence of deposit predictor features. If the true mineral deposit density were known, multiplying this density by the area of host permissive rock would provide an estimate of the number of deposits within the permissive area. Where deposit densities for several permissive areas are available, the true deposit density may be estimated by the mean deposit density for those areas. However, the frequency distribution of such deposit densities is commonly highly skewed thereby affecting estimates so that in many cases the median deposit density, which is less affected by skewness, may be a better choice than the mean (Singer, 1994; Singer et al. 2001, 2005). Using the mean, median or percentiles to estimate the number of deposits in this way may provide quick initial estimates of the number deposits, but such estimates disregard the relationship between the size of permissive area and deposit density.

One way to model the variability of deposit density with the size of permissive area is to employ regression analysis. A theoretical background to regression analysis is provided in Appendix 2. Deposit density studies by D.A. Singer and co-workers (Singer et al., 2001, 2005; Singer, 1994, 2008, 2010; Mosier et al., 2007) established that a power law relationship exists between mineral deposit density and the size of the host permissive area for several deposits types. These authors showed that, based on the power law, regression of deposit density on the size (area) of permissive areas constituted a robust model for estimating the number of deposits in less explored geologically similar areas. The use of deposit densities for estimating the number of undiscovered deposits is increasingly becoming the key method for making estimates in the context of the USGS three-part assessment method.

4.2.5 Global versus local deposit density regression models

The deposit density-based regression models of D.A. Singer and co-workers (1993; Singer, 1994, 2008, 2010; Singer et al., 2001, 2005; Mosier et al., 2007) are based on well explored control areas distributed globally and provide estimates for less explored, geologically similar terranes anywhere in the world. For example, to construct the global deposit density regression model for porphyry copper deposits, Singer et al. (2005) used 19 control areas from different parts of the world such as Philippines, Peru, China, Central Europe, Kazakhstan, Australia, the USA, Canada, Mexico, Chile and Argentina. The authors then applied the model to estimate the number of undiscovered porphyry copper deposits in Antarctica.

A local version of the deposit density regression model would be based on deposit densities for local control areas within a geological terrane, subject to existence of a density-area power law relationship similar to that found in global models. In this study, the 12 control area komatiite bodies (Table 4.1; Appendix 1) are used to test the power law between deposit density and size (km^2) of the control area komatiite bodies. Then local regression models for estimating the number of nickel deposits in less explored komatiite bodies in the Kalgoorlie Terrane are contracted using regression analysis (Appendix 2).

4.2.6 Mineral endowment density

Deposit density regression models provide estimates of the number of deposits only and are not used directly to estimate the sizes of these deposits. In the USGS three-part assessment method, grade and tonnage models (Cox and Singer, 1986; Singer, 1993b) which are frequency distributions of tonnages and average grades of well explored deposits worldwide are used to estimate the sizes of undiscovered deposits. The probability distribution of total endowment of an area is estimated through a Monte Carlo simulation that combines the probabilistic estimates of number of undiscovered deposits with the grade and tonnage model of the targeted deposit type.

In this study it is proposed that within a terrane the sizes of deposits can be estimated directly from regression analysis of the amount of metal/ km^2 on the area (size) of permissive host rocks in the same way that deposit densities are used to estimate the number of deposits. The amount of metal/ km^2 constitutes endowment density, defined as:

$$\text{Endowment density} = \frac{\text{total contained metal in permissive host rock (kt)}}{\text{area of permissive host rock (km}^2\text{)}} \qquad (4.2)$$

To proceed with regression analysis of endowment density, one should first assess the applicability of the power law between endowment density and the sizes (km^2) of the 12 local control areas.

Whereas nickel deposit density denotes the probability of deposit occurrence within a komatiite body, nickel endowment density may be thought of as the nickel 'grade' of a komatiite body.

4.3 Nickel deposit density and endowment density models, Kalgoorlie Terrane

The foregoing analyses suggest that both nickel deposit density (Fig. 4.10) and nickel endowment density (Fig. 4.11) exhibit power law relationships with the sizes (km^2) of komatiite bodies in 12 control areas within the Kalgoorlie Terrane. Figures 4.10b and 4.5b show regression analyses and 95% confidence and prediction intervals for the 12 komatiite bodies. The concepts of confidence and prediction intervals, explained in more detail in Appendix 2, may be envisaged as follows. There is a 95% chance that the true mean deposit density and mean endowment density for the total population of komatiite bodies in the Kalgoorlie Terrane lay within the respective 95% confidence intervals. The prediction interval denotes the range within which the deposit or endowment density for any komatiite body of known area in the Kalgoorlie Terrane may be expected to lie. Equations from which confidence (Fig. 4.10b; Eq. A4.9 in Appendix 2) and prediction (Fig. 4.11b; Eq. A4.10 in Appendix 2) intervals were derived are included in Appendix 2.

The quality and significance of the linear relationships espoused in linear regression models is usually assessed using the coefficient of determination (R^2) and through analysis of variance significance testing (Table A1), as explained in Appendix 2. The R^2 value (Figs. 4.10 and 4.11; Appendices 2 and 3) represents the proportion of variability in the deposit or endowment density that can be explained by changes in the sizes (areas) of the 12 control area komatiite bodies. The regression model for deposit density has $R^2 = 0.5997$ (Fig. 4.10b, Table A2 in Appendix 3) and the endowment density model has $R^2 = 0.4053$ (Fig. 4.11b, Table A3 in Appendix 3). Statistical significance testing (Tables A2 and A3 in Appendix 3) shows that the modelled relationship espoused between areas of komatiite bodies and deposit (and endowment) density are statistically significant at the 5 % level.

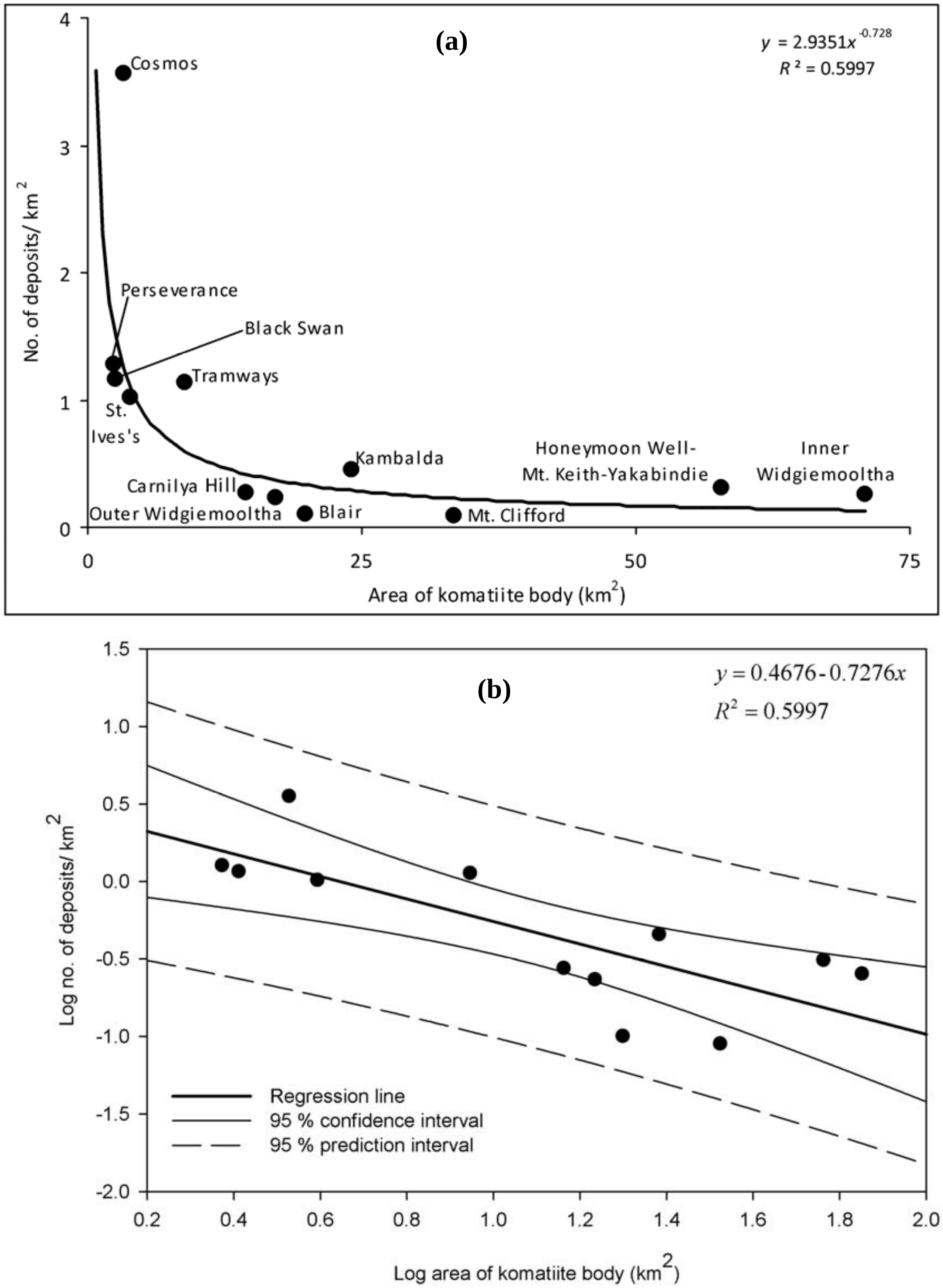

Fig. 4.10 Power law relationship between area of komatiite bodies and nickel sulphide deposit density, (a) untransformed power law and (b) log-transformation and regression analysis of the power law.

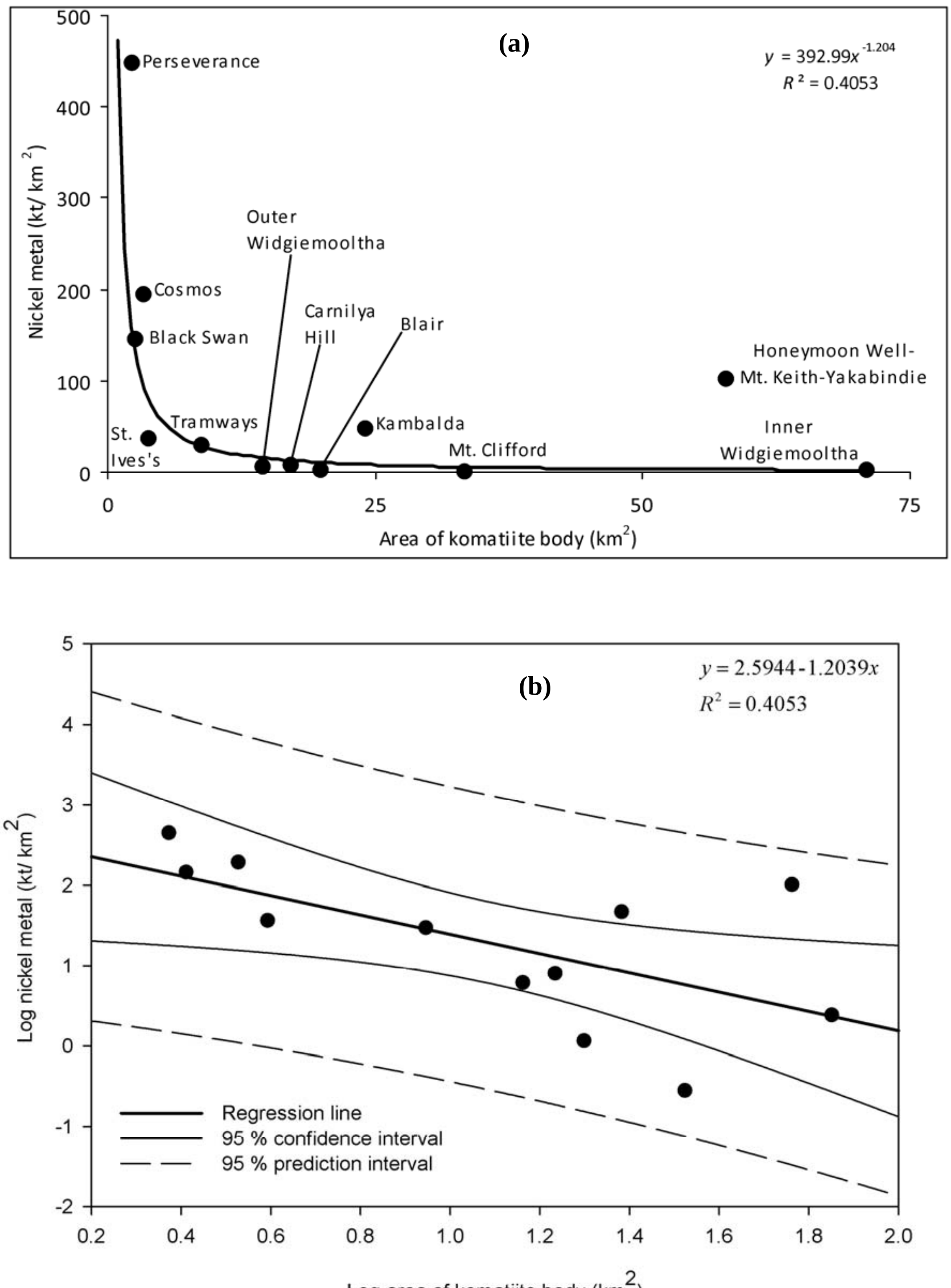

Fig. 4.11 Power law relationship between area of komatiite bodies and nickel endowment density, (a) untransformed power law and (b) log-transformation and regression analysis of the power law.

Thus although the relationship between endowment density and area of komatiite bodies is slightly weaker than that between deposit density and area of komatiite bodies, both relationships are statistically significant and are unlikely to have occurred by chance.

4.4 Selection of komatiite bodies for resource estimation

Komatiites in the Kalgoorlie Terrane are conceptually designated as 'favourable' or 'unfavourable' to nickel mineralisation based on volcanological and geochemical criteria (Lesher et al., 2001; Barnes et al., 2004; Barnes, 2006a, b; Fiorentini et al., 2008). Komatiitic peridotites with pathway subfacies (e.g. Kambalda), or komatiitic dunites with dunite lens subfacies (e.g. Mt. Keith) are considered favourable whereas thin differentiated flows (e.g. Monument Ultramafic Unit), dunite sills (e.g. Walter Williams Formation and Wiluna) may not be favourable. Geochemically, favourable environments exhibit characteristic crustal contamination signatures (e.g. Th-U-LREE enrichment, negative Nb-Ta-Ti anomalies) or sulphide segregation signatures (e.g. Co-Ni-Cu-PGE depletion) making their distinction from unfavourable environments theoretically possible.

In this study only favourable komatiites are of interest because inclusion of unfavourable komatiites, which may theoretically be regarded as having negligible probability of containing economic nickel mineralisation, would probably lead to first order errors in estimates. Twelve most explored of the 48 demonstrably mineralized komatiite bodies in the Kalgoorlie Terrane were selected as control areas (section 4.2.2) for developing local deposit and endowment density models (section 4.3), leaving 36 mineralised non-control area komatiite bodies (Table 4.2). Estimates in this study are restricted to the 36 favourable demonstrably mineralised komatiite bodies (Table 4.2).

Although the 36 komatiite bodies in Table 4.2 are all demonstrably mineralized, they can be sub-divided into komatiite bodies that contain deposits and those that contain only prospects. This is a necessary distinction because there is higher confidence about the presence of economic nickel mineralization in komatiites that contain known nickel sulphide deposits. The scheme used in this study to classify komatiites in the Kalgoorlie

Terrane for resources assessment (Fig. 4.12) shows the contextual the position of the 36 demonstrably mineralized komatiite bodies among the following categories:

1. Favourable, well explored komatiite bodies (control areas).
2. Favourable komatiite bodies with deposits
3. Favourable komatiite bodies with prospects only
4. Favourable komatiite bodies with no known deposits or prospects
5. Unfavourable komatiite bodies

Panels in Figure 4.13 show the regional distribution of komatiites of the various categories in the Kalgoorlie Terrane. More details on each panel are shown on enlargements in Figure 4.14. Category 1 komatiite bodies or control areas (Fig. 4.14) are the basis of deposit and endowment density of Mamuse et al. (2010b) used for assessments in this chapter. Komatiites in categories 2 and 3 (Figs. 4.12, 4.14; Table 4.2) constitute the 36 demonstrably mineralized komatiites targeted in the present assessment. Komatiites in categories 4 and 5 (Figs. 4.12, 4.14) are not easily distinguishable and are not considered in this study because, as indicated earlier, their inclusion may give rise to first order estimation errors.

4.5 Application of nickel deposit and endowment density models

The local mineral deposit and endowment density regression models (section 4.3) were applied to estimate the number of undiscovered nickel sulphide deposits and undiscovered nickel endowment in 36 demonstrably mineralized komatiite bodies (Table 4.2) in the Kalgoorlie Terrane (section 2.1; Table 4.2) as follows. First, the plan view area of each of the 36 komatiite bodies was determined in a GIS environment to select komatiite bodies with areas that were within the range of the regression models (2.4-71.0 km^2). Four favourable komatiite bodies with one or more deposits, and 10 favourable komatiite bodies with one or more prospects were excluded from the estimations because they are smaller than 2.4 km^2 (Table 4.2; Appendix 4). The Scotia komatiite body (104.2 km^2) was too large to be assessed using the models (Table 4.2; Appendix 4).

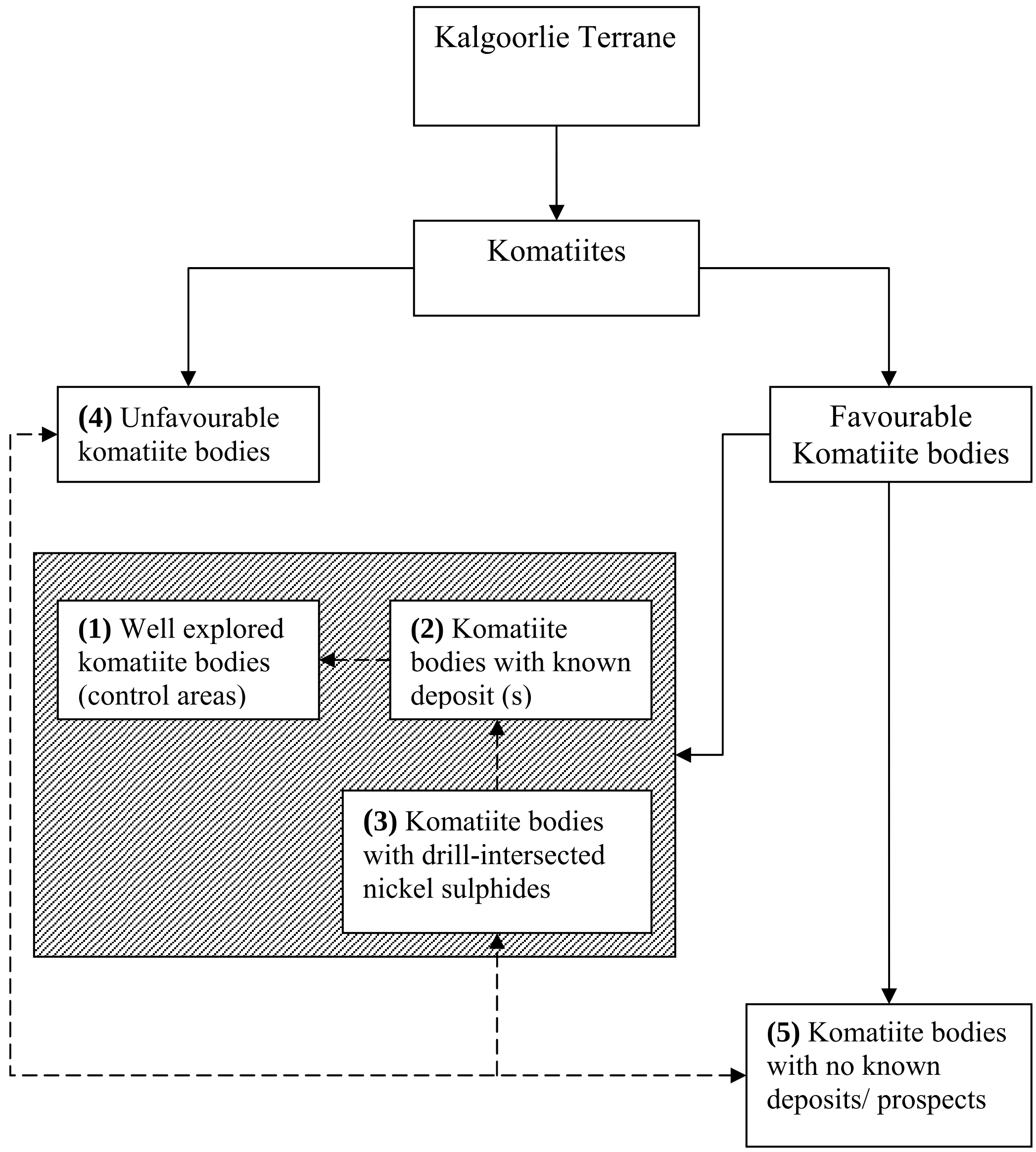

Fig. 4.12 Schematic illustration of the classification of komatiites adopted in resources assessments in this study. Numbers 1-5 are explained in the text. The shaded area encompasses demonstrably mineralized komatiites.

TABLE 4.2. List of demonstrably mineralised komatiite bodies selected for deposit and endowment density regression modelling in this chapter

Komatiite body					Nickel sulphide deposits		
Serial number	Name	Area (km^2)	Ref. Fig.	Contained nickel metal (kt)	Serial number	Deposit name	Contained nickel metal (kt)
Favourable komatiite bodies with at least one nickel sulphide deposit with published resources[1]							
1	Rocky's Reward (P)	0.01	4.14d	334.0	1	Rocky's Reward	334.0
2	Perseverance East (P)	0.01	4.14d		2	Perseverance East	
3	Harmony (P)	0.05	4.14d	74.0	3	Harmony	74.0
4	Melon-11 Mile Well (D)	0.33	4.14d	11.0	4	11 Mile Well	11.0
					5	Melon	
5	Mt. Jewel (P)	2.94	4.14l	1.7	6	Mt Jewel	1.7
					7	Ringlock	
6	Saints (P)	3.45	4.14l	5.0	8	St. Patrick's	5.0
					9	St. Andrew's	
7	Weebo (D)	3.75	4.14e	88.0	10	Weebo	88.0
8	Sinclair (P)	3.89	4.14e, f	47.3	11	Sinclair	47.3
					12	Skye	
9	Horn (P)	6.32	4.14e	8.3	13	Horn	8.3
					14	Roadside	
10	Cliffs (P)	7.21	4.14c	127.0	15	Cliffs	127.0
					16	Spinifex Park	
11	Nepean (P)	24.43	4.14m		17	Nepean	45.6
				45.6	18	Bouchers	
					19	Miriam	
12	Bluebush (P)	27.14	4.14o, p		20	Stockwell-Grimsby	20.8
				23.4	21	Cameron	2.6
					22	Lawry	
13	Scotia (P)	104.24	4.14l, n	37.2	23	Scotia	37.2
Favourable komatiite bodies for which drill-intersected nickel sulphides have been reported[1]							
14	Serp Hill (D)	0.13	4.14c		24	Serp Hill North	-
					25	Serp Hill South	-
15	Marshall (P)	0.42	4.14n		26	Marshall	-
16	Fly Bore (P)	0.66	4.14e		27	Fly bore	-
17	Mt. Newman (D)	1.03	4.14f		28	Mt Newman	-
18	Deep South	1.03	4.14e		29	Deep South	-

Notes

[1]Komatiitte bodies in each of the two groups are listed in ascending order of size (area in km^2).

TABLE 4.2 (continued) List of demonstrably mineralised komatiite bodies selected for deposit and endowment density regression modelling in this chapter

Komatiite body					Nickel sulphide deposits		
Serial number	Name	Area (km^2)	Map Ref.	Contained nickel metal (kt)	Serial number	Deposit name	Contained nickel metal (kt)
Favourable komatiite bodies for which drill-intersected nickel sulphides have been reported[1]							
19	Quinn Hills (P)	1.37	4.14h		30	Quinn Hills	334.0
20	Carthage (P)	1.56	4.14e		31	Carthage	
21	Sir Samuel (D)	1.58	4.14d		32	Sir Samuel	74.0
22	Schmitz Well (D)	1.98	4.14f		33	Schmitz Well	11.0
23	Riverina (P)	2.16	4.14j		34	Riverina	
24	Delphi (P)	2.67	4.14f		35	Delphi	1.7
25	Schmitz Well South (D)	3.35	4.14f		36	Schmitz Well South	
26	Jungle Jewel (P)	3.87	4.14e, f		37	Jungle Jewell	5.0
27	Antioch (P)	6.20	4.14f		38	Antioch	
28	Talbot Island (P)	8.59	4.14p		39	Talbot Island	88.0
29	Mt. Martin (P)	9.88	4.14n		40	Mt. Martin	47.3
30	Longbow (D)	11.51	4.14a		41	Longbow	
31	Golden Valley	13.30	4.14l, n		42	Golden Valley	8.3
32	Hayes (D)	14.14	4.14a		43	Hayes	
33	Amy Ricks (P)	14.66	4.14e		44	Amy Ricks	127.0
34	Antioch East (P)	21.48	4.14e, f		45	Antioch East	
35	Menzies (P)	40.02	4.14i		46	Menzies	45.6
36	Acacia Ridge (P)	59.76	4.14i		47	Acacia Ridge	

Notes

[1]Komatiitte bodies in each of the two groups are listed in ascending order of area (km^2).

The estimates of deposit and endowment densities were, respectively, based on the following equations (section 4.3; Mamuse et al., 2010b):

$$\text{Log}_{10}\text{ (deposit density)} = 0.46138\text{-}0.7254^{*}\ \text{Log}_{10}\text{ (area of komatiite body)} \qquad (4.3)$$

$$\text{Log}_{10}\text{ (endowment density)} = 2.5949\text{-}1.2048^{*}\ \text{log}_{10}\text{ (area of komatiite body)} \qquad (4.4)$$

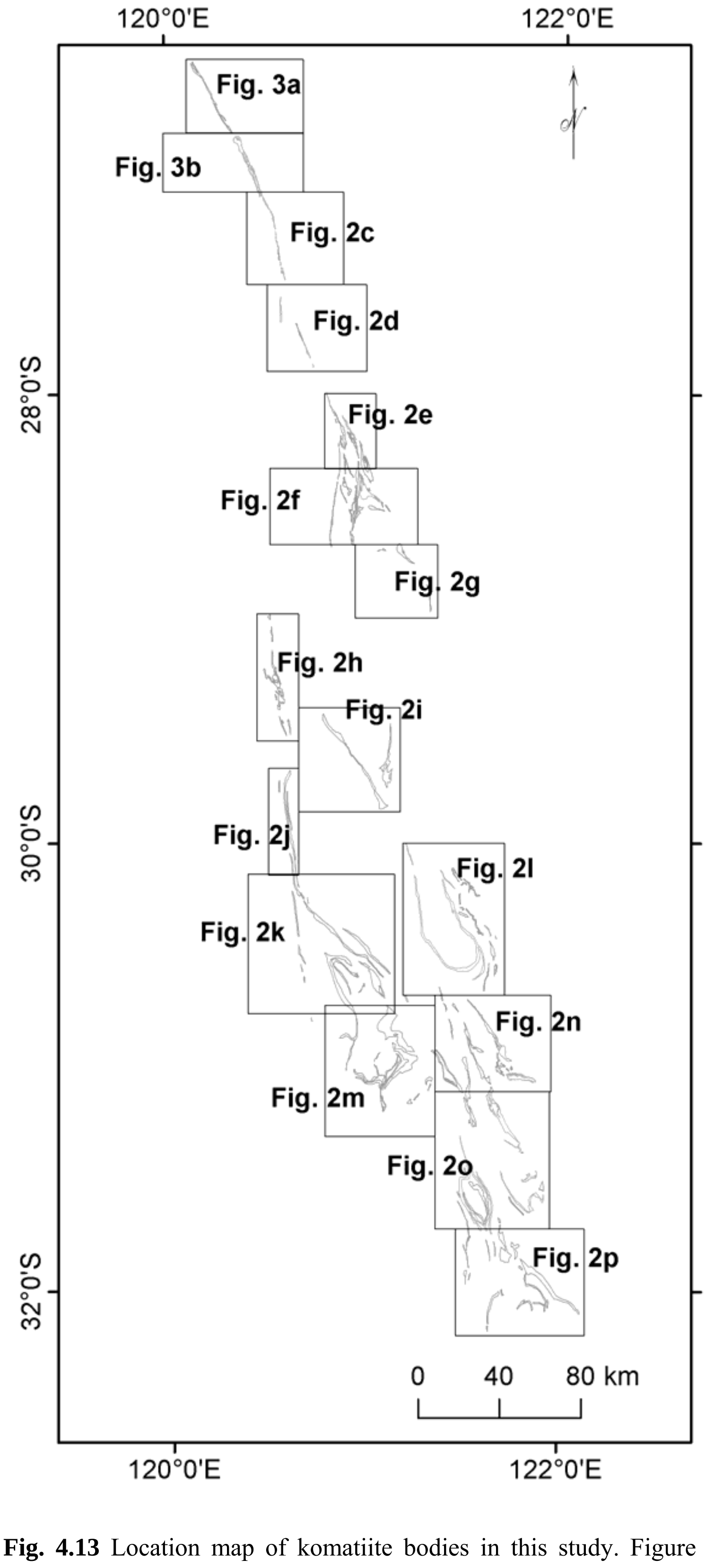

Fig. 4.13 Location map of komatiite bodies in this study. Figure numbers (Fig. 4.14a-4.14o) refer to enlargements shown in Figure 4.14.

Eq. 4.3 and Eq. 4.4 represent the mean of the regression estimates. Mamuse et al. (2010b) present equations for calculating confidence and prediction intervals about the mean regression estimates shown in Appendix 4. The confidence interval is the deposit or endowment density range with a specified probability of containing the true mean deposit or endowment density for komatiite bodies in the Kalgoorlie Terrane. The prediction interval is the deposit or endowment density range, at a specified probability, within which the deposit or endowment density for a komatiite body of a specified area will fall. The confidence (probability) level of 95% that was used in this study.

For komatiite bodies that contain some known deposits and nickel endowment, the number of undiscovered deposits is calculated as:

Undiscovered deposits = total deposit estimates – known number of deposits (4.5)

Undiscovered endowment = total endowment estimates – known endowment (4.6)

4.5.1 Cosmos and Kambalda komatiite bodies

Although Cosmos and Kambalda komatiite bodies were used as control areas by Mamuse et al. (2010b), their southern portions are not explored (Figs 4.14d; 4.14o; Appendix 4). Covered or unexplored parts of control areas are excluded in density estimates as they would inflate areas thereby affecting deposit and endowment densities (Singer et al., 2005; Singer and Menzie, 2008). Estimates of the number of nickel sulphide deposits and amount of nickel endowment for the covered or unexplored parts of Kambalda and Cosmos komatiites were calculated as described above for other komatiites.

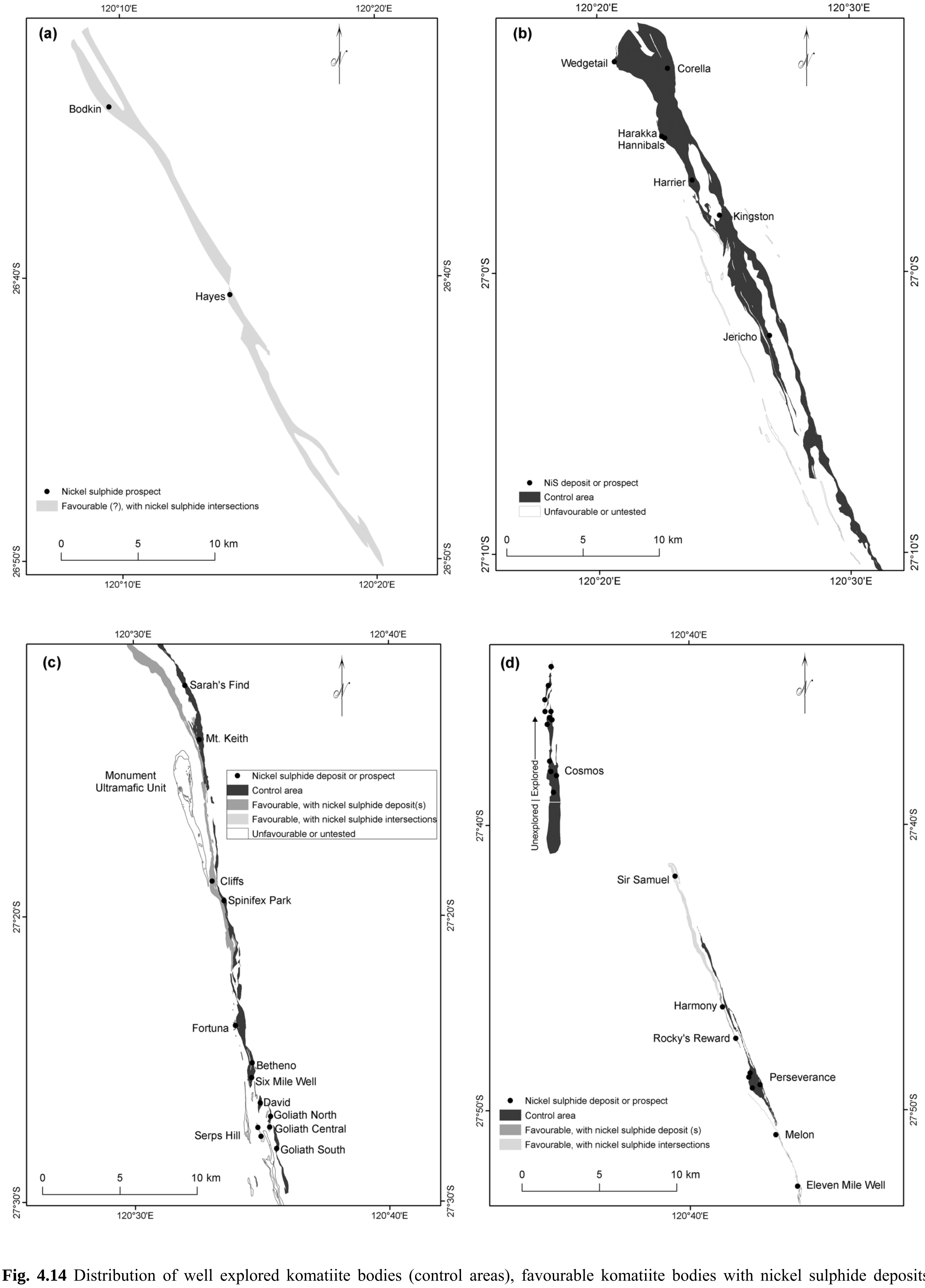

Fig. 4.14 Distribution of well explored komatiite bodies (control areas), favourable komatiite bodies with nickel sulphide deposits, favourable komatiite bodies with prospects and unfavourable/ untested komatiite bodies in the Kalgoorlie Terrane. The regional positions of the maps in are shown in Figure 4.13.

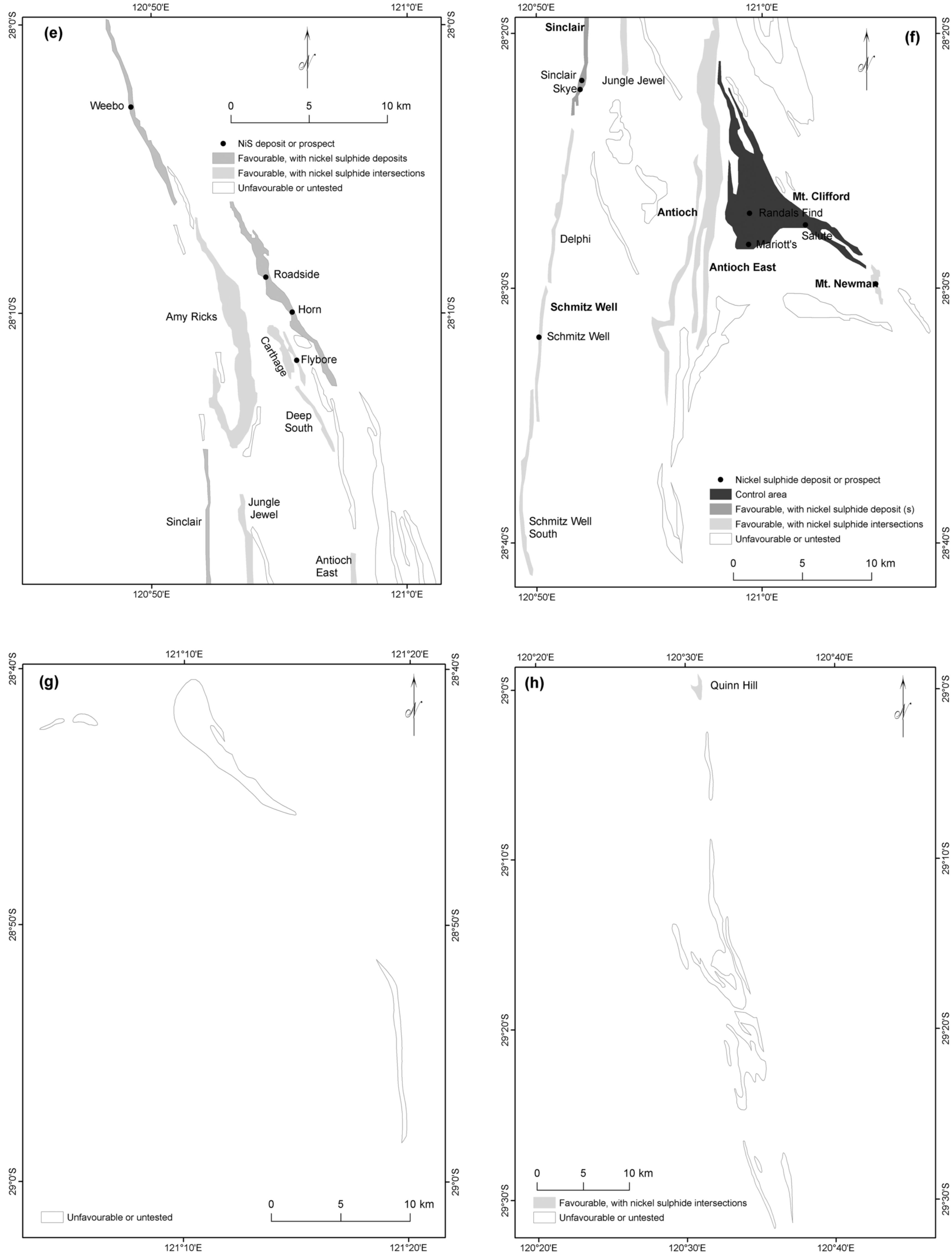

Fig. 4.14 (continued) Distribution of well explored komatiite bodies (control areas), favourable komatiite bodies with nickel sulphide deposits, favourable komatiite bodies with prospects and unfavourable/ untested komatiite bodies in the Kalgoorlie Terrane. The regional positions of the maps in are shown in Figure 4.13.

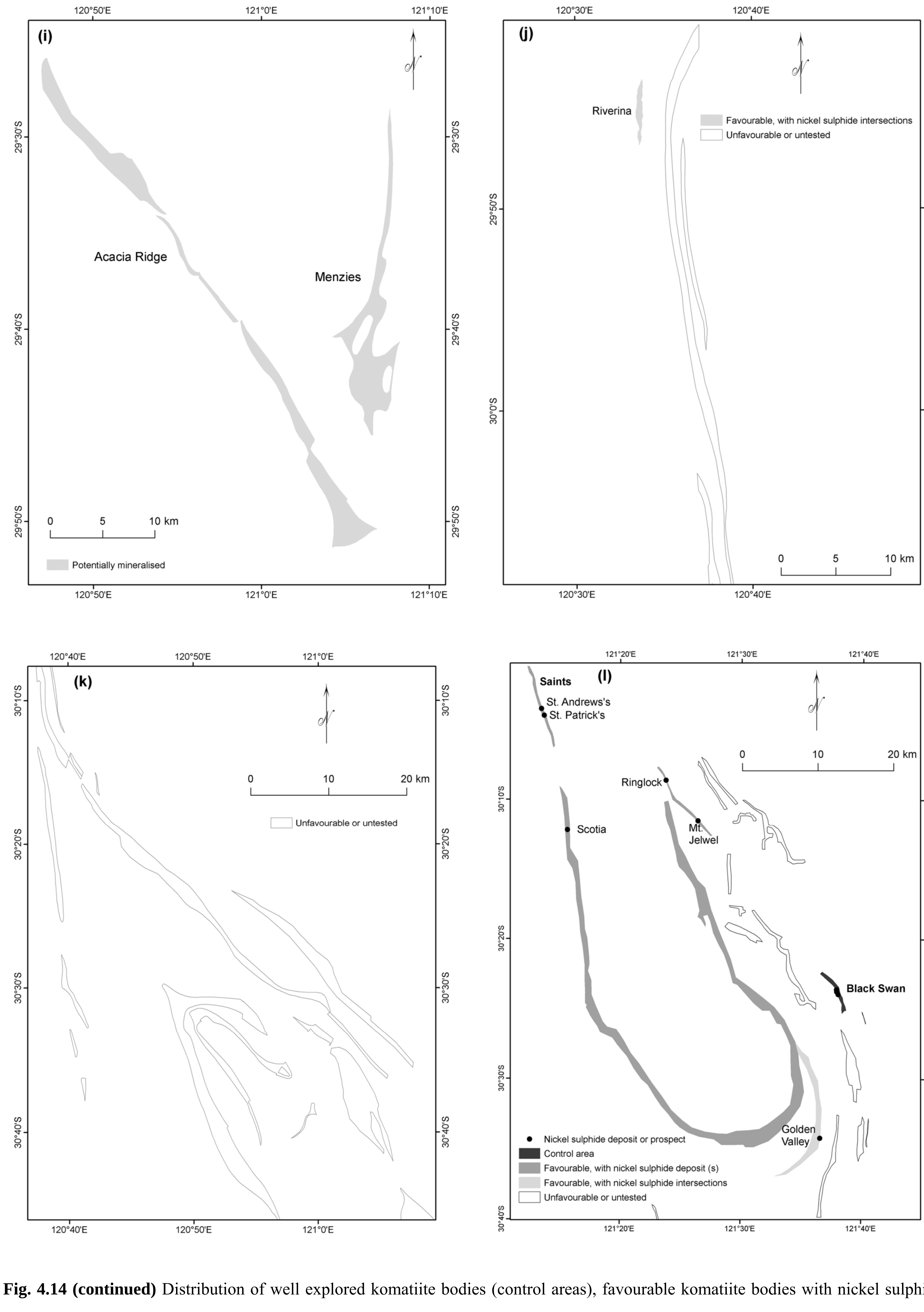

Fig. 4.14 (continued) Distribution of well explored komatiite bodies (control areas), favourable komatiite bodies with nickel sulphide deposits, favourable komatiite bodies with prospects and unfavourable/ untested komatiite bodies in the Kalgoorlie Terrane. The regional positions of the maps in are shown in Figure 4.13.

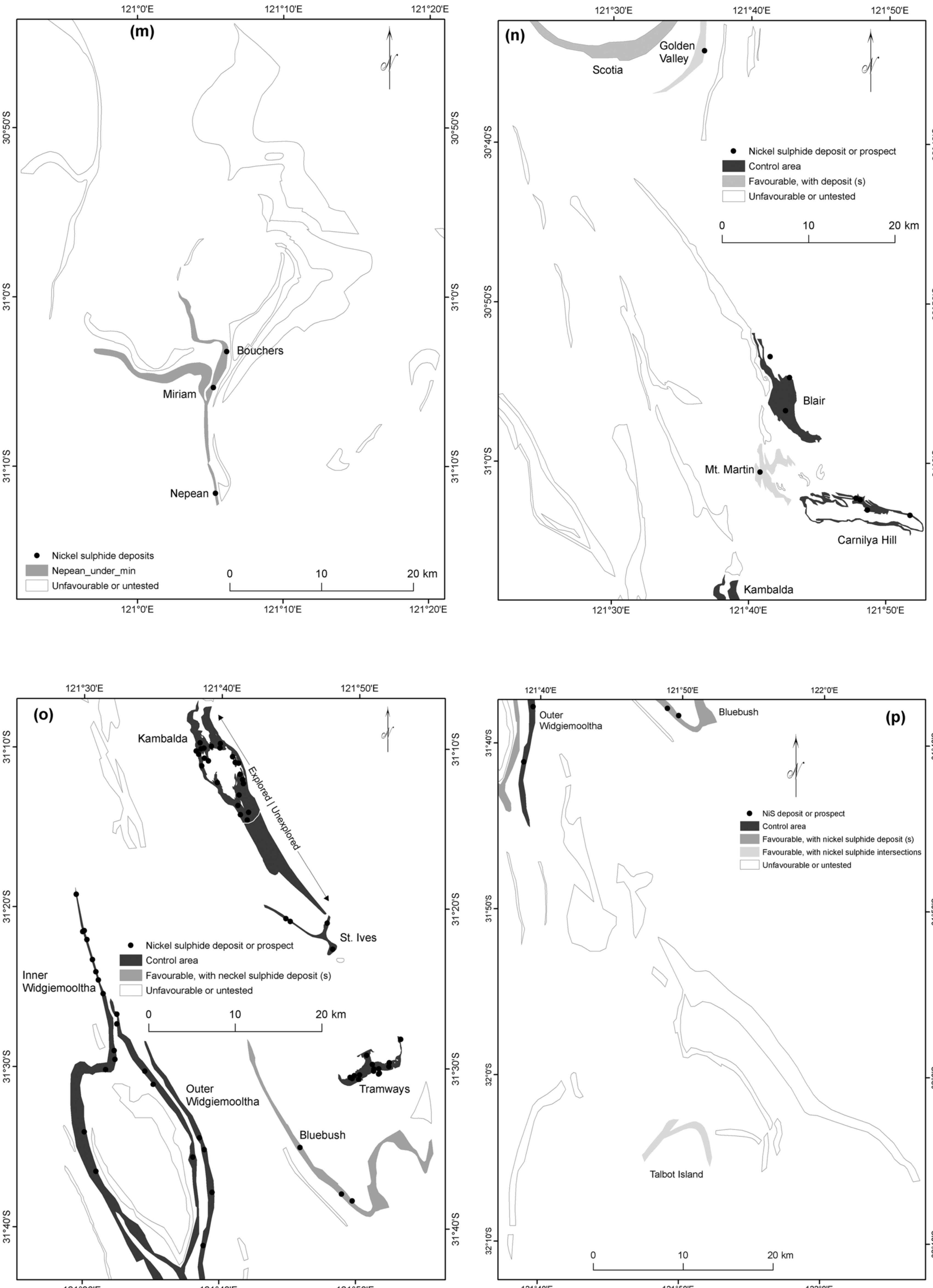

Fig. 4.14 (continued) Distribution of well explored komatiite bodies (control areas), favourable komatiite bodies with nickel sulphide deposits, favourable komatiite bodies with prospects and unfavourable/ untested komatiite bodies in the Kalgoorlie Terrane. The regional positions of the maps in are shown in Figure 4.13.

4.6 Nickel resources estimations using deposit and endowment density regression models

The raw estimates of mean number, as well as the confidence and prediction intervals of nickel sulphide deposits, and corresponding estimates of nickel endowment in the Kalgoorlie Terrane, are shown in Appendix 4. The number of undiscovered deposits and amount of undiscovered nickel metal, determined by subtracting the known values from the total estimates (Eqs. 4.5 and 4.6), are calculated in Tables 4.3 to 4.7, and summarized in Table 4.8. In the calculations, the term 'total deposit estimates' or 'total endowment estimates' in equations 4.5 and 4.6 is substituted with the mean regression estimates (Table 4.2), lower and upper confidence limits (Fig. 4.15; Tables 4.3 and 4.4), and lower and upper prediction interval limits (Fig. 4.15; Tables 4.5 and 4.6).

Table 4.8 summarises these regression estimates indicating that demonstrably mineralized komatiites in the Kalgoorlie Terrane may contain between 3.0-10.0 Mt (mean 5.5 Mt) undiscovered nickel metal in 59 – 210 (mean 114) undiscovered nickel sulphide deposits. Of the estimated undiscovered nickel endowment, 0.9-3.5 Mt (mean 1.8 Mt) is hosted by favourable komatiites with at least one known deposit, 1.1 – 5.6 Mt (mean 3.2 Mt) by favourable komatiites with prospects only and 0.33 – 0.96 Mt (mean 0.5 Mt) in southern extensions of Cosmos and Kambalda control area komatiite bodies (Fig 4.14; Tables 4.3 to 4.6; Appendix 4).

4.7 Estimating undiscovered nickel endowment in the Kalgoorlie Terrane using Zipf's Law

4.7.1 Background to Zipf's rank statistical analysis

Many natural systems (e.g. atmospheric, geological, ecological, and environmental) and socio-economic systems (e.g. economic, societal, and linguistics) generally distribute log-normally or abide by some form of power law (Koch 1966; Krige, 1966; Crow and Shimizu, 1988; Ott, 1978; Limpert et al., 2001). In particular, Zipf's law (Zipf, 1949) may be used to predict the natural mineral endowment of a geological terrane or oilfield based on the power law distributions of the sizes of mineral and petroleum accumulations of similar age and genetic origin.

TABLE 4.3 Mean regression estimates for the number of undiscovered nickel sulphide deposits and undiscovered nickel endowment for komatiite bodies in the Kalgoorlie Terrane

Komatiite body			Nickel sulphide deposits			Nickel metal endowment (kt)		
Name	Area (km^2)	Reference Figure	Known	Estimated	Undiscovered	Known	Estimated	Undiscovered
Favourable komatiite bodies containing at least one nickel sulphide deposit with published resources								
Mt. Jewel (P)	2.94	4.14l	1	4	3	2	316	314
Saints (P)	3.45	4.14l	2	4	2	5	305	300
Weebo (D)	3.75	4.14e	1	4	3	88	300	212
Sinclair (P)	3.89	4.14e, f	2	4	2	47	298	251
Horn (P)	6.32	4.14e	1	5	4	8	270	262
Cliffs (P)	7.21	4.14c	2	5	3	127	263	136
Nepean (P)	24.43	4.14m	1	7	6	46	205	159
Bluebush (P)	27.14	4.14o, p	3	7	4	37	200	163
Sub-total			*13*	*40*	*27*	*360*	*2,157*	*1,797*
Favourable komatiite bodies for which significant drill-intersected nickel sulphides have been reported								
Delphi (P)	2.67	4.14f	0	4	4	0	322	322
Schmitz Well S (P)	3.35	4.14f	0	4	4	0	307	307
Jungle Jewell (P)	3.87	4.14e, f	0	4	4	0	298	298
Antioch (P)	6.20	4.14f	0	5	5	0	271	271
Talbot Island (P)	8.59	4.14p	0	5	5	0	254	254
Mt. Martin (P)	9.88	4.14n	0	5	5	0	246	246
Longbow (D)	11.51	4.14a	0	6	6	0	239	239
Golden Valley (P)	13.30	4.14l, n	0	6	6	0	232	232
Hayes (D)	14.14	4.14a	0	6	6	0	229	229
Amy Ricks (P)	14.66	4.14e	0	6	6	0	227	227
Antioch East (P)	21.48	4.14e, f	0	7	7	0	210	210
Menzies (P)	40.02	4.14i	0	8	8	0	185	185
Acacia Ridge (P)	59.76	4.14i	0	9	9	0	171	171
Sub-total			*0*	*75*	*75*	*0*	*3,191*	*3,191*
Estimates for parts of komatiites under cover								
Kambalda (P)	21.68	4.14o, p	0	7	7	0	210	210
Cosmos (D)	2.53	4.14d	0	4	4	0	325	325
Sub-total			*0*	*11*	*11*	*0*	*535*	*535*
Total			**13**	**127**	**114**	**360**	**5,883**	**5,523**

The size (y) distribution of mineral deposits or deposit groups in a terrane can be generated by Zipf's law according to the formula:

$$y = cr^{-k} \tag{4.7}$$

where c is the size of the largest deposit or deposit group (rank 1), r the rank of a deposit or deposit group with size y, and k a constant that in geological systems is approximately equal to unity (Paliwal et al., 1986). In other words the product of the rank and the size of each mineral deposit or deposit group is approximately constant.

TABLE 4.4 Lower confidence interval limit estimates for the number of undiscovered nickel sulphide deposits and undiscovered nickel endowment for komatiite bodies in the Kalgoorlie Terrane

Komatiite body			Nickel sulphide deposits			Nickel metal endowment (kt)		
Name	Area (km^2)	Reference Figure	Known	Estimated	Undiscovered	Known	Estimated	Undiscovered
Favourable komatiite bodies containing at least one nickel sulphide deposit with published resources								
Mt. Jewel (P)	2.94	4.14l	1	3	2	2	247	245
Saints (P)	3.45	4.14l	2	3	1	5	243	238
Weebo (D)	3.75	4.14e	1	3	2	88	241	153
Sinclair (P)	3.89	4.14e, f	2	3	1	47	240	193
Horn (P)	6.32	4.14e	1	4	3	8	226	218
Cliffs (P)	7.21	4.14c	2	4	2	127	222	95
Nepean (P)	24.43	4.14m	1	6	5	46	171	125
Bluebush (P)	27.14	4.14o, p	3	6	3	37	166	129
Sub-total			*13*	*32*	*19*	*360*	*1754*	*1,394*
Favourable komatiite bodies for which significant drill-intersected nickel sulphides have been reported								
Delphi (P)	2.67	4.14f	0	4	4	0	249	249
Schmitz Well S (P)	3.35	4.14f	0	4	4	0	243	243
Jungle Jewell (P)	3.87	4.14e, f	0	4	4	0	240	240
Antioch (P)	6.20	4.14f	0	5	5	0	227	227
Talbot Island (P)	8.59	4.14p	0	5	5	0	216	216
Mt. Martin (P)	9.88	4.14n	0	5	5	0	211	211
Longbow (D)	11.51	4.14a	0	6	6	0	205	205
Golden Valley (P)	13.30	4.14l, n	0	4	4	0	199	199
Hayes (D)	14.14	4.14a	0	6	6	0	196	196
Amy Ricks (P)	14.66	4.14e	0	6	6	0	195	195
Antioch East (P)	21.48	4.14e, f	0	7	7	0	177	177
Menzies (P)	40.02	4.14i	0	8	8	0	148	148
Acacia Ridge (P)	59.76	4.14i	0	9	9	0	131	131
Sub-total			*0*	*73*	*73*	*0*	*2,636*	*2,636*
Estimates for parts of komatiites under cover								
Kambalda (P)	21.68	5.3o, p	0	6	6	0	177	177
Cosmos (D)	2.53	5.3d	0	3	3	0	250	250
Sub-total			*0*	*9*	*9*	*0*	*427*	*427*
Total			**13**	**114**	**101**	**360**	**4,817**	**4,457**

TABLE 4.5 Upper confidence interval limit estimates for the number of undiscovered nickel sulphide deposits and undiscovered nickel endowment for komatiite bodies in the Kalgoorlie Terrane

Komatiite body			Nickel sulphide deposits			Nickel metal endowment (kt)		
Name	Area (km^2)	Reference Figure	Known	Estimated	Undiscovered	Known	Estimated	Undiscovered
Favourable komatiite bodies containing at least one nickel sulphide deposit with published resources								
Mt. Jewel (P)	2.94	4.14l	1	5	4	2	404	402
Saints (P)	3.45	4.14l	2	5	3	5	384	379
Weebo (D)	3.75	4.14e	1	5	4	88	375	287
Sinclair (P)	3.89	4.14e, f	2	5	3	47	370	323
Horn (P)	6.32	4.14e	1	6	5	8	322	314
Cliffs (P)	7.21	4.14c	2	6	4	127	311	184
Nepean (P)	24.43	4.14m	1	8	7	46	245	199
Bluebush (P)	27.14	4.14o, p	3	9	6	37	242	205
Sub-total			*13*	*49*	*36*	*360*	*2,654*	*2,294*
Favourable komatiite bodies for which significant drill-intersected nickel sulphides have been reported								
Delphi (P)	2.67	4.14f	0	5	5	0	416	416
Schmitz Well S (P)	3.35	4.14f	0	5	5	0	388	388
Jungle Jewell (P)	3.87	4.14e, f	0	5	5	0	371	371
Antioch (P)	6.20	4.14f	0	6	6	0	324	324
Talbot Island (P)	8.59	4.14p	0	6	6	0	298	298
Mt. Martin (P)	9.88	4.14n	0	6	6	0	288	288
Longbow (D)	11.51	4.14a	0	7	7	0	278	278
Golden Valley (P)	13.30	4.14l, n	0	7	7	0	270	270
Hayes (D)	14.14	4.14a	0	7	7	0	267	267
Amy Ricks (P)	14.66	4.14e	0	7	7	0	266	266
Antioch East (P)	21.48	4.14e, f	0	8	8	0	250	250
Menzies (P)	40.02	4.14i	0	10	10	0	231	231
Acacia Ridge (P)	59.76	4.14i	0	12	12	0	222	222
Sub-total			*0*	*91*	*91*	*0*	*3,869*	*3,869*
Estimates for parts of komatiites under cover								
Kambalda (P)	21.68	4.14o, p	0	8	8	0	249	249
Cosmos (D)	2.53	4.14d	0	5	5	0	423	423
Sub-total			*0*	*13*	*13*	*0*	*672*	*672*
Total			**13**	**154**	**141**	**360**	**7,195**	**6,835**

Early proponents of the application of Zipf's law to petroleum and oil resources include Folinsbee (1977) and Rowlands and Sampey (1977). Subsequent studies by Schuenemeyer and Drew (1983), Paliwal et al. (1986), Blenkinsop (1995), Merriam et al. (2004), Fagan (2006), McCuaig and Guj (2006) and Guj et al. (2007) rekindled and reinforced the application of Zipf's law in mineral resource assessments. Although the study by Blenkinsop (1995) is presented in context of fractal geometry, it uses a power law similar to eq. 4.7 to estimate gold resources.

TABLE 4.6 Lower prediction interval limit estimates for the number of undiscovered nickel sulphide deposits and undiscovered nickel endowment for komatiite bodies in the Kalgoorlie Terrane

Komatiite body			Nickel sulphide deposits			Nickel metal endowment (kt)		
Name	Area (km^2)	Reference Map	Known	Estimated	Undiscovered	Known	Estimated	Undiscovered
Favourable komatiite bodies containing at least one nickel sulphide deposit with published resources								
Mt. Jewel (P)	2.94	4.14l	1	2	1	2	176	174
Saints (P)	3.45	4.14l	2	2	0	5	171	166
Weebo (D)	3.75	4.14e	1	2	1	88	169	81
Sinclair (P)	3.89	4.14e, f	2	2	0	47	168	121
Horn (P)	6.32	4.14e	1	3	2	8	154	146
Cliffs (P)	7.21	4.14c	2	3	1	127	150	23
Nepean (P)	24.43	4.14m	1	4	3	46	117	71
Bluebush (P)	27.14	4.14o, p	3	4	1	37	114	77
Sub-total			*13*	*23*	*10*	*360*	*1,218*	*858*
Favourable komatiite bodies for which significant drill-intersected nickel sulphides have been reported								
Delphi (P)	2.67	4.14f	0	2	2	0	178	178
Schmitz Well S (P)	3.35	4.14f	0	2	2	0	172	172
Jungle Jewell (P)	3.87	4.14e, f	0	2	2	0	168	168
Antioch (P)	6.20	4.14f	0	3	3	0	155	155
Talbot Island (P)	8.59	4.14p	0	3	3	0	145	145
Mt. Martin (P)	9.88	4.14n	0	3	3	0	141	141
Longbow (D)	11.51	4.14a	0	3	3	0	137	137
Golden Valley (P)	13.30	4.14l, n	0	3	3	0	133	133
Hayes (D)	14.14	4.14a	0	3	3	0	132	132
Amy Ricks (P)	14.66	4.14e	0	4	4	0	131	131
Antioch East (P)	21.48	4.14e, f	0	4	4	0	120	120
Menzies (P)	40.02	4.14i	0	5	5	0	104	104
Acacia Ridge (P)	59.76	4.14i	0	5	5	0	94	94
Sub-total			*0*	*43*	*43*	*0*	*1,811*	*1,811*
Estimates for parts of komatiites under cover								
Kambalda (P)	21.68	4.14o, p	0	4	4	0	210	210
Cosmos (D)	2.53	4.14d	0	2	2	0	120	120
Sub-total			*0*	*6*	*6*	*0*	*180*	*330*
Total			**13**	**72**	**59**	**360**	**3,208**	**2,999**

The known mineral deposits in a geological terrane may represent a sample of their true geologic and size distributions. The size distribution of all deposits constituting the natural endowment can be estimated from Zipf's law using this sample if the largest known deposit is also assumed to be the largest in the parent population comprising both known and unknown deposits. This assumption is consistent with the idea that the largest deposits, which tend to have the most obvious footprints, are generally likely to be discovered early in the exploration history of a terrane (Singer and Mosier, 1981; Chung et al., 1992; Hronsky and Schodde, 2006; Hronsky and Groves, 2008; Hronsky, 2009).

By applying Zipf law assuming *k* = 1 (Eq. 4.7), one can generate the theoretical size distribution of all the deposits or deposit groups constituting the original natural endowment, where the rank 2 deposit is 1/2 the size of the deposit or deposit group at rank 1, the rank 3 is 1/3 the size of the deposit at rank 1, and so on. Residual

TABLE 4.7 Upper prediction interval limit estimates for the number of undiscovered nickel sulphide deposits and undiscovered nickel endowment for komatiite bodies in the Kalgoorlie Terrane

Komatiite body			Nickel sulphide deposits			Nickel metal endowment (kt)		
Name	Area (km^2)	Reference Map	Known	Estimated	Undiscovered	Known	Estimated	Undiscovered
Favourable komatiite bodies containing at least one nickel sulphide deposit with published resources								
Mt. Jewel (P)	2.94	4.14l	1	7	6	2	567	565
Saints (P)	3.45	4.14l	2	7	5	5	545	540
Weebo (D)	3.75	4.14e	1	7	6	88	534	446
Sinclair (P)	3.89	4.14e, f	2	8	6	47	529	482
Horn (P)	6.32	4.14e	1	8	7	8	473	465
Cliffs (P)	7.21	4.14c	2	9	7	127	459	332
Nepean (P)	24.43	4.14m	1	12	11	46	359	313
Bluebush (P)	27.14	4.14o, p	3	13	10	37	352	315
Sub-total			*13*	*71*	*58*	*360*	*3,819*	*3,459*
Favourable komatiite bodies for which significant drill-intersected nickel sulphides have been reported								
Delphi (P)	2.67	4.14f	0	7	7	0	580	580
Schmitz Well S (P)	3.35	4.14f	0	7	7	0	549	549
Jungle Jewell (P)	3.87	4.14e, f	0	8	8	0	530	530
Antioch (P)	6.20	4.14f	0	8	8	0	475	475
Talbot Island (P)	8.59	4.14p	0	9	9	0	442	442
Mt. Martin (P)	9.88	4.14n	0	10	10	0	429	429
Longbow (D)	11.51	4.14a	0	10	10	0	415	415
Golden Valley (P)	13.30	4.14l, n	0	10	10	0	403	403
Hayes (D)	14.14	4.14a	0	11	11	0	398	398
Amy Ricks (P)	14.66	4.14e	0	11	11	0	396	396
Antioch East (P)	21.48	4.14e, f	0	12	12	0	368	368
Menzies (P)	40.02	4.14i	0	14	14	0	330	330
Acacia Ridge (P)	59.76	4.14i	0	16	16	0	309	309
Sub-total			*0*	*133*	*133*	*0*	*5,624*	*5,624*
Estimates for parts of komatiites under cover								
Kambalda (P)	21.68	4.14o, p	0	12	12	0	367	367
Cosmos (D)	2.53	4.14d	0	7	7	0	589	589
Sub-total			*0*	*19*	*19*	*0*	*956*	*956*
Total			**13**	**223**	**210**	**360**	**10,399**	**10,039**

TABLE 4.8. Summary of regression, confidence interval and prediction interval estimates of the number of undiscovered deposits and amount on undiscovered nickel endowment in selected komatiite bodies (Tables 4.2 to 4.8; Fig. 4.15; Appendix 4)

Estimator	Description	Reference	Estimates	
			No. of deposits	Nickel metal endowment (Mt)
Regression equation	Single summary mean value of the number of undiscovered deposits and endowment.	Eqs. 4.3 and 4.4; Fig. 4.15; Table 4.3	114	5.5
95 % confidence interval	Interval which has a 95% chance of containing the true mean values of the number of undiscovered nickel sulphide deposits and nickel endowment for the tabulated komatiite bodies (Tables 4.3-4.7)	Fig. 4.15; Table 4.4; Table 4.5	101 to 141	4.5 to 6.8
95 % prediction interval	The full interval (not the mean of the interval) or spread of the numbers of undiscovered deposits and amount of undiscovered nickel metal for the tabulated komatiite bodies (Tables 4.3 -4.7).	Fig. 4.15; Table 4.6; Table 4.7	59 to 210	3.0 to 10.0

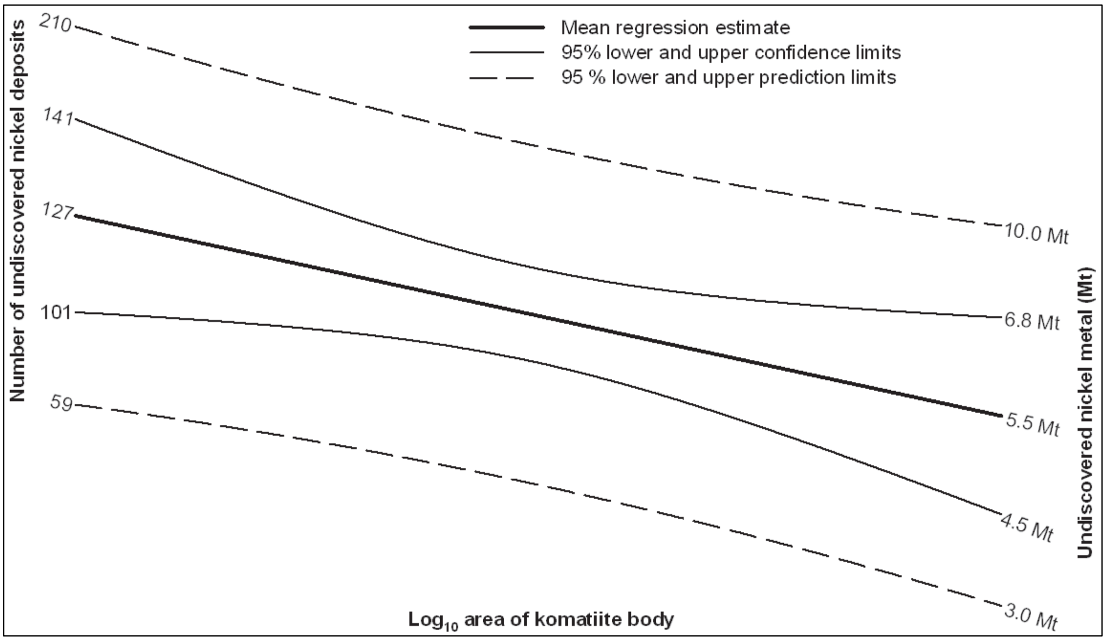

Fig. 4.15 Schematic representation of regression mean estimates, confidence interval estimates and prediction interval estimates of the numbers of undiscovered nickel sulphide deposits and nickel metal endowment in the Kalgoorlie Terrane. The vertical axes are logarithms of deposit and endowment densities on which values calculated using equations 4.3 and 4.4, respectively, are superposed as reflected by the axis labels.

endowment is a good indicator of the prospectivity or alternatively of the degree of exploration maturity of a terrane.

4.7.2 Deposits dataset used in Zipf's Law analysis in this study

The deposits dataset (Appendix 1, Table 4.9) consists of 95 individual nickel sulphide deposits in the Kalgoorlie Terrane that currently have, or historically have had, a quoted nickel resource. Like the datasets used for deposit and endowment density modelling above, Table 4.9 was extracted from Appendix 1. All individual deposits with a quoted resource were selected and grouped according to magma pathways as described in section 4.2.3. This procedure gave a total of 80 magma pathways, with a total known nickel endowment of 10.8 Mt nickel metal (Table 4.9).

The attribute of main interest in this study is the amount of contained nickel metal. For deposits not yet in production, the quantity of contained nickel indicated in Appendix 1 and Table 4.9 denotes the total pre-mining resource. For operating or closed mines, the contained nickel metal comprises cumulative production up to 31 December 2008 or up to closure, plus the total resources not yet mined at that date. The reported amount includes past production as well as measured, indicated and inferred resources.

4.7.3 Size of largest (rank 1) deposit in this study

If Zipf's law really holds, all that is required to estimate the endowment of a terrane is full delineation of the largest deposit in the terrane. But how can one be sure at the outset that the largest deposit has been discovered? A commonly applied principle is that the largest deposits generally discovered in the early stages of exploration history because they tend to have the largest foot-prints. Supposing that this is true, at what stage can one be satisfied that a deposit has been fully delineated or exhausted?

There are no easy answers to these questions but in principle, a deposit is fully delineated if it is 'reported in literature as well explored in three dimensions and not open in any part and to have published tonnages and grades' (Singer, 2010:7). The requirement of three dimensional closure is not always easily attainable.

TABLE 4.9 Known and Zipf's law-predicted nickel endowment in the Kalgoorlie Terrane

				Nickel metal endowment (kt)			
				Zipf's law-predicted estimates			
				Based on current[2] Mt. Keith size		Based on projected[3] Mt. Keith size	
Deposit Group[1]	Deposit Name	Rank	Known resources	Total estimate	Residual[4]	Total estimate	Residual[4]
Mt. Keith	Mt. Keith-MKD 5	1	2767.0	2767.0	0.0	4150.0	1383.0
Six Mile	Six Mile	2	1198.0	1383.5	185.5	2075.0	877.0
Perseverance	Perseverance	3	1055.0	922.3	-132.7	1383.3	328.3
Goliath North	Goliath North	4	458.0	691.8	233.8	1037.5	579.5
Otter Juan-Durkin	Durkin	5	440.4	553.4	113.0	830.0	389.6
Harrier	Harrier	6	379.3	461.2	81.9	691.7	312.4
Cosmos	Cosmos	7	351.5	395.3	43.7	592.9	241.3
Rocky's Reward	Rocky's Reward	8	334.0	345.9	11.9	518.8	184.8
Corella	Corella	9	322.9	307.4	-15.5	461.1	138.2
Black Swan	Black Swan	10	296.0	276.7	-19.3	415.0	119.0
Hannibals	Hannibals	11	290.0	251.5	-38.5	377.3	87.3
Wedgetail	Wedgetail	12	260.6	230.6	-30.0	345.8	85.3
Long	Long	13	241.4	212.8	-28.6	319.2	77.8
Jericho	Jericho	14	207.0	197.6	-9.4	296.4	89.4
Lunnon	East Alpha	15	186.2	184.5	-1.7	276.7	90.5
Cliffs	Cliffs	16	127.0	172.9	45.9	259.4	132.4
Anomaly 1	Anomaly 1	17	120.0	162.8	42.8	244.1	124.1
Helmut-Deacon	Deacon	18	106.2	153.7	47.5	230.6	124.4
Alec Mairs	Alec Mairs	19	88.6	145.6	57.0	218.4	129.8
Weebo	Weebo	20	88.0	138.4	50.4	207.5	119.5
Foster	Foster	21	86.9	131.8	44.8	197.6	110.7
Durkin North-Gibb-Victor	Durkin North	22	82.5	125.8	43.3	188.6	106.1
Prospero	Prospero	23	79.2	120.3	41.1	180.4	101.2
McMahon-Ken	Ken	24	75.0	115.3	40.3	172.9	97.9
Harmony	Harmony	25	74.0	110.7	36.7	166.0	92.0
Carnilya East	Carnilya East	26	65.3	106.4	41.1	159.6	94.3
Mariners	Mariners	27	58.9	102.5	43.6	153.7	94.8
Winner-Schmitz-Skinner	Schimitz	28	50.9	98.8	47.9	148.2	97.3
Jan	Jan	29	49.4	95.4	46.0	143.1	93.7
Lanfranchi	Lanfranchi	30	47.4	92.2	44.8	138.3	90.9

Notes

[1]Deposits are grouped by magma pathways as described in section 4.2.3.

[2]The currently known resources for the rank 1 deposit, Mt. Keith is 2,767 kt nickel metal

[3]The projected figure for the actual size of the rank 1 deposit, Mt. Keith is 4,150 kt nickel metal

[4]Residual nickel endowment is the difference between the Zipf's law estimate and the known nickel resources at each rank.

TABLE 4.9 (continued) Known and Zipf's law-predicted nickel endowment in the Kalgoorlie Terrane

				Nickel metal endowment (kt)			
				Zipf's law-predicted estimates			
				Based on current[2] Mt. Keith size		Based on projected[3] Mt. Keith size	
Deposit Group[1]	Deposit Name	Rank	Known resources	Total estimate	Residual[4]	Total estimate	Residual[4]
Sinclair	Sinclair	31	47.3	89.3	42.0	133.9	86.6
Nepaean	Nepean	32	45.6	86.5	40.9	129.7	84.1
Fisher	Fisher	33	43.8	83.8	40.1	125.8	82.0
Cygnet	Cygnet	34	40.0	81.4	41.4	122.1	82.1
Miitel	Miitel	35	39.9	79.1	39.2	118.6	78.7
Wannaway	Wannaway	36	38.9	76.9	37.9	115.3	76.3
Silver Swan	Siver Swan	37	38.0	74.8	36.8	112.2	74.2
Scotia	Scotia	38	37.2	72.8	35.6	109.2	72.0
Redross	Redross	39	37.0	70.9	33.9	106.4	69.4
Hunt	Hunt	40	33.0	69.2	36.2	103.8	70.8
Harakka	Harakka	41	29.6	67.5	37.9	101.2	71.6
Cruikshank	Cruikshank	42	28.4	65.9	37.5	98.8	70.4
26N-Mt Edwards	26N-Mt Edwards	43	26.0	64.3	38.4	96.5	70.5
Spargoville 5D	Spargoville 5D	44	23.8	62.9	39.1	94.3	70.5
Blair	Blair	45	22.0	61.5	39.5	92.2	70.2
Beta	Beta	46	22.0	60.2	38.2	90.2	68.2
Stockwell-Grimsby	Stockwell-Grimsby	47	20.8	58.9	38.1	88.3	67.5
John-McComish	John	48	18.6	57.6	39.1	86.5	67.9
Goodyear	Goodyear	49	16.0	56.5	40.5	84.7	68.7
Armstrong	Armstrong	50	12.0	55.3	43.3	83.0	71.0
Eleven Mile Well	11 Mile Well	51	11.0	54.3	43.3	81.4	70.4
McEwen-360N	McEwen-360N	52	11.0	53.2	42.2	79.8	68.8
Widgie 3	Widgie 3	53	10.5	52.2	41.7	78.3	67.8
Tapinos	Tapinos	54	10.5	51.2	40.7	76.9	66.4
Zabel-384N	Zabel-384N	55	10.5	50.3	39.8	75.5	65.0
Mariott's	Marriott's	56	9.4	49.4	40.0	74.1	64.7
Edwin	Edwin	57	9.0	48.5	39.5	72.8	63.8
132N	132N	58	8.4	47.7	39.3	71.6	63.2
Horn	Horn	59	8.3	46.9	38.6	70.3	62.0
Gordon-Wroth	Gordon	60	8.0	46.1	38.1	69.2	61.1

Notes

[1]Deposits are grouped by magma pathways as described in section 4.2.3.

[2]The currently known resources for the rank 1 deposit, Mt. Keith is 2,767 kt nickel metal

[3]The projected figure for the actual size of the rank 1 deposit, Mt. Keith is 4,150 kt nickel metal

[4]Residual nickel endowment is the difference between the Zipf's law estimate and the known nickel resources at each rank.

TABLE 4.9 (continued) Known and Zipf's law-predicted nickel endowment in the Kalgoorlie Terrane

				Nickel metal endowment (kt)			
				Zipf's law-predicted estimates			
				Based on current[2] Mt. Keith size		Based on projected[3] Mt. Keith size	
Deposit Group[1]	Deposit Name	Rank	Known resources	Total estimate	Residual[4]	Total estimate	Residual[4]
332N	332N	61	7.0	45.4	38.4	68.0	61.0
Dunlop	Dunlop	62	5.8	44.6	38.9	66.9	61.2
East Cooee	East Cooee	63	5.5	43.9	38.4	65.9	60.4
St. Patricks	St. Patrick's	64	5.0	43.2	38.2	64.8	59.8
Munda	Munda	65	5.0	42.6	37.6	63.8	58.8
Spargoville 2 or 5B	Spargoville 2 or 5B	66	4.9	41.9	37.1	62.9	58.0
Wannaway North	Wannaway North	67	4.3	41.3	37.0	61.9	57.7
14N	14N	68	3.0	40.7	37.7	61.0	58.0
Cameron	Cameron	69	2.6	40.1	37.5	60.1	57.5
Cooke-166N	Cooke-166N	70	2.5	39.5	37.0	59.3	56.8
NW Foster	NW Foster	71	2.4	39.0	36.5	58.5	56.0
Coronet-Loreto	Coronet	72	2.4	38.4	36.1	57.6	55.3
Dordie Rocks North	Dordie Rocks North	73	2.2	37.9	35.7	56.8	54.6
Martin	Martin	74	2.0	37.4	35.4	56.1	54.1
Zone 29	Zone 29	75	1.8	36.9	35.1	55.3	53.5
Mt. Jewel	Mt Jewel	76	1.7	36.4	34.7	54.6	52.9
Unmin 1	Unmin 1	77	1.4	35.9	34.6	53.9	52.5
Spagoville 5A	Spagoville 5A	78	1.1	35.5	34.4	53.2	52.1
Blair South	Blair South	79	1.0	35.0	34.0	52.5	51.5
Ham	Ham	80	0.8	34.6	33.7	51.9	51.0
Total			10,766	13,740	2,974	20,607	9,841

Notes

[1]Deposits are grouped by magma pathways as described in section 4.2.3.

2The currently known resources for the rank 1 deposit, Mt. Keith is 2,767 kt nickel metal

[3]The projected figure for the actual size of the rank 1 deposit, Mt. Keith is 4,150 kt nickel metal

[4] Residual nickel endowment is the difference between the Zipf's law estimate and the known nickel resources at each rank.

At present Mt. Keith, the rank 1 deposit in the Kalgoorlie Terrane has a defined resource of 2,767 kt nickel metal (Table 4.9) but it has often been speculated that the actual resource might be significantly larger than this. It is generally accepted that the deposit is yet to be fully delineated because the focus of exploratory drilling to date has been directed to prove up open-cuttable reserves to the exclusion of deeper resources. Following this line of thinking, Mamuse and Guj (submitted) estimated that the resources at Mt. Keith may currently be under-stated by at least half (Fig.

4.16), a proposition which has been corroborated by informal enquiries among industry experts who have intimate knowledge of the deposit. The final figure applied by Mamuse and Guj (submitted) is 4.15 Mt nickel metal for the Mt. Keith deposit (Fig. 4.16). In their study covering the evolution of the residual gold endowment of the Yilgarn Craton, Guj et al. (submitted), highlighted the significance of growth over time in resources in structurally complex deposit settings wherein deposits are difficult to fully delineate. They showed how growth in the size of the rank 1 deposit progressively lifts the entire Zipf curve increasing both the estimates of the original natural and of the residual endowments and as a consequence the size of undiscovered deposits.

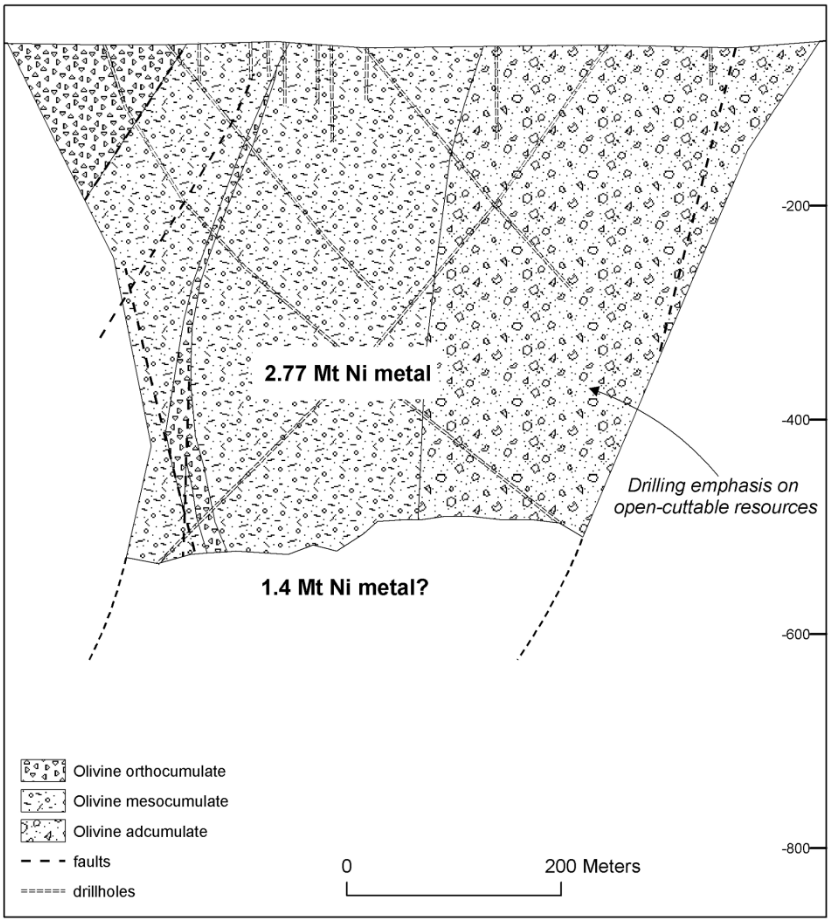

Fig. 4.16 Geological cross section through the Mt. Keith deposit indicating potential nickel sulphide resource continuation below current open cut depths. Modified from Hill et al. (1995).

4.7.4 Zipf law estimates of undiscovered nickel endowment in the Kalgoorlie Terrane

For interpreting the results from Zipf's law analysis, the term deposit should be understood in the context of deposit groupings (section 4.2.3; section 4.7.2). Deposits used in this study are listed in descending order of contained nickel metal in Table 4.9. Mt. Keith deposit (2,767 kt Ni) is at rank one and Ham deposit (0.8 kt Ni) is at rank 80, the lowest rank. The top 10 deposits contain 9.2 Mt of nickel metal or 86% of the total known nickel metal in the Kalgoorlie Terrane (10.8 Mt Ni metal), a testament to the highly skewed size distribution of the deposits (Fig. 4.17) wherein most metal is contained in a few large deposits.

For each rank in Table 4.9, three values of nickel endowment are listed, namely: (i) the known nickel endowment as stated above, (ii) the nickel endowment predicted from Zipf's law based on the current size of Mt. Keith deposit, and (iii) the nickel endowment predicted from Zipf's law based on the projected size of Mt. Keith deposit estimated as described in section 4.7.3. The size distribution of known nickel sulphide deposits more closely follows Zipf's law curve derived from the current size of Mt. Keith deposit than the curve based on the projected size of Mt. Keith deposit (Fig. 4.17). Nickel endowment estimated from the Zipf curve based on the projected size of Mt. Keith deposit are higher than the known endowment figures for all ranks. In contrast, deposit sizes estimated using the current size of Mt. Keith deposit are only consistently larger than known endowment from about rank 15 downwards.

For closer inspection, untransformed values for ranks 1 to 15 are plotted in Fig 4.18. The top 15 ranks, from Mt. Keith (2,767 kt Ni) to East Alpha (0.19 kt Ni), account for 82% (8.8 Mt nickel metal) of the known nickel resources in the Kalgoorlie Terrane.

The Zipf estimate residual (or undiscovered) endowment in the Kalgoorlie Terrane is simply the sum of the pair-wise differences between the Zipf-predicted and known values of contained nickel metal (Fig. 4.17; Table 4.9). The natural (or total) endowment predicted by Zipf analysis using the current size of Mt. Keith deposits is 13.74 Mt nickel metal. Subtracting the known10.77 Mt nickel metal from this figure gives 2.97 Mt in undiscovered nickel metal. Similarly, using the projected size of Mt.

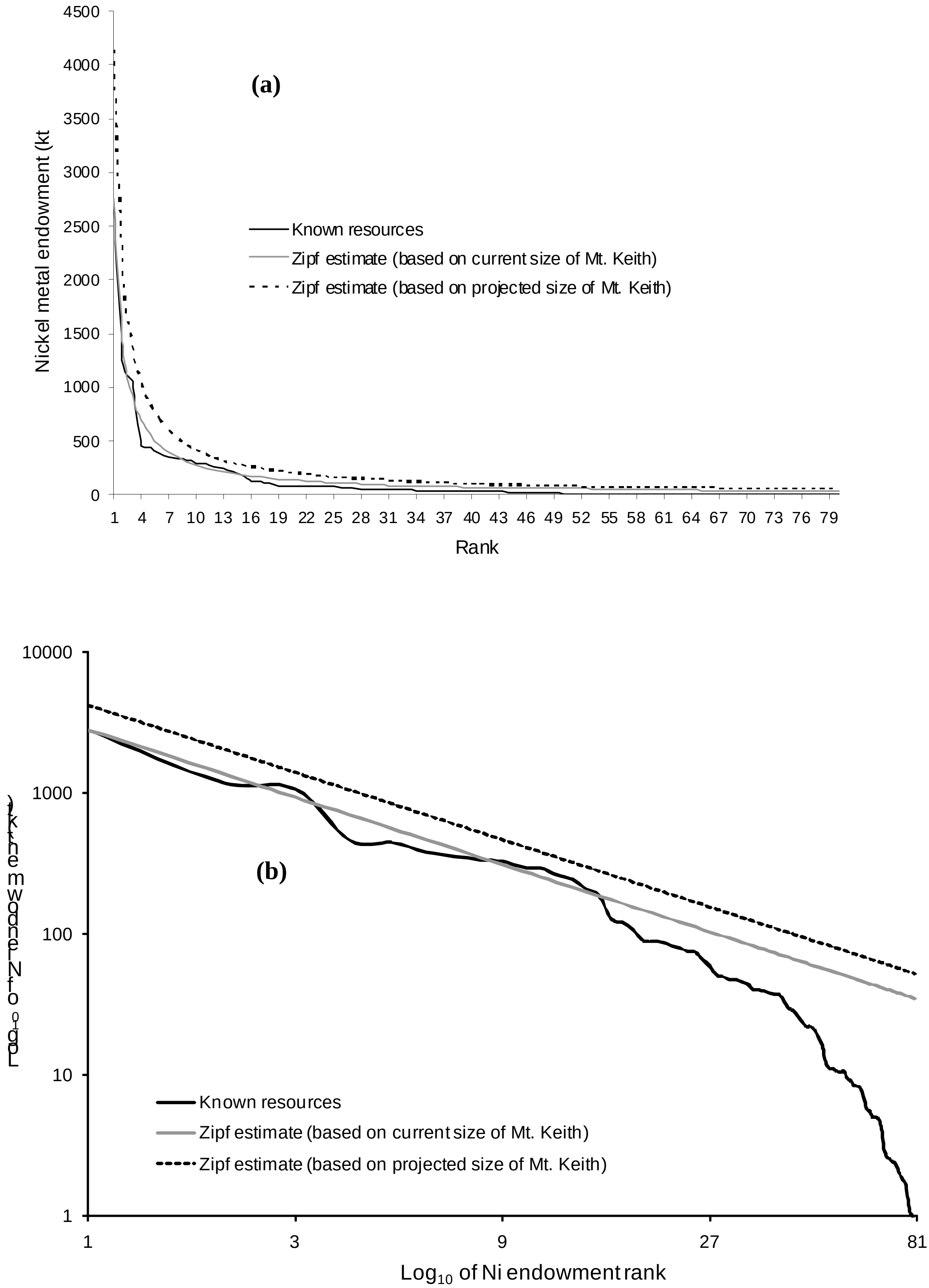

Fig. 4.17 Rank-wise comparison of known and Zipf-predicted nickel endowment (see section 4.7.3 for explanation of the projected size of Mt. Keith deposit), (a) plot of untransformed values, and (b) log-log plot.

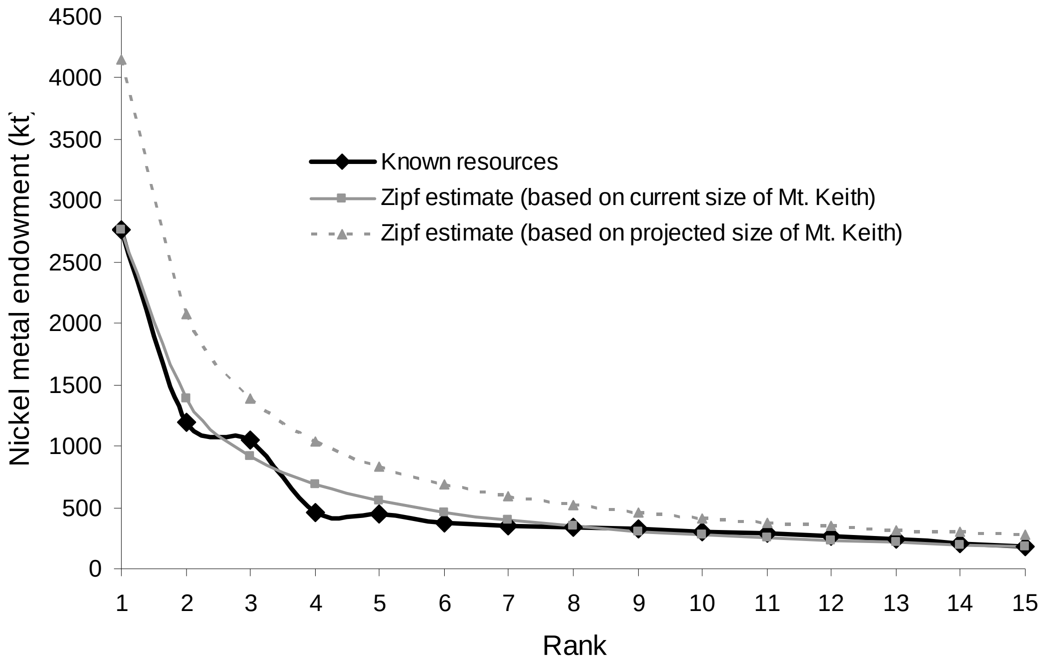

Fig. 4.18 Rank-wise comparison of known and Zipf-predicted nickel endowment for the top 15 ranks (see section 4.7.3 for explanation of the projected size of Mt. Keith deposit).

Keith, the undiscovered nickel metal endowment of 9.84 Mt nickel metal is obtained by subtracting the known endowment from the predicted 20.61 Mt nickel metal.

An indication of the distribution of the undiscovered nickel endowment across the ranks is depicted in Figure 4.19. For the Zipf analysis based on the current size of Mt Keith the bulk of the undiscovered endowment (88.7 %) is associated with ranks 16 to 80. For the analysis based on the projected size of Mt. Keith, ranks 16-80 account for only 49.4% (4.98 Mt nickel metal) of the undiscovered endowment.

In summary, it can be stated that using the lower (current size of Mt. Keith used) and upper (projected size of Mt. Keith used) bounds of the Zipf estimates, the Kalgoorlie Terrane may contain between 3.0 and 10.0 Mt in undiscovered nickel metal.

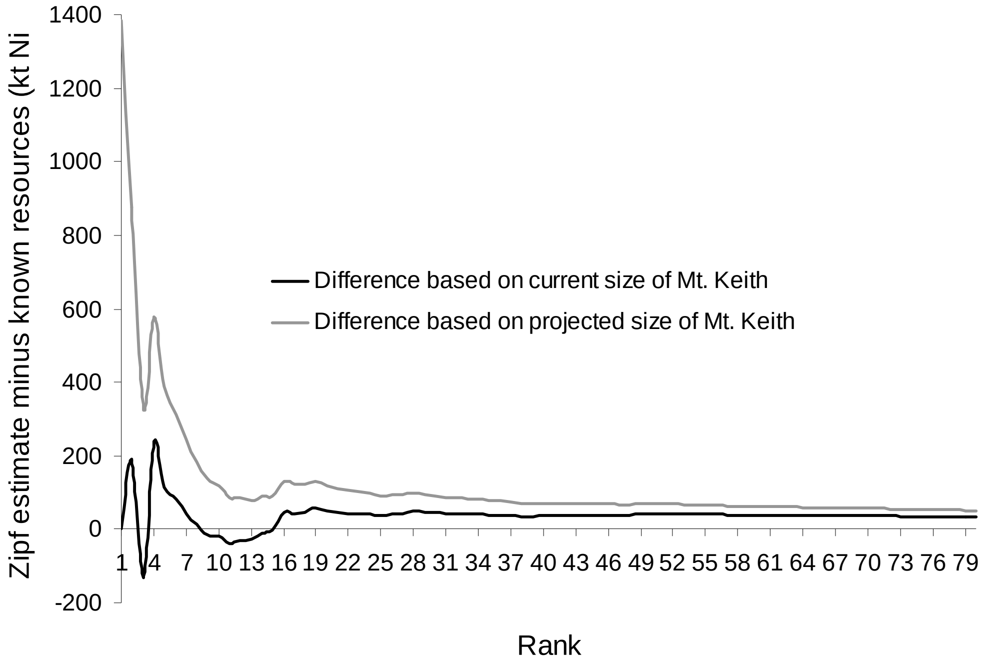

Fig. 4.19 Distribution of the pair-wise differences between the Zipf estimates and known nickel endowment for all ranks (see section 4.7.3 for explanation of the projected size of Mt. Keith deposit).

4.8 Discussion

This chapter complementarily uses two methods based on power law relationships that manifest at two different scales to estimate nickel sulphide resources in the Kalgoorlie Terrane, Western Australia. One method, regression analysis of deposit and endowment density on area of komatiite bodies, is reminiscent of the empirically well established power law relationship between mineral deposit density (number of deposits per km^2) and the size of the permissive tracts for particular deposit types (Singer, 1994, 2008, 2010; Singer et al., 2001; 2005; Mosier et al., 2007). This chapter shows that the similar power law relationships exist at the local scale as well, thus permitting estimation of nickel sulphide resources for individual komatiite bodies. However the local models are applied on demonstrably mineralised komatiite bodies only in order to avoid gross errors that may arise from applying the models to komatiites that may not contain any nickel mineralisation. In order to estimate undiscovered nickel endowment in komatiites that are not at present demonstrably mineralised Zipf's law, another power law, is used. According to Zipf's law, the size of the largest deposit is twice the size of the second, thrice the size of the third, four times the fourth, and so on. This chapter demonstrates use of this relationship to estimate the total undiscovered nickel endowment of the Kalgoorlie Terrane. The difference between the Zipf's law estimate and the regression estimate is interpreted to be indicative of the undiscovered nickel endowment outside demonstrably mineralised komatiite bodies in the Kalgoorlie Terrane.

In nature power law and lognormal relationships are thought to emanate fundamentally from the multiplicative physico-chemical processes at the atomic and molecular level on the earth's materials, which also control the formation and preservation of mineral deposits (Limpert et al., 2001; Singer, 2008). Existence of power laws at both the larger and smaller scales may indicate that mineralization and deposit preservation processes could be approximately self-replicating across scales.

4.8.1 Deposit and endowment density models

The coefficients of determination (R^2) for both the deposit density regression model (R^2 = 0.5997) and endowment density regression model (R^2 = 0.4053) are only moderate, indicating that the variations of nickel sulphide deposit and endowment densities are not entirely accounted for by the variation in area of komatiite bodies. This implies either that the variation in deposit and endowment densities is influenced by other explanatory variables apart from area, or that area does not fully capture the intrinsic explanatory variable or variables. For example komatiite bodies which host the nickel sulphide deposits are three-dimensional bodies and not two dimensional bodies, suggesting that volume may be the more appropriate explanatory variable than area. This resonates with genetic models of komatiite-associated nickel sulphide deposits which regard voluminous, channelized, thick and laterally persistent komatiites as marking the potential sites of maximum magma flux favourable to hosting this style of nickel mineralisation (Barnes, 2006a, b; Beresford et al., 2007; McCuaig et al., in press).

Other factors, such as the attitude of komatiite bodies, may also confound the variation of komatiite area with nickel deposit density or endowment density. For example, flat-lying komatiite bodies would tend to exhibit maximal surface areas and, consequently, minimal deposit and endowment densities. In contrast, steeply dipping komatiite bodies would tend to express minimal surface areas and maximal deposit and endowment densities. However as volumes of komatiites in the Kalgoorlie Terrane are neither readily available nor easily and reliably calculable, this study uses komatiitite area for density estimations. Although the power law relationships between komatiite area and deposit or endowment density are not very strong but only moderate, analysis of variance (Tables A2 and A3 in Appendix 3) shows that the power law relationship are statistically significant at the 5% level. This implies that the power law relationships are not due to chance and may, respectively, be validly used for estimating the number of nickel sulphide deposits and amount of nickel endowment within the Kalgoorlie Terrane. Therefore komatiite area may, after all, be a suitable proxy for komatiite volume in deposit and endowment density estimations.

The concept of mineral endowment density introduced in this study may be thought of as the nickel ‘grade’ of the host komatiite bodies. The definition of endowment density could be improved to depict, say, kt Ni/ km^3 of komatiite body, or kt Ni/ kt of komatiite body if the data are available. Although endowment density (R^2 =0.4053) exhibits a slightly lower coefficient of determination than deposit density (R^2 = 0.5997), endowment density is likely to be the more fundamental property of terranes than deposit density. Whereas deposit density is likely to be sensitive to changes in deposit numbers, say by alternative deposit grouping, endowment density is unlikely to be affected because it is based on cumulative endowment over all deposits. Thus although the deposit and endowment density models applied in this study suggest that 59 to 210 (mean 114) nickel sulphide deposits containing 3.0 to 10.0 (mean 5.5Mt) Mt nickel metal are yet to be discovered in demonstrably mineralized komatiite bodies in the Kalgoorlie Terrane (Appendix 4, Figs. 4.12, 4.14, 4.15; Tables 4.2 to 4.8), more emphasis is placed on the endowment estimates. However, it is likely that in the early stages of a terrane’s exploration history, endowment density may be less useful than deposit density because of the lag between deposit discovery and full resources delineation. For example within the Kambalda camp, delineation of the Otter Juan deposit, the first and largest producer in the camp, continues to date more than 40 years after its initial discovery. Another example is that of the Moran deposit which was discovered in 2008 south of the Long channel (Fig. 4.2a). Its maiden resource of 32.4 kt nickel metal was announced too late (Independence

Mining Group N.L., 2009) to be included in this study. Yet the deposit itself (as part of the Long channel) had, by default, been counted in advance.

Both deposit density and endowment density may be affected by complexities in delineation of komatiite bodies. For example although Honeymoon Well, Mt. Keith and Yakabindie are generally considered as separate areas, there is currently no sufficient mapped geological criterion that can be objectively used to demarcate the three areas. Therefore to minimise arbitrary subdivisions which can affect spatial analyses, the Honeymoon Well-Mt. Keith-Yakabindie area is considered as one control area in this study (Fig. 4.11b). In spatial statistics, the variation of statistical results purely as a consequence of changes in the aggregation or partitioning of spatial analysis units is termed the modifiable areal unit problem (MAUP) (Openshaw and Taylor, 1981; Openshaw, 1984; O'Sullivan and Unwin, 2003). In essence, the application of rules for deposit grouping in spatial analyses can be viewed as attempts to reduce effects of MAUP. Similarly, the use in this study of natural analysis units defined by komatiite bodies, as opposed to some arbitrarily defined units, may minimise the effects of MAUP.

A limitation of the endowment density models of Mamuse et al. (2010b) used in this study (section 4.3) is that the models can only be reliably applied to estimate nickel sulphide resources for komatiite bodies that are in the size range 2.4 to 71.0 km^2. Extrapolation, that is, regression estimation based on komatiite bodies whose sizes fall outside this range is risky and unreliable. Thus the estimates in this study exclude deposits and endowment in 14 under-size komatiite bodies and the oversize Scotia komatiite body (Table 4.2; Appendix 4). Another restriction as to which komatiite bodies could be assessed arose from confining the estimations to demonstrably mineralized komatiite bodies in order to minimize first order errors which arise if areas that are not really mineralized were included (Singer et al., 2005).

Although estimates can be made on komatiite bodies considered favourable to, but which currently contain no known nickel deposits or prospects, such estimates are highly uncertain because the komatiite bodies could either return significant nickel mineralization in future or they could, subject to intensive exploration, turn out to be unmineralised (Fig. 4.12). The presence of nickel sulphides in komatiite that are conceptually considered unfavourable for nickel mineralization suggests that the converse can also be true, that is, economic nickel mineralization can potentially occur in 'unfavourable' komatiite bodies. For example the Hayes and Longbow prospects which host drill intersected nickel sulphides are located in the Wiluna section of the Kalgoorlie Terrane dominated by conceptually unfavourable dunite sills (Barnes, 2004; Fiorentini et al., 2008). Thus although komatiites at Wiluna may appear to be volcanologically unfavourable to hosting nickel sulphide deposits, the presence of nickel-enriched magmatic sulphides indicates that nickel-sulphide deposit forming processes occurred, raising the possibility that nickel sulphide deposits remain to be discovered at Wiluna or that they were eroded (Barnes et al., 2004; Fiorentini et al., 2008). In general, there is room to update the estimates presented here, either upwards (if new komatiites turn out be mineralized) or downwards (if exhaustive exploration indicates that some komatiites in the present assessment are not significantly mineralized).

4.8.2 Zipf's law

Two key assumptions that underlie the application of Zipf's law in estimating undiscovered mineral resources are: (i) the size distribution of deposits within the terrane follows Zipf's law and, (ii) the size of the largest deposit is known within an acceptable degree of confidence. Under these assumptions, it is not a necessary condition that the currently known resources in the terrane follow Zipf's law; that would be the case only for a fully mature terrane. There are two aspects to knowing the size of the largest deposit: first, is the deposit designated as the largest really the largest in that terrane, and second, if it indeed is the largest deposit, has it been fully delineated yet?

If one was to assume that the Mt. Keith deposit has been fully delineated and contains about 2.77 Mt nickel metal (although there are indications that this may not be the case), only about 3.0 Mt nickel metal would remain to be discovered in the Kalgoorlie Terrane. In this case, there is a close fit between known endowment and Zipf-predicted endowment, especially for the top 15 ranks (Figs. 4.17; 4.18), possibly presaging the terrane's exploration maturity. However, the close fit can only be a definitive mark of maturity if the size distribution of the parent deposit population in the terrane actually obeys Zipf's law (i.e. if the first assumption above actually holds). The relatively more pronounced departure from the Zipf's law curve from rank 16 to rank 80 (Fig. 4.17) is associated with relatively insignificant residual nickel endowment estimates (Table 4.9), the largest (45.9 kt nickel metal) of which is smaller than the endowment for the smallest known rank (47.4 kt nickel metal)

If, as widely speculated, the actual size of the Mt. Keith deposit is about 4.15 Mt nickel metal, that is, about twice its currently known size, about 10.0 Mt nickel metal remain undiscovered in the Kalgoorlie Terrane. In this case the estimated Zipf curve lies consistently above the curve for known endowment (Fig. 4.17).

4.8.3 Synthesis

The endowment density regression estimates relate to demonstrably mineralized komatiites in the Kalgoorlie Terrane whereas Zipf's estimates pertain to the whole terrane. The regression analyses predict that there is a 95 % chance that the mean undiscovered nickel endowment in demonstrably mineralised komatiites in the terrane amounts to 3.0 Mt or more, a 5% chance that it is 10.0 Mt or more, and a 50% chance that it is 5.5 Mt or more. In addition to demonstrably mineralized komatiites, there are other komatiites in the Kalgoorlie Terrane for which no nickel mineralization has ever been reported (section 4.4). A comparison of the regression estimates (3.0 – 10.0 Mt nickel metal) with estimates from Zipf's law (3.0 or 10.0 Mt nickel metal) is indicative of the amount of undiscovered nickel endowment outside the demonstrably mineralised komatiite bodies in the Kalgoorlie Terrane. The implication is that there may not be significant nickel endowment in komatiites in the Kalgoorlie Terrane that are not presently demonstrably mineralized. In other words, most komatiites that contain deposits may have already been discovered. This supports the hypothesis of Hronsky and Schodde (2006) that if there are presently unknown mineralised komatiites in the Kalgoorlie Terrane, it is more likely that they are covered rather than exposed.

The speculation that the Kalgoorlie Terrane or parts of it might be approaching exploration maturity is not new, but that does not necessarily spell doom for nickel exploration. In 1998, a senior research geologist with Western Mining Corporation

(WMC), the company credited for modelling, discovering and developing nickel sulphide deposits at the Kambalda camp presented a paper (Stone, 1998) which embodied this speculation. According to Stone (1998), there was limited opportunity for discovering additional deposits containing greater than 100 kt nickel metal at or near the surface on the Kambalda Dome. He pointed out that this justified the shift in exploration focus to the search for deeper deposits lacking obvious surface footprints and suggested the use three dimensional data analyses to guide the process.

Essentially exploring deeper as advocated by Stone (1998) is one way of opening up a new exploration search space (Hronsky and Schodde, 2006; Hronsky, 2009). According to Hronsky and Schodde (2006:10), 'the next driver for creating a new parameter space in the Yilgarn might be associated with the development of innovative techniques that allow the explorer to "see" through deep cover'. Therefore designation of a terrane or camp as mature is relative to the extent to which the current search space has been explored and identification of a new search space can generate new targets leading to new discoveries that may be more significant than earlier ones (Hronsky, 2009). Projecting the size of Mt. Keith deposit to twice its current size (i.e. to 4.15 Mt nickel metal) based on deeper drilling beyond open-cuttable resources is probably an implicit assumption of a new exploration search space.

4.9 Conclusions

1. Endowment density regression modelling suggests that there is a 95 % chance that the undiscovered nickel endowment in less explored demonstrably mineralised komatiite bodies in the Kalgoorlie Terrane is 3.0 Mt or more. Zipf's law predicts that the total undiscovered nickel endowment for the entire terrane, based on the current size of Mt. Keith deposit, is about 3.0 Mt nickel metal. Collectively, these results suggest there is unlikely to be any significant undiscovered nickel endowment in known komatiite bodies in the Kalgoorlie Terrane that are not at present demonstrably mineralised.

2. If the projected size of Mt. Keith (4.15 Mt nickel metal) is applied, the Zipf's law estimate jumps to 10.0 Mt nickel metal. This can be explained in terms of a new exploration search space, wherein the Kalgoorlie Terrane is probably

approaching nickel exploration maturity within the current exploration search space embodied by the current size of Mt. Keith deposit. The undiscovered 3.0 Mt nickel metal in the initial search space plus 7.0 Mt nickel metal in the next search space make up the 10.0 Mt nickel metal predicted by projecting the size of the Mt. Keith deposit to 4.15 Mt nickel metal.

3. This chapter strongly supports the hypothesis of Hronsky and Schodde, (2006: 10): 'the only realistic opportunities for finding entire new belts (nickel mineralised komatiites) in the Yilgarn province are where such belts are largely covered'.

4. The methodology presented in this chapter is potentially applicable in other komatiite provinces that are relatively well-explored, such as those in Canada and Finland. Eventually the methods may become applicable komatiite provinces that are presently less-explored such as those in Southern Africa and Brazil when sufficient numbers of suitable control areas accrue with exploration maturity. Importantly, the methodology presented in this chapter can be extended to other syngenetic mineral systems (e.g. volcanogenic massive sulphide deposit systems), or to any other mineral system where a representative number of control areas can be defined.

References

Australian Mines Limited, 2007. Quarterly report on activities for the period ended 30th June 2007. Australian Mines Limited, Perth, 20 pp.

Ahrens, L.H., 1954. The log-normal distribution of the elements (A fundamental law of geochemistry and its subsidiary). Geochimica et Cosmochimica Acta 5, 49-73.

Barnes, S.J., 2006a. Komatiite-hosted nickel sulphide deposits: geology, geochemistry, and genesis, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, p. 51-97.

Barnes, S.J., 2006b. Komatiites: petrology, volcanology, metamorphism, and Geochemistry, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists, Special Publication 13, p. 13-49.

Barnes, S.J., Perring, C.S., 2006. Appendix. Summary of geological features of nickel sulphide deposits of the Yilgarn craton, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, p. 99-118.

Barnes, S.J., Lesher, C.M. and Keays, R.R., 1995. Geochemistry of mineralised and barren komatiites from the Perseverance Nickel Deposit, Western Australia. Lithos 34, 209-234.

Baddeley, A., 2008. Analysing spatial point patterns in R. Workshop Notes, version 3. Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, 199 pp. http://www.csiro.au/resources/pf16h.html (accessed August 14, 2009).

Beresford, S., During, P., Florentine, M., Rosengren, N., Bleaker, W., Barley, M., CASs, R., Tait, M., Wallace, H., 2004, The Structural and Stratigraphic Architecture of the Agnew/Wiluna Belt, WA, Project P710 Project Final Report. AMIRA International Limited (unpublished report), 511 pp.

Beresford, S.W., Fiorentini, M., Hronsky, J.M.A., Rosengren, N., Bertuch, D.I., Saleem, A., Cas, R.A.F., Stone, W.E., Duuring, P., Bekker, A., Barley, M., 2007. Komatiite-hosted Ni-Cu-(PGE) deposits: understanding deposit and camp footprints, in: Bierlein F.P. and Knox-Robinson C.M., (eds.), 2007. Proceedings of Geoconferences (WA) Inc. Kalgoorlie '07 Conference, 25-27 September 2007, Kalgoorlie, Western Australia. Geoscience Australia Record 2007/14, 249 pp.

Blenkinsop, T.G. 1995. Fractal measures for the size and spatial distributions of gold mines: economic applications, in: T.G. Blenkinsop and P.L. Tromp (Eds.), Sub-Saharan Economic Geology. Geological Society of Zimbabwe Special Publication 3, Balkema, Rotterdam, p.177-186.

Blenkinsop, T.G., 2004, Applications of fractal geometry to mineral exploration, in: Muhling, J., Goldfarb, R., Vielreicher, N., Bierlein, F., Stumpfl, E., Groves, D., Kenworthy, S. (Eds.), Predictive Mineral Discovery Under Cover, Extended Abstracts. SEG 2004 Conference, 27 September-1 October 2004 Perth, Western Australia, p. 158-161.

Blenkinsop, T.G., Sanderson, D.J., 1999. Are gold deposits in the crust fractals? A study of gold mines in the Zimbabwean craton, in: McCaffrey, K.J.W., Lonergan, L., Wilkinson, J.J. (Eds.), Fractures, Fluid Flow and Mineralization. Geological Society Special Publication 155, p. 141-151.

Bliss, J.D., Menzie, W.D., 1993. Spatial mineral-deposit models and the prediction of undiscovered mineral deposits, in: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), Mineral deposit modeling. Geological Association Canada Special Paper 40, p. 693-706.

Bliss, J.D., Menzie, W.D., Orris, G.J., Page, N.J., 1987. Mineral deposit density – a useful tool for mineral-resource assessment, in: Sachs, J.S. (Ed.), U.S. Geological Survey Research of Mineral Resources - 1987 Program and Abstracts, U.S. Geological Survey Circular 995, p. 6.

Bonham-Carter, G.F., 1994. Geographic Information Systems for geoscientists – modelling with GIS. Elsevier Science, New York, 398 pp.

Biondini, R. 1976. Cloud motion and rainfall statistics. Journal of Applied Meteorology 15, 205-224.

Cassidy, K.F., Champion, D.C., Krapez, B., Barley, M.E., Brown, S.J.A., Blewett, R.S., Groenewald, P.B., Tyler, I.M., 2006. A revised tectonic framework for the Yilgarn craton, Western Australia. Geological Survey of Western Australia, Record 2006/8, 8 pp.

Chung, C.F., Singer, D.A., and Menzie, W.D., 1992. Predicting sizes of undiscovered mineral deposits - an example using mercury deposits in California. Economic Geology 87, 1174-1179.

Cox, D., 1993. Estimation of undiscovered quantitative mineral resource assessments-Examples from Venezuela and Puerto Rico, Nonrenewable Resources 2, 82-91.

Cox, D.P., Singer, D.A., eds., 1986. Mineral deposit models. U.S. Geological Survey Bulletin 1693, 379 pp.

Cowden, A.C., Roberts, D.E., 1990. Komatiite-hosted nickel sulphide deposits, Kambalda, in: Hughes, F.E. (Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy: Melbourne, Monograph 14, p. 567-581.

Crow, E.L., Shimizu, K., 1988. Log-normal Distributions: Theory and Application. Dekker, New York.

Donaldson, M.J., Lesher, C.M., Groves, D.I., Gresham, J.J., 1986. Comparison of

Archaean dunites and komatiites associated with nickel mineralisation in Western Australia: implications for dunite genesis. Mineralium Deposita 21, 296–305.

Fagan, R.K., 2006. Modelling how much gold is left to be found in the Eastern Goldfields of W.A. Outcrop to orebody: innovative geoscience in exploration and mining, Abstract Volume. Kalgoorlie 2006 Conference, 30 April to 4 May 2006, Kalgoorlie. Australian Institute of Geoscientists Bulletin 44, 23-25.

Fiorentini, M.L., Beresford, S.W. and Barley, M.E., 2008. Ruthenium-chromium variation: a new lithogeochemical tool in the exploration for komatiite-hosted Ni-Cu-(PGE) deposits, Economic Geology 103, 431-477.

Folinsbee RE., 1977. World's view-from Alph to Zipf. Geological Society of America Bulletin 88, 897-907.

GSWA (Geological Survey of Western Australia), 2008. 1:500 000 Interpreted bedrock geology of Western Australia, 2008 update. http://mapserver.doir.wa.gov.au/datacentre/ (accessed on August 01, 2008).

Gresham, J.J., Loftus-Hills, G.D., 1981. The geology of the Kambalda nickel field, Western Australia: Economic Geology, 76, 1373-1416.

Groenewald, P.B., Riganti, A., 2004. East Yilgarn 1:100 000 Geological Information series-an explanatory note. Geological Survey of Western Australia Report 95, 58 pp.

Guj P., McCuaig, T.C., Garzon, R. 2007. Can the petroleum industry's probabilistic approach to targeting and resources definition be applied in predicting mineral discoveries?. Conference Proceedings, Mineral Exploration and Research: Digging Deeper. 9th Biennial SGA Meeting.

Guj, P., Fallon, M., McCuaig T.C., Fagan R., in review. A time-series audit of the Zipf's law as a measure of terrane endowment and maturity in mineral exploration. Economic Geology.

Hill, R.E.T., Gole, M.J., 1990. Nickel sulphide deposits of the Yilgarn Block, in: Hughes, F.E. (Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea, Australasian Institute of Mining and Metallurgy Monograph 14, p. 557-559.

Hill, R.E.T., Barnes S.J., Gole M.J., Dowling, S.E. 1990. Physical volcanology of komatiites. A field guide to the komatiites of the Norseman-Wiluna Greenstone Belt, Eastern Goldfields Province, Yilgarn Block, Western Australia, Excursion guide book no. 1. Geological Survey of Western Australia, 100 pp.

Hill, R.E.T., Barnes, S.J., Gole, M.J., Dowling, S.E., 1995. The volcanology of komatiites as deduced from field relationships in the Norseman-Wiluna greenstone belt, Western Australia. Lithos 34, 59-188.

Hill, R.E.T., Barnes, S.J., Dowling, S.E., Thordarson, T., 2004. Komatiites and nickel sulfide orebodies of the Black Swan area, Yilgarn Craton, Western Australia. 1: petrology and volcanology of host rocks. Mineralium Deposita 39, 684-706.

Hirano, S.S., Nordheim, E.V., Arny, D.C., Upper, C.D., 1982. Log-normal distribution of epiphytic bacterial populations on leaf surfaces. Applied and Environmental Microbiology 44, 695-700.

Hoatson, D.M., Jaireth, S., Jaques, A.L., 2006. Nickel sulphide deposits in Australia: characteristics, resources and potential. Ore Geology Reviews 29, 177-241.

Hronsky, J.M.A., 2004. The science of exploration targeting, in: Muhling, J., Goldfarb, R., Vielreicher, N., Bierlein, F., Stumpfl, E., Groves, D., Kenworthy, S. (Eds.), Predictive Mineral Discovery Under Cover, Extended

Abstracts. SEG 2004 Conference, 27 September-1 October 2004, Perth, Western Australia Perth, p. 129-133.

Hronsky, J.M.A., 2009. The exploration search space concept: key to a successful exploration strategy. CET Quarterly Newsletter 8, June 2009.

Hronsky, J.M.A., Groves, D.I., 2008. Science of targeting: definition, strategies, targeting and performance measurement, Australian Journal of Earth Sciences 55, 3-12.

Hronsky, J.M.A, and Schodde, R.C., 2006. Nickel exploration of the Yilgarn Craton: from the nickel boom to today, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists, Special Publication 13, 1-11.

Independence Group N.L., 2009. Growing a great company, Annual General Meeting, 25 November, 2009. http://www.independencegroup.com.au/IRM/content/investor/presentations.htm (accessed December, 18, 2009).

Jubilee Mines N.L., 2005. Quarterly report for the period ended June 30, 2005. Jubilee Mines N.L., Sydney, 13 pp.

Jubilee Mines N.L., 2007. Significant increase to Sinclair resource. Australian Stock Exchange (ASX) announcement, 24 September 2007. Jubilee Mines N.L., Sydney, 2 pp.

Keays, R.R., 1995. The role of komatiitic and picritic magmatism and S saturation in the formation of the ore deposits. Lithos 34, 1-18.

Koch, A.L., 1966. The logarithm in biology. I. Mechanisms generating the log-normal distribution exactly. Journal of Theoretical Biology 23, 276-290.

Krige, D.G., 1966. A study of gold and uranium distribution patterns in the

Klerksdorp Gold Field. Geoexploration 4, 43-53.

Lesher, C.M., Burnham, O.M., Keays, R.R., Barnes, S.J., Hulbert, L., 2001. Geochemical discrimination of barren and mineralized komatiites associated with magmatic Ni-Cu-(PGE) sulfide deposits. Canadian Mineralogist 39, 673-696.

Lesher, C.M., Keays, R.R., 2002. Komatiite-associated Ni-Cu- (PGE) deposits, in: Cabri, L.J. (Ed.), The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements. Canadian Institute of Mining Metallurgy and Petroleum Volume 54, p. 579-617.

Limpert, E., Abbt, M., Asper, R., Graber, W.K., Godet, F., Stahel, W.A., Windhab, E.J., 2000. Life is log normal: Keys and clues to understand patterns of multiplicative interactions from the disciplinary to the transdisciplinary level, in: Klein, J.T., Grossenbacher-Mansuy, W., Häberli, R., Scholz, R.W., Bill, A.,Welti., M. (Eds.), Transdisciplinarity: Joint Problem-Solving among Science, Technology and Society. Haffmans, Zurich, Switzerland, p. 20-24.

Limpert, E., Wener, A.S., Markus, A., 2001. Log-normal distributions across the sciences. Bioscience 51, 341-352.

Loper, J.E., Suslow, T.V., Schroth, M.N., 1984. Log-normal distribution of bacterial populations in the rhizosphere. Phytopathology 74, 1454-1460.

Magurran, A.E. 1988. Ecological Diversity and its Measurement. Croom Helm, London, 179 pp.

Malanca, A., Gaidolfi, L., Pessina, V., Dallara, G., 1996. Distribution of 226-Ra, 232-Th, and 40-K in soils of Rio Grande do Norte (Brazil). Journal of Environmental Radioactivity 30, 55–67.

Mamuse, A., Beresford, S., Porwal, A., and Kreuzer, O.P., 2010b. Assessment of undiscovered nickel sulphide resources, Kalgoorlie Terrane, Western Australia. Part 1. Deposit and endowment density models. Ore Geology Reviews 37, 141 – 157.

Mamuse, A., Porwal, A., Kreuzer, O., Beresford, S.W., 2010a. Spatial statistical analysis of the distribution of komatiite-hosted nickel sulfide deposits of the Kalgoorlie Terrane, Western Australia: clustered or not? Economic Geology 105, 129-142.

Marston, R.J., 1984. Nickel mineralization in Western Australia. Geological Survey of Western Australia Mineral Resources Bulletin 14, 271 pp.

Marston, R.J., Groves, D.I., Hudson, D.R., Ross, J.R., 1981. Nickel sulphide deposits in Western Australia: a review. Economic Geology 76, 330-1363.

McCuaig, T.C.M, Beresford, S.W., and Hronsky, J.M.A., 2010. Translating the mineral systems approach into an effective exploration targeting system. Ore Geology Reviews, in press, doi:10.1016/j.oregeorev.2010.05.008.

McCuaig, T.C., and Guj, P., 2006. Balancing risk and reward in the face of increasing global exploration maturity. Outcrop to orebody: innovative geoscience in exploration and mining, Abstract Volume. Kalgoorlie 2006 Conference, 30 April to 4 May 2006, Kalgoorlie. Australian Institute of Geoscientists Bulletin 44, 3-8.

Merriam, D.F., Drew, L. J., Schuenemeyer, J.H., 2004. Zipf's Law: a viable geological paradigm? Natural Resources Research 13, 265-271.

Mincor Resources NL, 2008. Annual Report 2008. http://mincor.ice4.interactiveinvestor.com.au/Mincor0802/Annual%20Report%202008/EN/body.aspx?z=1&p=-1&v=2&uid=# (accessed September 22, 2009)

Mincor Resources NL, 2007. Profits and growth in nickel, Diggers and Dealers, Kalgoorlie, August 2007. http://www.mincor.com.au/images/mincor-46--foubi.pdf (accessed August 13, 2009).

MINEDEX database. Western Australia Department of Mines and Petroleum http://mapserver.doir.wa.gov.au/meta/arcMetaPage.asp?Id=532 (accessed January 14, 2009).

MINMET database, Intierra Pty Ltd. http://www.intierra.com/ (accessed January 14, 2009).

Mosier, D.L., Singer, D.A., Berger, V.I., 2007. Volcanogenic massive sulfide deposit density. US Geological Survey Scientific Investigations Report 2007-5082, 21 p. http://pubs.usgs.gov/sir/2007/5082/ (accessed August 29, 2009).

Myers, J.S., Hickman, A.H., 1990. Pilbara and Yilgarn cratons- regional geology and Mineralisation, in: Hughes, F.E. (Ed.), Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 14, p. 129-133.

Naldrett, A.J., 2004. Magmatic Ore Deposits. Geology, Geochemistry and Exploration. Springer-Verlag, Berlin, 727 pp.

Nelson, D.R., 1998. Granite-greenstone crust formation on the Archaean earth - a consequence of two superimposed processes. Earth and Planetary Science Letters 158, 109-119.

Onley, P., Stephenson, W., Miller, A., Payne, P., Mappleson, D., Woodward, G., 2006. Lanfranchi Nickel Project, Western Australia. Technical Report, Golder Associates, Perth, 88 pp.

Openshaw, S. 1984. The modifiable areal unit problem. Concepts and Techniques in Modern Geography 38 Geo Books, Norwich, U.K., 41 pp.

Openshaw, S., Taylor, P.J. 1981. The modifiable areal unit problem, in: Wrigley, N., Bennett, R.J. (Eds.), Quantitative Geography: a British view. Routledge and Kegan Paul, London, p. 60-69.

O' Sullivan, D., Unwin, D.J. 2003. Geographic information analysis, John Wiley & Sons, New Jersey, 436 pp.

Ott, W.R., 1978. Environmental Indices. Ann Arbor (MI), Ann Arbor Science.

Paliwal, H.V., Bhatnagar, S.N., Haldar, S.K., 1986. Lead-zinc resource prediction in India: an application of Zipf's law. Mathematical Geology 18, 539-549.

Panoramic Resources Limited, undated. Geology. http://www.panoramicresources.com/go/operations/lanfranchi/geology (accessed September 22, 2009)

Panoramic Resources Limited, 2009. Site visit Review, 29 June 2009. http://www.panoramicresources.com/files/090625_Stonebridge.pdf (accessed September 22, 2009).

Quirk, D.G., Ruthrauff, R., 2006. Analysis of reserves discovered in petroleum exploration. Journal of Petroleum Geology, 29, 125 -146.

Razumovsky, N.K., 1940. Distribution of metal values in ore deposits. Comptes Rendus (Doklady) de l'Académie des Sciences de l'URSS 9, 814-816.

Reliance Mining Limited, 2004. Quarterly report for the period ended 31 March 2004. Reliance Mining Limited, Perth, 11 pp.

Reliance Mining Limited, 2005. Beta Hunt Project Update, Company Announcements, Australian Stock Exchange, 12 January 2005. Reliance Mining Limited, Perth, 3 pp.

Root, D.H., Menzie, W.D., Scott, W.A., 1992. Computer Monte Carlo simulation in quantitative resource estimation: Nonrenewable Resources 1, 125–138.

Rowlands. N.J., Sampey, D., 1977. Zipf's law-an aid to resource inventory prediction in partially explored areas. Mathematical Geology 9, 383-391.

Rosengren, N.M., Beresford, S.W., Grguric, B.A., Cas, R.A.F., 2005. An intrusive origin for the komatiitic dunite-hosted Mount Keith nickel sulfide deposit, Western Australia. Economic Geology 100, 149-156.

Schuenemeyer, J.H., Drew, L.J., 1983. A procedure to estimate the parent population of the size of oil and gas fields as revealed by a study of economic truncation. Mathematical Geology 15: 145-161.

Singer, D.A., 1993a. Basic concepts in three-part quantitative assessments of undiscovered mineral resources. Nonrenewable Resources 2, 69–81.

Singer, D.A., 1993b. Development of grade and tonnage models for different deposit Types, in: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), Mineral deposit modeling. Geological Association Canada Special Paper 40, p. 21-30.

Singer, D.A., 1994. Conditional estimates of the number of podiform chromite deposits. Nonrenewable Resources 3, 200–204.

Singer, D.A., 2008. Mineral deposit densities for estimating mineral resources. Mathematical Geosciences 40, 33-46.

Singer, D.A., 2010. Progress in integrated quantitative mineral resource assessments. Ore Geology Reviews, doi:10.1016/j.oregeorev.2010.02.001.

Singer, D.A., Menzie, W.D., 2008. Map scale effects on estimating the number of undiscovered mineral deposits. Natural Resources Research 17, 79-86.

Singer, D.A., Mosier, D.L. 1981. Review of regional mineral resource Assessment methods. Economic Geology 76, 1006-1015.

Singer D.A., Berger, V.I., Menzie, W.D., Berger, B.R., 2005. Porphyry copper density. Economic Geology 100, 491–514.

Singer, D.A., Menzie, W.D., Sutphin, D., Mosier, D.L., Bliss, J.D. 2001. Mineral deposit density - an update, in: Schulz, K.J. (Ed.), Contributions to global mineral resource assessment research. US Geological Survey Professional Paper 1640-A, A1–A13. (also available online at http://pubs.usgs.gov/prof/p1640a/)

Stone, W.E., Archibald, N.J., 2004. Structural controls on nickel sulphide oreshoots in Archaean komatiite, Kambalda, WA: the volcanic trough controversy revisited. Journal of Structural Geology 26, 1173–1194.

Stone, W.E., Rutter, J.B., Stone, M.S., Archibald, N.J., Ketelaar, P.B., 1998. Three-dimensional GIS and nickel exploration at Kambalda. Annual conference of the Australian academy of technological sciences. Proceedings of the 1998 symposium, Fremantle, pp. 97–111.

Sugihara, G. 1980. Minimal community structure: An explanation of species abundance patterns. American Naturalist 116, 770-786.

Sulway, R.M., Glacken, A.M., Earl, A. 2005. LionOre Mining International Ltd: Independent Technical Report, Black Swan Nickel Project 4966. Snowden, Perth, 57 pp.

Swager, C.P., 997. Tectonostratigraphy of late Archaean greenstone terranes in the southern Eastern Goldfields, Western Australia. Precambrian Research 83, 11-42.

Swager, C.P., Griffin, T.J., Witt, W.K., Wyche, S., Ahmat, A.L., Hunter, W.M., McGoldrick, P.J., 1995. Geology of the Archaean Kalgoorlie Terrane- an explanatory note, Geological Survey of Western Australia Report 48 (reprint of Record 1990/12), 26 pp.

Walpole, R.E., Myers, R.H., Myers, S.L., Ye, K., 2002. Probability and statistics for engineers and scientists, 7th edition. Prentice Hall, New Jersey, 730 pp.

Zipf, G.K., 1949. Human behaviour and the principle of least effort: an introduction to human ecology. Addison-Wesley, Reading, MA, 573 pp.

CHAPTER 5

SPATIAL CENTROGRAPHIC ANALYSIS OF NICKEL ENDOWMENT, KAMBALDA DOME, KALGOORLIE TERRANE

Spatial analyses in Chapter 3 indicate that nickel sulphide deposits within komatiite bodies in the Kalgoorlie Terrane are not clustered, yet chapter 4 emphasises that the aggregation of nickel endowment is the more fundamental property of a terrane compared to the aggregation of deposits. This raises the question of how to meaningfully analyse the spatial distribution of mineral endowment separately from that of deposits. This chapter, based on a paper (Mamuse et al.[1,2]., 2009) published in *Ore Geology Reviews* presents a method that may be applied to accomplish this.

Abstract

Mineral deposits are relatively small fortuitous expressions of a mineral system. Their spatial pattern over an area does not necessarily coincide with the spatial pattern of the area's mineral endowment. The distribution of mineral endowment over an area may be better represented by statistical slices estimated from several deposits. In this chapter, a spatio-statistical centrographic method for charactering the spatial pattern of mineral endowment is demonstrated using nickel sulphide deposits of the relatively well explored Kambalda Dome, Western Australia. In this method, the standard distance circle divides the cluster into a more endowed inner part and a less endowed peripheral part. The standard deviational ellipse, another centrographic object, depicts the preferred northwest–southeast trend of nickel orebodies at Kambalda. Weighted centrography shows that nickel endowment is greater in the eastern than western part of the cluster. The spatio-geometric interaction of the circle and ellipse splits the cluster into several partitions. The relative concentration of nickel orebodies or endowment within a partition in relation to their concentration within the entire cluster is termed 'capture efficiency'. Komatiite areal trace exhibits higher nickel orebody capture efficiency than spatio-geometric partitions; however, some spatio-geometric partitions exhibit nickel endowment capture efficiencies comparable to that of komatiite. Furthermore, nickel orebody and endowment capture efficiencies of komatiite are elevated only within the standard distance circle.

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[1]Mamuse, A., Porwal, A., Kreuzer, O.P., Beresford, S., 2009. A new method for centrographic analysis of mineral deposit clusters. Ore Geology Reviews 36, 293-305.

[2]The lead author (PhD candidate) contributed more than 90% of the origination, content and preparation of this chapter and the published paper.

These results suggest that at Kambalda, (i) the standard distance circle is a prime window for understanding the komatiite-hosted nickel system, and (ii) spatio-geometric partitions are plausible locales for spatial analysis of nickel orebodies and endowment. The proposed centrographic method is potentially useful in mineral resource estimations and mineral exploration targeting.

5.1 Introduction

Spatial analyses in Chapter 3 show that nickel sulphide deposits within komatiite bodies in the Kalgoorlie Terrane are not clustered. In particular, according to the spatial analyses, the spatial pattern of nickel sulphide deposits within the Kambalda Dome is not significantly different from a random distribution. Random distributions, characterised by a lack of data structure, present particular theoretical and practical challenges. To a spatial point pattern analyst, they mark a dead end because non-randomness is the minimal prerequisite for any serious attempt to model the pattern any further (Diggle, 1983). To a mineral explorationist they signal the onset of a changeover point from predictive exploration methods (based on presence of a non-random pattern) to direct detective methods because there is equal chance of finding a deposit on every unit area (Hronsky and Groves, 2008; Mamuse et al., 2010a; McCuaig et al., 2010). However, a pragmatic analyst should be able to see 'forests' (groups of deposits) made up of the randomly distributed 'trees' (individual mineral deposits) because a system is not simply the sum of its components (Knoring and Dech, 1993).

In order to characterise the spatial distribution of nickel sulphide endowment on the Kambalda Dome, this chapter applies the centrographic method described in detail by Mamuse et al. (2009). The method is based on simple geometric forms (circles and ellipses) and statistical measures such as mean and standard deviation. Standard distance deviation (also known as standard distance and analogous to standard deviation in classical statistics) (Furfey, 1927; Bachi, 1957), is a distance that is applied as the radius of a circle known as standard distance circle (SDC) centred at the spatial mean centre of the spatial point pattern. The SDC therefore represents the geographic spread of points about the mean centre of the point pattern. A related concept, standard deviational ellipse (SDE) (Lefever, 1926; Yuill, 1971; Ebdon, 1988; Levine, 2007) measures not only the dispersion of geographic points around the mean centre, but also their spatial trend.

Spatial centrographic measures have been applied in public health planning (Tanaka et al., 1981), crime analysis (Levine, 2007; Kent and Leitner, 2008), geography (Myint, 2008) seismology (Flinn, 1965; Evernden, 1969; Bratt and Bache, 1988), volcanology (Klausen, 2004) and structural geology (Bhattacharyya and Czeck, 2008). This chapter uses the SDC and SDE to characterize komatiite-hosted nickel sulphide deposits of the Kambalda camp within the Kalgoorlie Terrane, Western Australia. Through further geometric and empirical manipulations, spatio-geometric partitions from the SDC-SDE space are extracted and defined. Komatiites provide the benchmark for evaluating the effectiveness of these partitions as nickel deposit and endowment locales.

5.2 Methodology

5.2.1 Definition of the Kambalda camp

Although what is generally referred to as the Kambalda camp includes all deposits shown on Figure 4.8, this chapter is concerned with the portion of that camp defined by applying a statistically derived radial distance for grouping nickel sulphide deposits of the Kambalda Domain (see Chapter 2 for definition).The radial distance was obtained using $\hat{K}(r)$ function analysis, in its $\hat{L}(r)$ function transformation form. The $\hat{K}(r)$ and $\hat{L}(r)$ functions are described in Chapter 3, so here only the specific use of the $\hat{L}(r)$ function in deriving the radial distance is described. In Eq. 3.3 in Chapter 3, the $\hat{L}(r)$ function is expressed as:

$$\hat{L}(r) = \sqrt{\frac{\hat{K}(r)}{\pi}}. \qquad (5.1)$$

Alternatively, the $\hat{L}(r)$ function can be expressed as

$$\hat{L}(r) = \sqrt{\frac{\hat{K}(r)}{\pi}} - r. \qquad (5.2)$$

If simulations of the function in Eq. 5.2 are run as described in Chapter 3 and $\hat{L}(r)$ plotted against (r), the peak of the $\hat{L}(r)$ function (Fig. 5.1) provides an estimate of a suitable radial deposit grouping distance (Hwang, 1999; Goreaud, 2000; ESRI, 2009; Marcon and Puech, 2009) which, in this case, is about 5 km. A nearest neighbour routine accessed from the software Crimestat (Levine, 2007) was applied to group the deposits that are closer than 5 km to one or more other deposits in the Kambalda Domain.

The purpose of the above exercise was to extract a spatially well defined group of deposits to best illustrate centrographic concepts. Accordingly, the Kambalda group used in this analysis (Fig. 5.2) excludes the Alpha and Beta deposits in the southern extremity of the camp, to the east of a major N-S trending fault (Fig. 4.8; Fig. 5.2). The group used here consists of 22 known nickel sulphide deposits (Appendix 1). The dataset utilized in this study was compiled from MINEDEX database (Western Australia Department of Mines and Petroleum), MINMET database (Intierra Pty. Ltd.) and company reports (technical and stock exchange reports).

Each of the 22 deposits comprises one or more nickel sulphide orebodies. The nickel sulphide orebodies are commonly termed ore shoots and consist of ore surfaces or subshoots (Woolrich et al., 1981). Some ore shoots are subdivided into sections, which are arbitrarily defined groups of ore surfaces. For purposes of this study, an orebody is defined as a mappable discrete (in plan projection) nickel sulphide ore entity (Fig. 5.2). Thus in the present usage, the term orebody includes ore shoots (e.g., Lunnon shoot), ore surfaces (e.g. Fisher ore surfaces) or sections (e.g. Juan West section) (Fig. 5.2). Fisher and Otter-Juan deposits, which are structurally and spatially complex orebodies (Fig. 5.2), are termed complexes (Marston, 1984). The orebodies (Fig. 5.2) are depicted as polygons rather than points because the mapping scale is fairly detailed, but for centrographic analysis, the centroids of the orebodies are used.

5.2.2 Defining the association of komatiites with Kambalda nickel sulphide deposits

All nickel sulphide deposits in the Kalgoorlie Terrane, including the Kambalda camp, are genetically associated with komatiites. Although the term komatiite-hosted nickel sulphide deposits is often used synonymously with the term komatiite-associated nickel sulphide deposits, distinguishing the two adds to clarity in centrographic analyses proposed here. Komatiite-hosted nickel sulphide deposits may be thought of as that subset of komatiite-associated nickel sulphide deposits that is fully contained within mapped komatiites. Komatiite-associated nickel sulphide deposits additionally include those deposits that are genetically related to, but apparently not contained within komatiites (see Chapter 1, section 1.2). For example, Coronet deposit and Banana-Juan Horst orebody (the southernmost orebody on the Otter-Juan complex) (Fig. 5.2) do not lie within the komatiite polygon due to tectonic remobilization or concealment (Gresham and Loftus-Hills, 1981; Marston, 1984; Beresford et al., 2005). However as most nickel sulphide deposits in the Kambalda camp are fully contained within mapped komatiites, komatiites constitute a reliable geological benchmark for evaluating the results of centrographic analysis proposed in this study. Conversely, centrographic analysis confined to the komatiite areal trace may aid in assessing the variability of nickel sulphide mineralization intensity within komatiites.

5.2.3 Centrography concepts and calculations

Centrographic analysis of a mineral deposit group involves fitting the standard distance circle (SDC) and standard deviational ellipse (SDE) about the spatial mean centre of the group using appropriate statistical formulations, as explained below.

Each mineral deposit in a group has a geographic location defined by the *x*-coordinate and *y*-coordinate, (X, Y). The location of the mean centre of the deposit group is given by $(\overline{X}, \overline{Y})$, the average of the *x*-coordinates and *y*-coordinates of all the deposits in the group. Standard distance (also known as standard distance deviation), S_{xy}, is the standard deviation of the distance of each deposit from the mean centre of the group. It is calculated as (Mitchell, 2005; Levine, 2007):

$$S_{XY} = \sqrt{\sum_{i=1}^{N} \frac{(d_{iMC})^2}{N-2}} \tag{5.3}$$

where d_{iMC} is the distance between each deposit, i, and the mean centre of the group, MC, and N is the total number of deposits within the group. The standard distance can be graphically represented by a standard distance circle (SDC), a circle of radius equal to the standard distance. The greater the standard distance deviation, the wider the spread of deposits within the group.

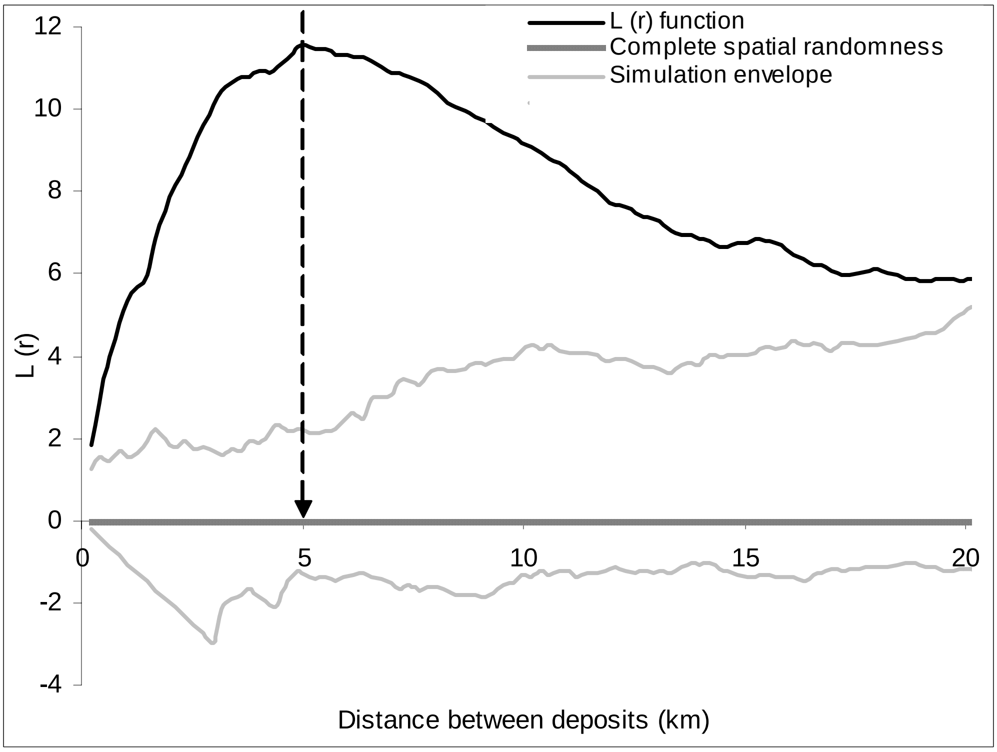


Fig. 5.1 Use of *L (r)* function in the determination of the radial distance used for defining the Kambalda deposit group

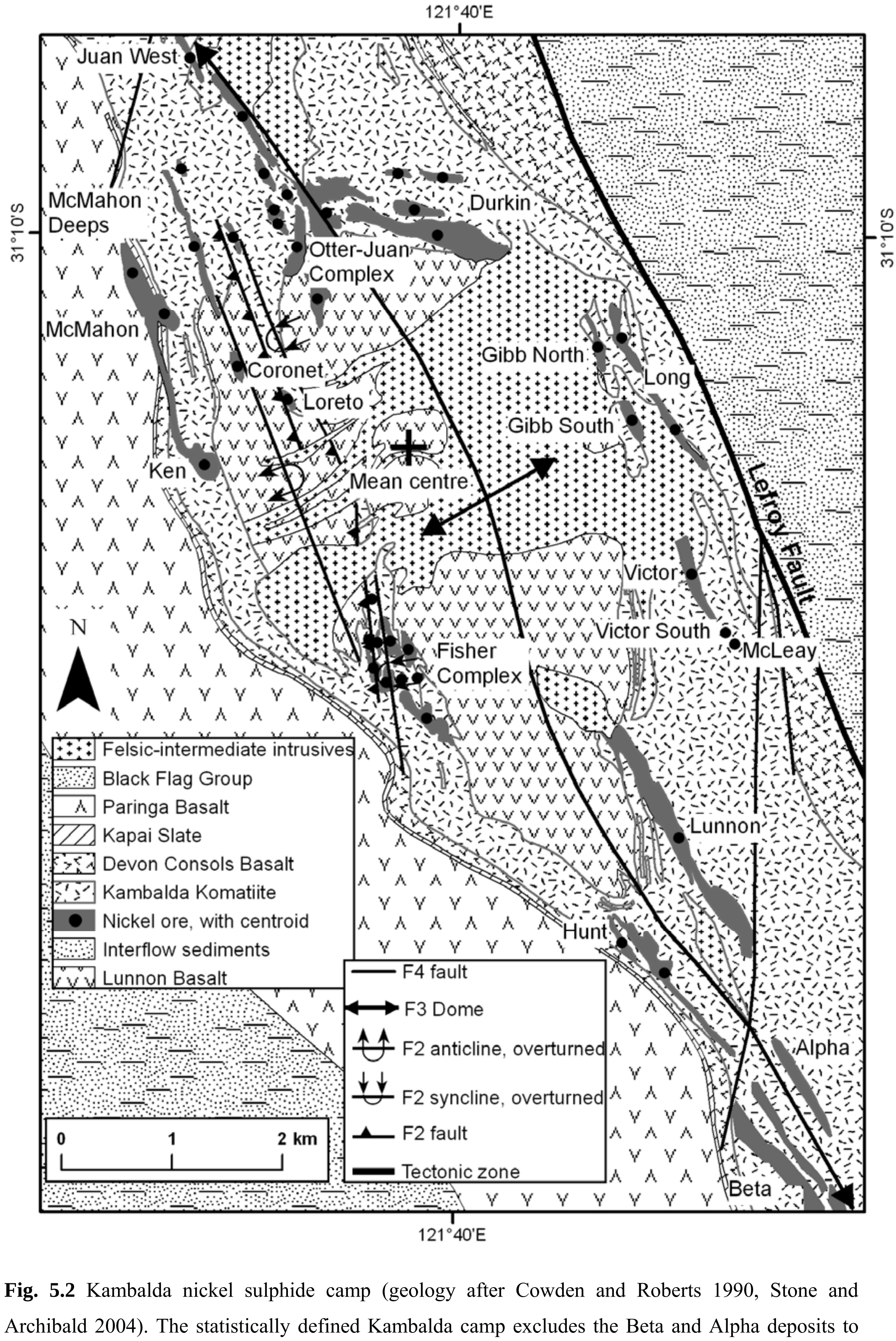


Fig. 5.2 Kambalda nickel sulphide camp (geology after Cowden and Roberts 1990, Stone and Archibald 2004). The statistically defined Kambalda camp excludes the Beta and Alpha deposits to the south of the north-south fault.

The distribution of mineral deposits may not always be isotropic as implied by the application of the circular measurement depicted by standard distance circle. Rather, deposits are commonly controlled by linear structures such as faults or shear zones that may impart a preferred directional trend. To measure both dispersion and directional trend of deposit points within a group, the standard deviational ellipse (SDE) is used. A series of calculations (Ebdon, 1988; Levine, 2007; de Smith et al., 2007) are required to fit the SDE to a set of points. These calculations involve rotating the x-axis and y-axis in small steps so as to minimise the sum of squares of distances between the deposit points and the axes. The angle of rotation is given by:

$$\theta = \tan^{-1}\left(\frac{\sum(X_i - \overline{X})^2 - \sum(Y_i - \overline{Y})^2 + \sqrt{C}}{2\sum(X_i - \overline{X})(Y_i - \overline{Y})}\right), \tag{5.4}$$

$$\text{where, } C = \left(\sum(X_i - \overline{X})^2 - \sum(Y_i - \overline{Y})^2\right)^2 + 4\sum\left((X_i - \overline{X})(Y_i - \overline{Y})\right)^2$$

and all summations are for i = 1 to i = N. The standard deviations along the transposed x-axis and y-axis are given by:

$$SD_X = \sqrt{\frac{2\sum\left((X_i - \overline{X})\cos\theta - (Y_i - \overline{Y})\sin\theta\right)^2}{N-2}} \tag{5.5}$$

$$SD_Y = \sqrt{\frac{2\sum\left((X_i - \overline{X})\sin\theta - (Y_i - \overline{Y})\cos\theta\right)^2}{N-2}} \tag{5.6}$$

The lengths of the ellipse's orthogonal x-axis and y-axis are $2\times SD_X$ and $2\times SD_Y$. There is a long standing controversy as to whether the SDE is a true mathematical ellipse (Furfey, 1927; Gong, 2002) and different software packages apply slightly different formulae. *Crimestat* (Levine, 2007), which was employed in this analysis, uses the above formulations.

5.2.4 Weighted centrographic measures

The above centrographic measures are based only on the location of mineral deposits under the assumption that all deposits have equal weight or importance. Thus the above unweighted centrographic analysis is applicable where the focus is on analysing only the presence or absence of mineral deposits. However in many cases other attributes of mineral deposits such as the tonnage, grade, metal content, and geochemistry of the ore are also of interest. The values of such attributes can be incorporated in weighted centrographic calculations. In this case the coordinates of the weighted mean centre, $(\overline{X}_w, \ \overline{Y}_w)$, are given by:

$$\overline{X}_w = \frac{\sum_i^N X_i w_i}{\sum_i^N w_i}, \overline{Y}_w = \frac{\sum_i^N Y_i w_i}{\sum_i^N w_i} \tag{5.7}$$

where w is the weight for each deposit. The weighted standard distance, SD_w, is calculated as:

$$SD_w = \sqrt{\frac{\sum_i w_i (X_i - \overline{X})^2}{\sum_i w_i} + \frac{\sum_i w_i (Y_i - \overline{Y})^2}{\sum_i w_i}} \tag{5.8}$$

The weighted SDE is obtained by similarly applying weights to Eq. 5.5 and 5.6. In this chapter the weights used in weighted centrographic analyses are the amounts of nickel endowment (contained Ni metal in kt) for each nickel deposit.

Mineral deposit patterns with smaller SDCs or SDEs than others in the same geographic area are spatially more compact or less dispersed. Tables 5.1 to 5.5 list complementary statistical indices that provide additional information about the distribution of orebodies and metal endowment within the SDC or SDE of a mineral deposit pattern. A particularly useful index is the capture efficiency, defined as:

$$\textbf{Capture efficiency} = \textbf{\% FCAV in SDC or SDE} \times \frac{\textbf{\% FCAV in SDC or SDE}}{\textbf{\% area of pattern in SDC or SDE}}, \quad (5.9)$$

where FCAV stands for feature counts or attribute values. Hence, the higher the capture efficiency, the greater is the efficiency of the SDC or SDE of capturing the spread of a point pattern.

5.3. Results of this study

This study is based on several spatio-geometric partitions. Various partitioning schemes are presented. The reader is referred to Table 1 which describes the main partitioning schemes reported in this study.

5.3.1 SDC and SDE

The unweighted and weighted (by contained Ni metal in kt) centrographic SDCs and SDEs for the Kambalda nickel sulphide deposit group are shown in Figure 5.3. Table 5.2 depicts the dimensions of the SDCs and SDEs as well as the proportions of nickel sulphide deposits and endowment in the unweighted and weighted SDCs and SDEs. Geometrically, the weighted mean centre is a translation of the unweighted mean centre by 730 m in the *x*-direction and 180 m in the *y*-direction (Fig. 5.3).

The weighted SDC and SDE (25.5 km^2 and 9.1 km^2, respectively) are smaller than the unweighted ones (26.2 km^2 and 17.5 km^2, respectively) (Table 5.2). This indicates that the spatial distribution of contained nickel within the Kambalda group is skewed to the east and is more compact compared to the spatial distribution of nickel sulphide orebodies.

The unweighted SDC and SDE have higher capture efficiencies than the weighted SDC and SDE (Fig. 5.4; Table 5.2). This is as expected because unweighted centrographic measures act directly on deposit coordinates thereby maintaining centrality whereas weighted centrographic measures are based a weighted mean centre which has been shifted from the deposit mean centre by weighting (Fig. 5.3), resulting in lower capture efficiency.

As expected the weighted SDE accounts for higher nickel endowment (70 %) than the unweighted SDE (49 %), and has higher capture efficiency (Table 5.2; Fig. 5.4b, d). However, contrary to expectation, the unweighted SDC encloses a larger proportion of the nickel endowment (72 %) than the weighted SDC (67 %), and exhibits slightly higher capture efficiency (Fig. 5.4a, c). Although the unweighted SDC accounts for more nickel endowment (72 %) than even the weighted SDE (70 %) the latter exhibits greater capture efficiency (150) than the former (106). In this case the nickel endowment density of the ellipse (43 kt/ km^2) is higher than that of the circle (29 kt/ km^2).

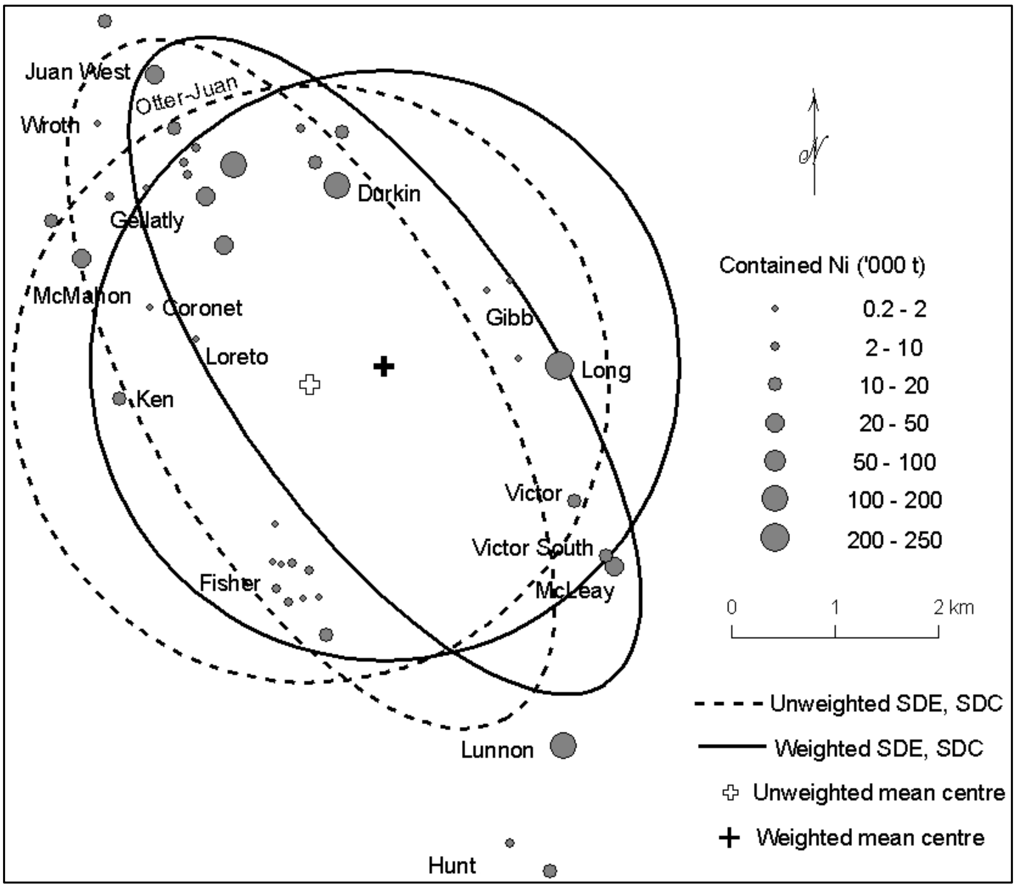


Fig. 5.3 Unweighted and weighted mean centres, SDCs and SDEs of nickel sulphide orebodies within the Kambalda group.

5.3.2 Spatio-geometric interaction of SDC and SDE

The areal units emanating from spatio-geometric interaction of the SDC and SDE can be used to statistically partition mineral deposit groups. This is demonstrated in Figure 5.5 wherein weighted and unweighted partitions of the Kambalda nickel sulphide deposit group are labelled I to VI. Table 5.3 summarises properties of the Kambalda partitions. If unweighted centrography is conceptually a better descriptor of spatial distribution of nickel orebodies than weighted centrography (section 5.3.1), then only partitions III and V which contain more orebodies in unweighted compared to weighted centrography (Table 5.3) conform to concept. On the other hand, superiority of weighted centrography as a descriptor of contained nickel is apparent in all partitions except partition V. It would appear therefore that amongst all partitions, partition III (geometric intersection of the SDC and SDE) is the most stable discriminator of the relative effectiveness of unweighted and weighted centrography with respect to orebody counts and nickel endowment within the Kambalda deposit group.

Thus for unweighted centrography, partition III occupies only 16 % of the area of Kambalda nickel sulphide deposit group, but accounts for the bulk (61 %) of the group's total orebody counts (Table 5.3). Similarly for weighted centrography, partition III constitutes 15 % of the area of Kambalda nickel sulphide deposit group, yet it hosts 61 % of the group's nickel endowment (Table 5.3).

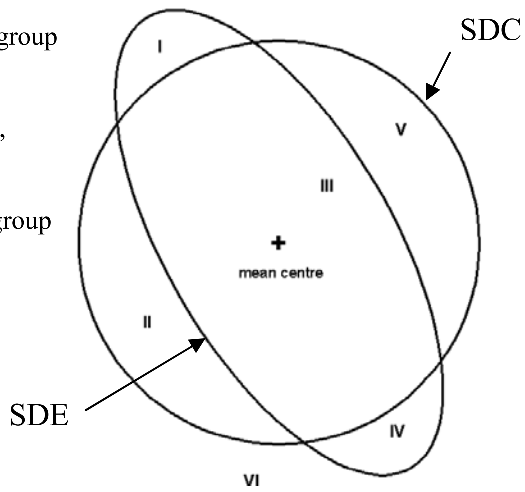
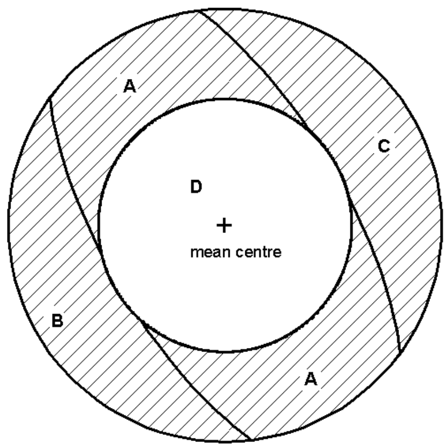
5.3.3 Prime and peripheral parts of the Kambalda camp

The Kambalda nickel sulphide deposit camp may be regarded as consisting of (i) a prime part within the standard distance circle incorporating partitions II, III and V, and (ii) a peripheral part (partitions I, IV and VI) which lies outside the standard distance circle (Fig. 5.5; Table 5.1). The prime part contains most of, and exhibits a much higher concentration of the group's nickel orebodies and endowment compared to the peripheral part (Table 5.4).

5.3.4 Annular bands

Partitions II, III and V constitute geometric spatio-statistical partitions of the prime part (part within the SDC) of the Kambalda nickel sulphide deposit camp (Table 5.1). An alternative scheme involves binary partitioning of the prime part into an annular band within which the concentration of nickel orebodies and/or endowment is maximized, and the remaining space within which there is lower concentration of nickel orebodies and/or endowment. As in the case of SDC and SDE, the annular bands are estimated for both weighted and unweighted centrography. A method to estimate the annular bands is captured in the Algorithm 1.

TABLE 5.1 Key to various partitions used in this chapter

Partition	Description	Graphic illustration
Interaction of SDC and SDE		
I	Outside SDC, inside SDE, northwest of group	
II	Inside SDC, outside SDE, west of group	
III	Geometric intersection of SDC and SDE, central part of group	
IV	Outside SDC, inside SDE, southeast of group	
V	Inside SDC, outside SDE, east of group	
VI	Outside SDC and SDE	
I, III and IV	SDE	
II, III and V	SDC or prime part of group	
I, IV and VI	Peripheral part of group	
Interaction of annular band and partition III		
A	Geometric intersection of annular band and partition III, northwest and southeast of group	
B	Inside annular band, outside partition III, west of group	
C	Inside annular band, outside partition III, east of group	
D	Inside partition III, outside annular band, 'hole' in centre of group	
A and D	Partition III	
A, B and C	Annular band (hatched)	
A, B, C and D	SDC or prime part of group	

Notes

SDC stands for standard distance circle

SDE stands for standard deviational ellipse

Algorithm 1 was implemented for the Kambalda group to estimate the unweighted (for nickel orebodies) and weighted (for nickel endowment) annular bands within the SDC. The plot in Fig. 5.6a indicates that the concentration of nickel orebodies is maximized at a radial distance of 1,200 m from the periphery of the SDC (CASE-2 in Algorithm 1). The prime part of the Kambalda group was therefore split into binary partitions: an orebody annular band having maximum concentration of nickel orebodies, and the remaining space with lower concentration of nickel orebodies.

The spatio-geometric representation of the unweighted annular band is shown in Fig.5.7a, and its empirical properties are summarized in Table 5. 5. The annular band corresponds to the one depicted by Eq. 5.13 in Figure 5.8. The concentration of the nickel endowment is also maximized at a radial distance of 1,200 m from the periphery of the SDC (CASE-2 in Algorithm 1; Fig. 5.6b). The weighted annular band is depicted in Fig. 5.7b, and exemplifies Eq. 5.13 in Figure 5.8. Empirical properties of the band are shown in Table 5.5.

TABLE 5.2 Attributes of unweighted and weighted SDCs and SDEs of the Kambalda nickel sulphide camp

		Unweighted			Weighted		
		SDC	SDE	Group	SDC	SDE	Group
Area of SDC and SDE	Size (sq. km)	26.2	19.1	67.8	25.5	17.5	67.8
	% of total	38.7	28.2	100.0	37.7	25.8	100.0
Orebodies	Count	32	27	41	29	21	41
	% of total	78.0	65.9	100.0	70.7	51.2	100.0
	Density (orebodies/ sq. km)	1.2	1.4	0.6	1.1	1.2	0.6
	Capture efficiency	157.4	153.6	100.0	132.8	101.7	100.0
Orebody area	Size (sq. km)	1.4	1.1	1.6	1.2	1.0	2.0
	% of parent group's orebody area	88.7	70.4	100.0	59.4	51.2	100.0
	% area of total parent group area	5.3	5.8	2.3	4.7	5.9	3.0
Nickel endowment	Contained Ni (kt)	769.9	523.4	1075.9	723.7	749.0	1075.9
	% of total Ni endowment of group	71.6	48.6	100.0	67.3	69.6	100.0
	Ni endowment density (kt Ni/ sq. km)	29.4	27.4	15.9	28.4	42.8	15.9
	Capture Efficiency	132.3	83.8	100.0	120.1	187.8	100.0
	Average contained Ni per orebody	24.1	19.4	26.2	25.0	35.7	26.2

5.3.5 Spatio-geometric Interaction of annular bands and partition III

The directional anisotropy in the distribution of orebodies and endowment for unweighted and weighted centrography can be captured by superposing the SDE over respective annular bands (Table 5.1; Figs. 5.7; 5.8). This geometric manipulation creates partitions of the annular band which are labelled A to D (Table 5.1; Fig. 5.8). The intersection of partition III and annular band creates partition A

(Fig. 5.6; Table 5.1; Fig. 5.8) which is potentially the most important partition as it captures the space of maximal concentration of nickel orebodies (or nickel endowment) as well as the prevailing directional trend of nickel orebodies (or endowment). This space can take several geometric forms, some of which are illustrated in Fig. 5.8.

TABLE 5.3 Unweighted and weighted areal partitions of the SDC-SDE spatio-geometric space of the Kambalda nickel sulphide group (Partition labels I to VI follow Table 5.1)

Areal partitions based on unweighted centrographic measures										
		I	II	III	IV	V	VI	SDC	SDE	Group
Area	Size (km^2)	1.4	4.9	16.4	1.4	4.9	27.8	26.2	19.1	67.8
	% of total	2.0	7.2	24.2	2.0	7.2	41.0	38.7	28.2	100.0
Orebodies	Count	2	1	25	0	6	7	32	27	41
	% of total	4.9	2.4	61.0	0.0	14.6	17.1	78.0	65.9	100.0
	Orebodies/ km^2	1.5	0.2	1.5	0.0	1.2	0.3	1.2	1.4	0.6
	Density per zone/ density for group	3.1	0.4	3.3	0.0	2.6	0.5	2.6	3.0	1.3
Area of orebodies	Size (km^2)	0.1	0.2	0.9	0.1	0.3	0.4	1.4	1.1	1.6
	% of parent group's orebody area	5.6	13.1	59.0	5.7	16.6	26.6	88.7	70.4	100.0
	% area of total parent group area	6.5	4.2	5.7	6.5	5.3	1.5	5.3	5.8	2.3
Nickel endowment	Contained Ni (kt)	48.4	20.0	475.0	0.0	274.9	257.6	769.9	523.4	1075.9
	% of total	4.5	1.9	44.1	0.0	25.5	23.9	71.6	48.6	100.0
	Ni endowment density (kt Ni/ km^2)	35.4	4.1	29.0	0.0	56.1	9.3	29.4	27.4	15.9
	Density per zone/ density for group	2.9	0.3	2.4	0.0	4.6	0.8	2.4	2.2	1.3
	Average per orebody	24.2	20.0	19.0	0.0	45.8	36.8	24.1	19.4	26.2

Areal partitions based on centrographic measures weighted by contained nickel										
		I	II	III	IV	V	VI	SDC	SDE	Group
Area	Size (km^2)	1.3	5.3	14.9	1.3	5.3	28.5	25.5	17.5	67.8
	% of total	1.9	7.9	22.0	1.9	7.9	42.1	37.7	25.8	100.0
Orebodies	Count	3	12	17	1	0	8	29	21	41
	% of total	7.3	29.3	41.5	2.4	0.0	19.5	70.7	51.2	100.0
	Orebodies/ km^2	2.3	2.3	1.1	0.8	0.0	0.3	1.1	1.2	0.6
	Density per zone/ density for group	4.6	4.5	2.3	1.5	0.0	0.6	2.3	2.4	1.2
Area of orebodies	Size (km^2)	0.1	0.3	0.9	0.1	0.0	0.7	1.2	1.0	2.0
	% of parent group's orebody area	3.5	14.4	43.9	3.8	1.1	33.2	59.4	51.2	100.0
	% area of total parent group area	5.3	5.4	5.9	5.9	0.4	2.3	4.7	5.9	3.0
Nickel endowment	Contained Ni (kt)	62.4	65.8	658.0	28.6	0.0	261.2	723.7	749.0	1075.9
	% of total	5.8	6.1	61.2	2.7	0.0	24.3	67.3	69.6	100.0
	Ni endowment density (kt Ni/ km^2)	47.8	12.4	44.2	21.9	0.0	9.2	28.4	42.8	15.9
	Density per zone/ density for group	3.7	1.0	3.4	1.7	0.0	0.7	2.2	3.3	1.2
	Average per orebody	20.8	5.5	38.7	28.6	0.0	32.6	25.0	35.7	26.2

5. 4 Discussion

In spatial statistical analyses, known deposits (and endowment) are invariably a subset of their true geologic distribution because of incomplete deposit discovery, incomplete resource delineation, and resource economic truncation (Bultman et al., 1992; Blenkinsop, 2004). However, it is commonly assumed that such a subset is a random sample of the true population of geologic deposits (Blenkinsop and Sanderson, 1999). If this assumption is correct, the centrographic approach proposed in this chapter may enhance delineation of mineralised geologic units, a task that remains to be perfected (Singer, 2010).

Some statistical partitions of the Kambalda Dome such as partition A and partition III (Fig. 5.5; 5.8) closely match the nickel sulphide deposit and endowment capture efficiency of komatiite areal trace (Fig. 5.9), the ultimate geological locale for nickel sulphide deposits and endowment. Komatiite areal trace is the most efficient locale of orebody counts (Figs. 5.10a and 5.11c), whereas partition A is a more efficient locale of nickel endowment (Figs. 5.10b and 5.11b). Although optimized annular bands capture almost as many orebodies (Figs. 5.10a and 5.11a) as, and more nickel endowment (Figs. 5.10b and 5.11b) than the komatiite areal trace the bands occupy an area 2.3 times larger (Table 5.3), rendering them less efficient. Therefore although komatiite areal traces tend to exhibit higher nickel deposit and endowment capture efficiencies than other partitions, in some cases it is possible to approximately delineate komatiites by applying spatial centrography on known nickel sulphide deposits. Weighted centrography enables delineation of nickel endowment locales rather than mere locales of deposits, thus providing a statistical ranking tool of a deposit camp. The parts of high ranking partitions that do not currently contain known deposits or endowment may be considered priority exploration targets. For komatiite-associated nickel sulphide deposits, false positives that can arise this way may be eliminated based on country rock type, but this can result in exclusion of nickel sulphide mineralisation remobilised away from komatiites. As the centrographic partitions are statistical slices that are based solely on location of deposits and endowment, this technique may potentially be useful for delineating potentially mineralised geologic units in mineral systems that are not confined to specific lithologies such as orogenic gold.

Coronet deposit and the Banana-Juan Horst orebody (most southerly orebody at Otter–Juan) are, rather atypically, not directly on the komatiite areal trace (Figs. 5.2 and 5.9) thereby reducing its capture efficiency. Coronet is concealed beneath a structural wedge of the footwall Lunnon basalt (Stone and Masterman, 1998; Beresford et al., 2005). Similarly Banana-Juan Horst is concealed by a thickened overthrusted tongue of the footwall Lunnon basalt (Gresham and Loftus-Hills, 1981; Marston, 1984). This further illustrates why komatiite areal trace may not always be most efficient as a locale for characterizing nickel orebodies and endowment. In addition, as illustrated in Figure 5.12, the capture efficiency differential between komatiite areal trace and the other partitions is maximised within the SDC and is lower outside the SDC. This may imply that the SDC delineates the spatial extent of relatively more intense nickel ore formation and/or preservation processes. If this is correct, the SDC may denote an optimal spatial analytical window for studying processes of nickel ore formation and preservation at Kambalda.

TABLE 5.4 Distribution of nickel orebodies and endowment in the prime and peripheral parts of the Kambalda nickel sulphide deposit group

		Prime part	Peripheral part	Group total
		Unweighted centrography		
Area	Size (sq. km)	26.2	27.8	67.8
	% of group	38.7	41.1	100.0
Orebodies	Count	32.0	9.0	41.0
	% of group	78.0	22.0	100.0
	Capture efficiency	157.4	11.7	100.0
Endowment	Ni (kt)	769.9	306.1	1075.9
	% of group	71.6	28.4	100.0
	Capture efficiency	132.3	19.7	100.0
		Weighted centrography		
Area	Size (sq. km)	25.5	42.2	67.8
	% of group	37.7	62.3	100.0
Orebodies	Count	29.0	12.0	41.0
	% of group	70.7	29.3	100.0
	Capture efficiency	132.8	13.7	100.0
Endowment	Ni (kt)	723.7	352.2	1075.9
	% of group	67.3	32.7	100.0
	Capture efficiency	120.1	17.2	100.0

Algorithm 1: Estimating orebody and endowment annular bands

1. Select an appropriate radius increment value based on the resolution of the input data such that the radius of the SDC is an exact integral multiple of the radius increment.
2. Draw a concentric circle *X* of radius *r* within the SDC such that the area of *X* is half the area of the SDC. Calculate the number of orebodies and endowment within *X*.
3. CASE-1: The number of orebodies and or/endowment within *X* are more than half of the total number of orebodies and/ or endowment in the entire SDC (Eq. 5.10 and 5.11in Figure 5.8)
    a. Calculate the percent cumulative (i) areas, (ii) numbers of orebodies, and (iii) endowments for annular bands of increasing radii, starting at the centre of the SDC. The radius is sequentially increased by the increment selected in Step 1.
    b. Plot the curves for percent cumulative (i) areas, (ii) numbers of orebodies, (iii) endowments and, (iv) orebody and endowment capture efficiencies against the radial distance from the centre of SDC,
    c. The threshold outer radius of the unweighted annular band is defined by the radial distance from the centre of SDC where there is the widest separation between the curves for cumulative areas and cumulative numbers of orebodies. The rationale is that the curve for cumulative percent areas represents the expected distribution of orebodies if they were randomly located in the cluster space, while the curve for cumulative numbers of orebodies represents the observed distribution. The optimal annular band is the one which has the largest separation between the observed and expected distributions. This is separation may be amplified if the orebody capture efficiency is used instead of the cumulative number of orebodies.
    d. Based on the same reasoning, the threshold outer radius of the weighted annular band is defined by the radial distance from the centre of SDC where there is the widest separation between the curves for cumulative areas and cumulative endowments or endowment capture efficiency.
4. CASE-2: The number of orebodies and endowment within *X* are less than half of the total number of orebodies and/or endowment in the entire SDC (Eq. 5.12 and 5.13 in Figure 5.8)
    a. Calculate the percent cumulative (i) areas, (ii) numbers of orebodies, and (iii) metal endowments for annular bands of decreasing radii, starting at the periphery of the SDC. The radius is decreased by the increment selected in Step 1.
    b. Plot the curves for percent cumulative (i) areas, (ii) numbers of orebodies, (iii) metal endowments and, (iv) orebody and endowment capture efficiencies against the radial distance from the periphery of SDC.
    c. As explained in Step 3c, the threshold inner radius of the unweighted annular band is defined by the radial distance from the periphery of SDC where there is the widest separation between the curves for cumulative areas and cumulative numbers of orebodies or orebody capture efficiency.
    d. The threshold inner radius of the weighted annular band is similarly defined by the radial distance from the periphery of SDC where there is the widest separation between the curves for cumulative areas and cumulative endowment or endowment capture efficiency.

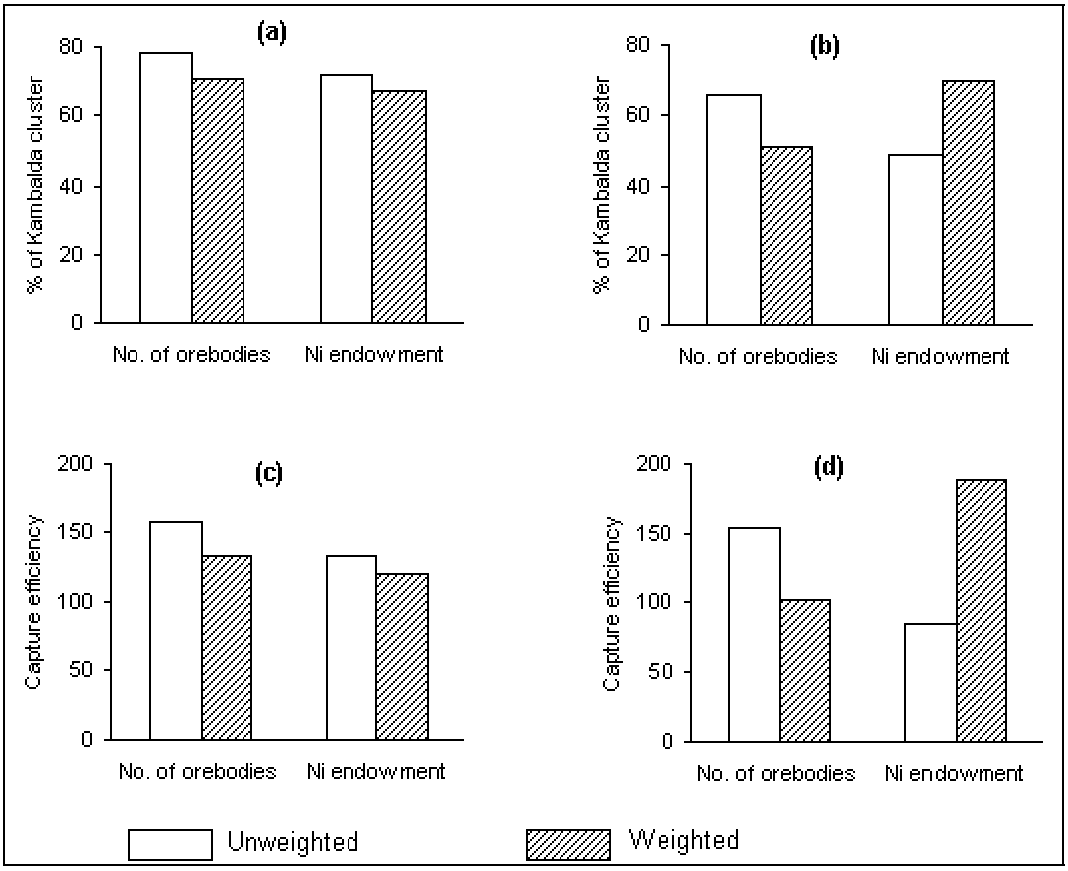


Fig. 5.4 Distribution of nickel endowment and nickel orebodies within unweighted and weighted (a) SDC's and, (b) SDE's, and capture efficiency ratios for weighted and unweighted (c) SDC's and (d) SDE's of the Kambalda nickel sulphide deposit group.

Another point to note is that unweighted centrography presents the more general case based on the presence or absence of deposits and does not discriminate between high and low endowment. Weighted centrography provides the means to partition the centrographic space according to endowment. This partitioning is non-trivial and in the Kambalda Dome it reflects underlying geological variation. For example, weighted centrography shows that the eastern side of the Kambalda Dome has more nickel endowment that the western side. This has been explained in terms of geological observations that, from east to west: the Kambalda komatiite formation thins, channel facies (ore environments) become less well-defined, and sheet flow facies (non- ore environment) become more dominant (Gresham and Loftus-Hills, 1981; Marston, 1984; Gresham, 1986; Cowden and Roberts, 1990; Williams et al., 1993; Beresford et al., 2002).

TABLE 5.5 Nickel orebody counts and endowments of various partitions of the annular band in the Kambalda group (Partition labels follow Table 5.1)

	Orebodies				Area		Contained nickel			
Partition	Count	% of SDC	per km^2	Capture efficiency	km^2	% of SDC	kt Ni	% of SDC	kt per km^2	Capture efficiency
Unweighted										
A (Northwest)	13	40.6	3.5	115.1	3.8	14.3	397.3	51.6	105.7	185.7
B	1	3.1	0.2	0.5	4.9	18.6	20.0	2.6	4.1	0.4
A (Southeast)	9	28.1	2.4	55.1	3.8	14.3	43.0	5.6	11.4	2.2
A (combined)	22	68.8	2.9	164.8	7.52	28.7	440.3	57.2	16.8	114.0
C	6	18.8	1.2	18.9	4.9	18.6	274.9	35.7	56.5	68.6
A to C (annular band)	29	90.6	1.7	124.7	17.3	65.8	735.2	95.5	42.6	138.5
D	3	9.4	0.3	2.6	9.0	34.2	34.6	4.5	3.9	0.6
SDC	32	100	1.2	100	26.2	100	769.9	100.0	29.4	100
Weighted by contained nickel										
A (Northwest)	12	40	3.6	122.7	3.3	13.0	381.5	52.7	114.5	213.0
B	12	40	2.3	79.4	5.1	20.1	65.8	9.1	12.8	4.1
A (Southeast)	3	10	0.9	7.7	3.3	13.0	275.6	38.1	82.7	111.2
A (combined)	15	50	2.2	95.9	6.7	26.1	657.1	90.8	25.7	316.1
C	0	0	0.0	0	5.1	20.1	0.0	0.0	0.0	0.0
A to C (annular band)	27	90	1.6	122.0	17.0	66.4	722.8	99.9	42.6	150.3
D	3	10	0.4	3.0	8.6	33.5	0.9	0.1	0.1	0.0
SDC	30	100	1.2	100	25.5	100.0	723.7	100.0	28.3	100.0

5.5 Conclusions

The main outcome of the present work is a centrographic approach to spatio-statistically depict the distribution of deposits and endowment in mineral deposit clusters, leading to the following conclusions:

1. Centrographic statistical partitions can be used to represent mineralised geological space that depicts the varying concentrations of mineral deposits or mineral endowment.

2. The standard deviational circle (SDC) of a deposit group is potentially a prime analytical window for studying processes of ore formation and preservation.

3. The centrographic approach provides a means to accomplish delineation in terms of spatial geometries instead of geological variables. Coincidence of the two in the case of komatiite-associated nickel sulphide system suggests potential extension of applications to other mineral systems, potentially benefitting non

lithology-specific mineral systems (e.g. orogenic gold) the most. As centrographic partitions are statistical, there is opportunity for comparisons across mineral systems and areas.

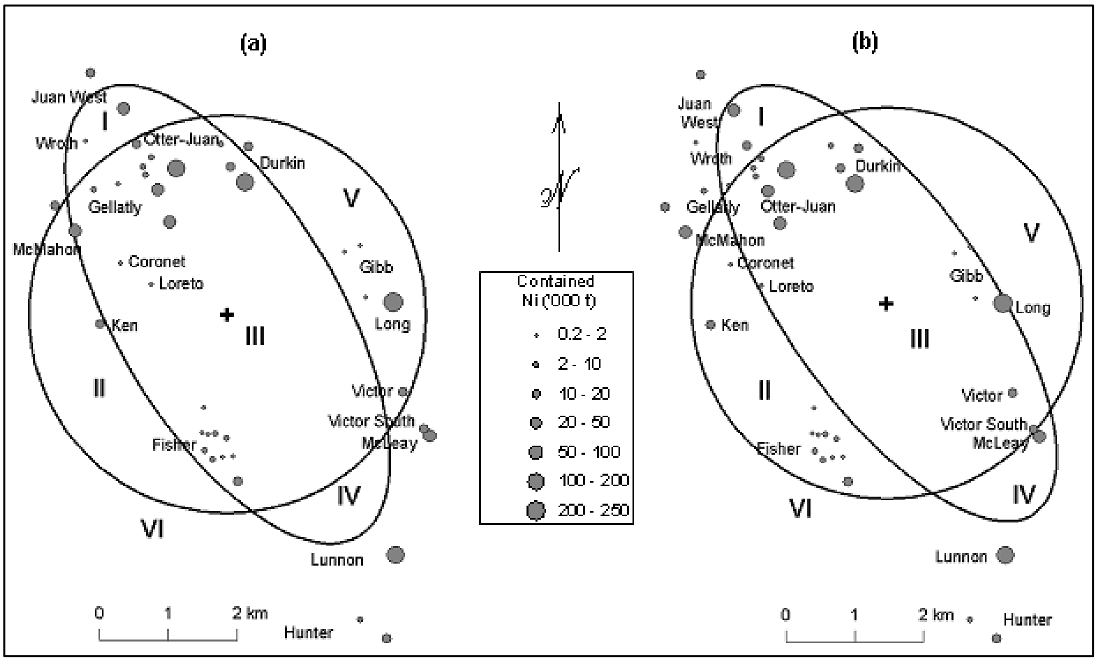


Fig. 5.5 Partitions of the SDC-SDE space for (a) unweighted and, (b) weighted (by contained Ni) centrography of the Kambalda nickel sulphide deposit group. Partition nomenclature (I to VI) is explained in Table 5.1.

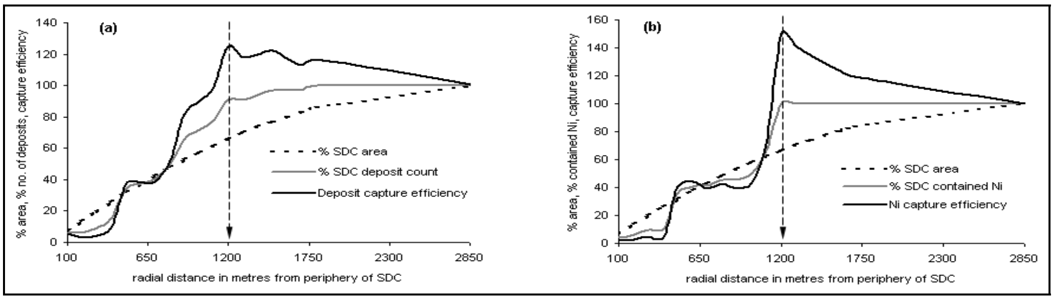


Fig. 5.6 Variation of key indices of annular bands with radial distance from the periphery of the SDC for: (a) nickel orebody counts and, (b) nickel endowment.

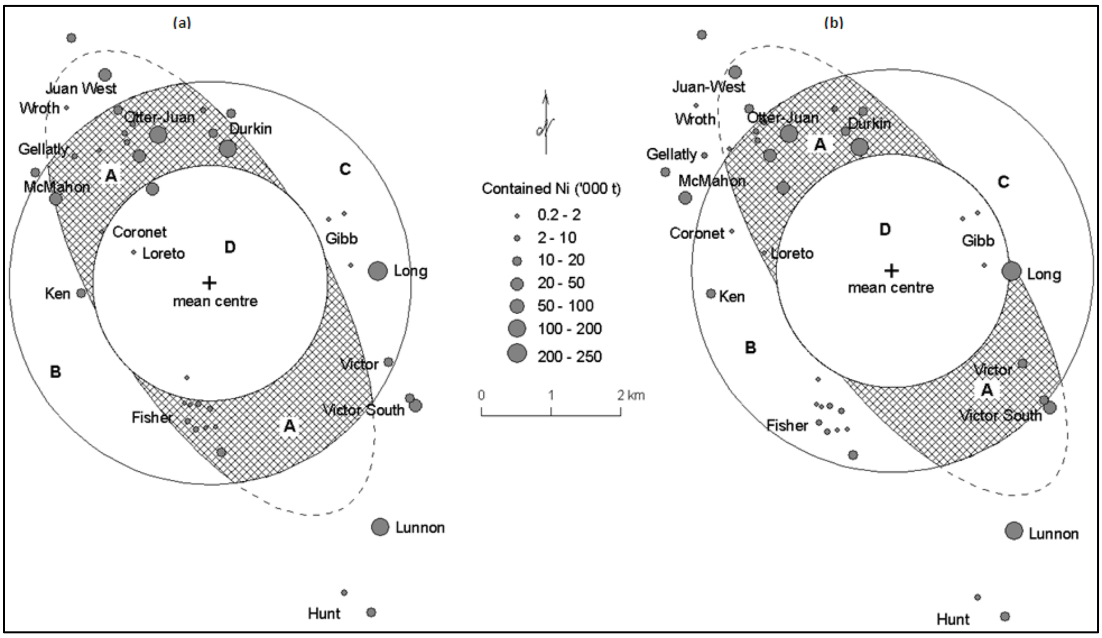


Fig. 5.7 Maximised annular band (A, B, C) for the distribution of (a) nickel orebodies and (b) nickel endowment within the Kambalda group. Partitions labels A to D are explained in Table 5.1 and Fig. 5.8.

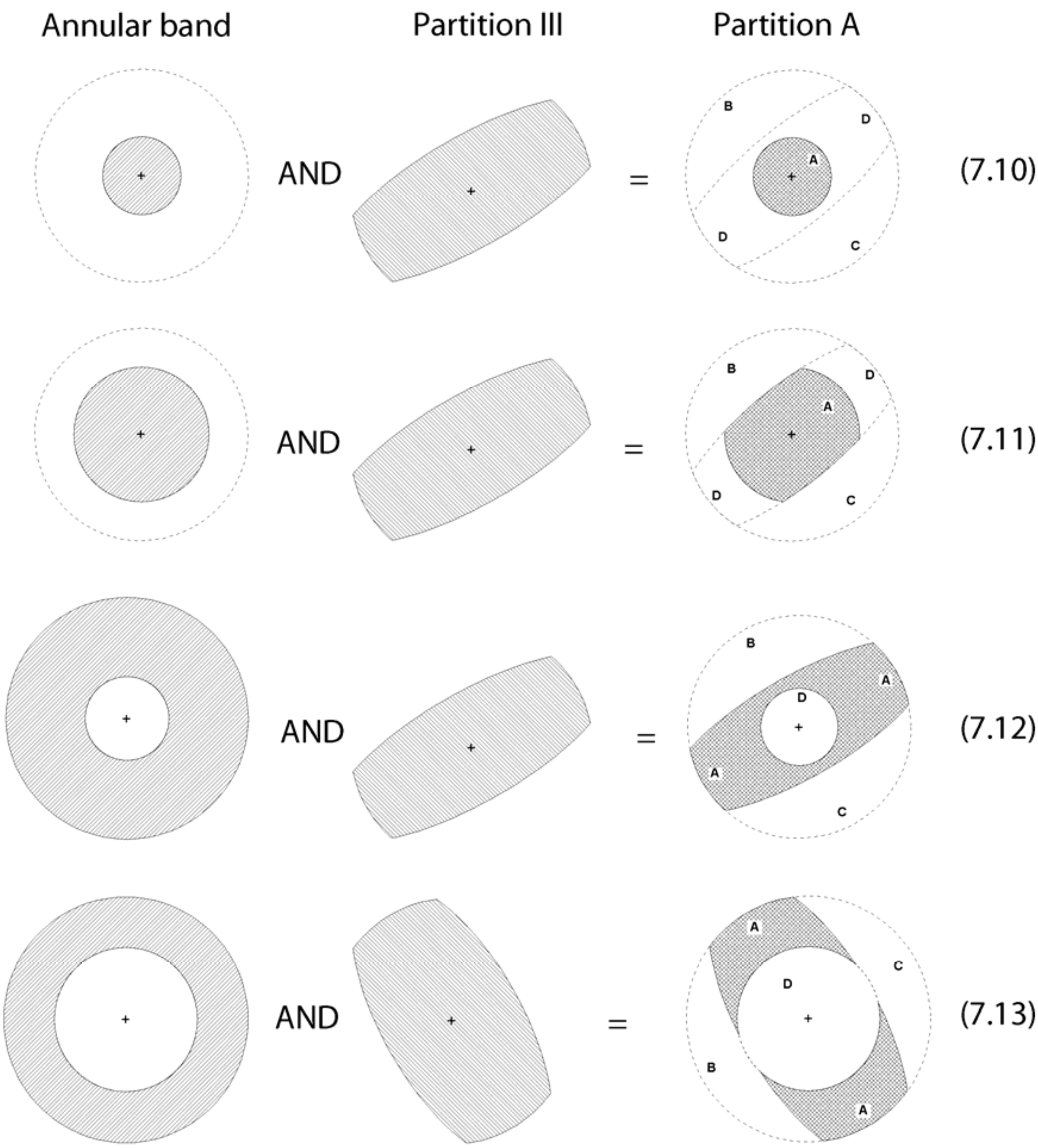


Fig. 5.8 Possible forms of partition A from various geometric combinations (see Table 5.1 for nomenclature)

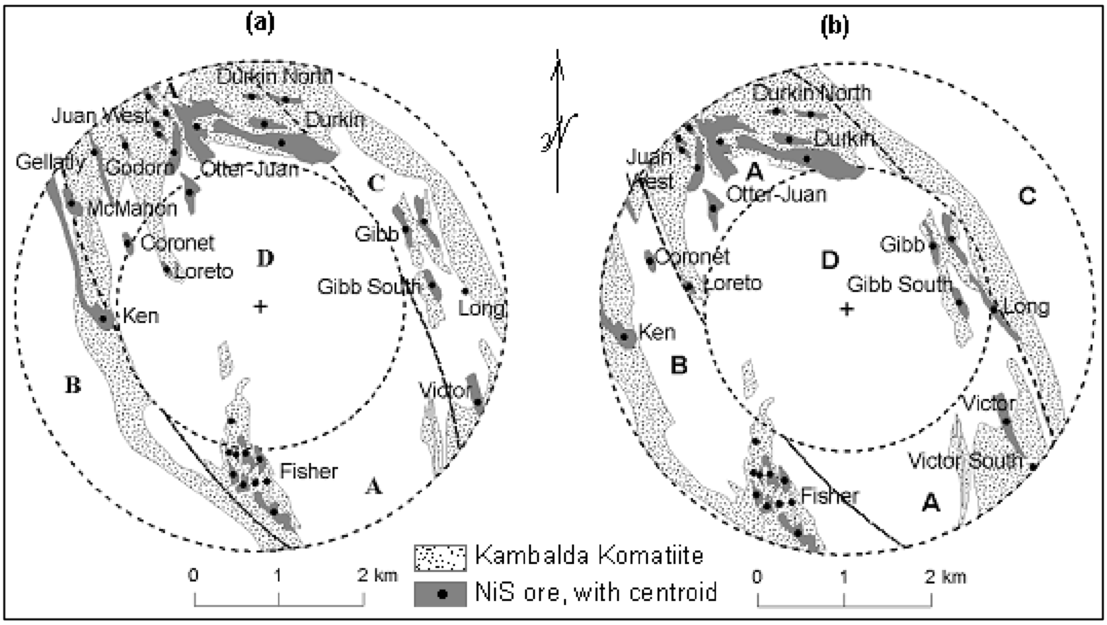


Fig. 5.9 Komatiite areal trace with respect to SDC and optimized annular bands for (a) unweighted, and (b) weighted centrography for the Kambalda group. Labels A to D are explained in Table 5.1 and Fig. 5.8.

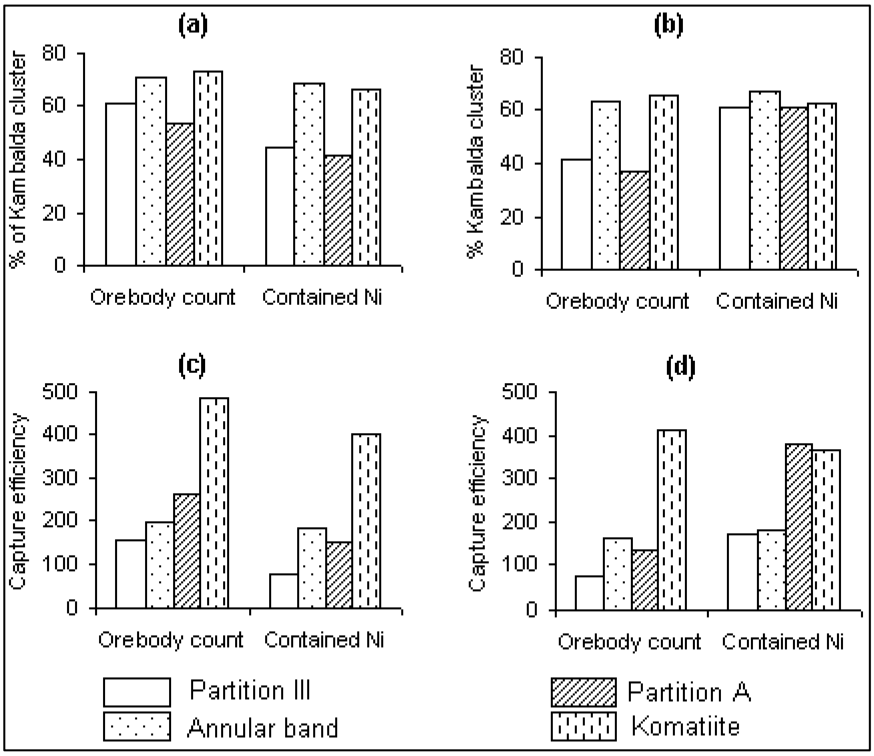


Fig. 5.10 Orebody counts and contained nickel within various partitions as percentages of the entire Kambalda group for (a) unweighted centrography, (b) weighted centrography, and capture efficiencies for (c) unweighted partitions and (d) weighted partitions.

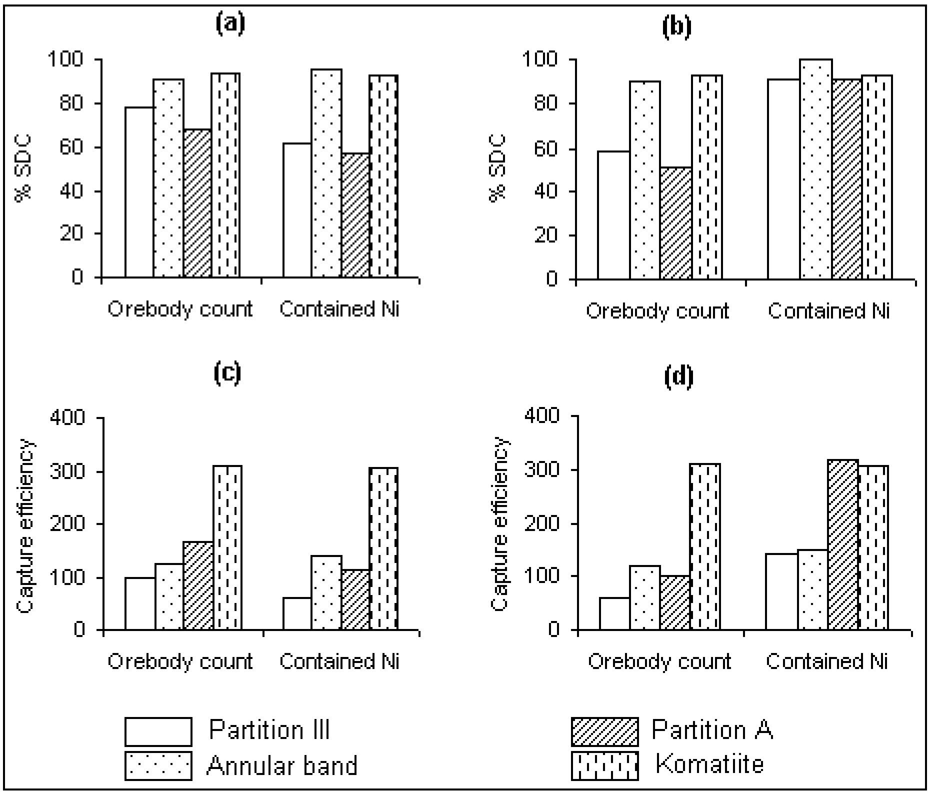


Fig. 5.11 Orebody counts and contained nickel within various partitions as percentages of the standard distance circle (SDC) for (a) unweighted centrography, (b) weighted centrography, and capture efficiencies for (c) unweighted partitions and (d) weighted partitions.

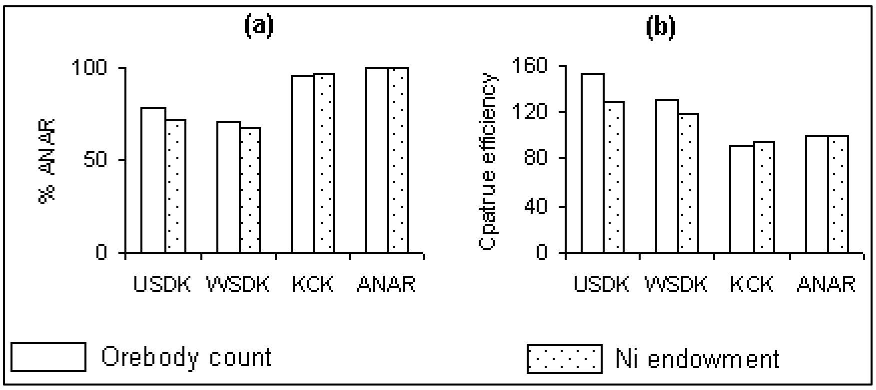


Fig. 5.12 Plots of (a) proportion of orebody counts and nickel endowment, and (b) capture efficiency for komatiite in various partitions of the Kambalda group. The partitions are unweighted SDC komatiite (USDK), weighted SDC komatiite (WSDK), Kambalda group komatiite (KCK) and all nickel associated rocks (ANAR).

References

Bachi, R., 1957. Statistical analysis of geographical series. Bulletin de l'Institut International de Statistique 36, 229-240.

Barnes, S.J., 2006. Komatiite-hosted nickel sulphide deposits: geology geochemistry and genesis, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, p. 51-97.

Barnes, S.J., Perring, C.S., 2006. Appendix. Summary of geological features of nickel sulphide deposits of the Yilgarn craton, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, p. 99-118.

Beresford, S., Cas, R., Lahaye, Y., Jane, M., 2002. Facies architecture of an Achaean komatiite-hosted Ni-sulphide ore deposit, Victor, Kambalda, Western Australia: implications for komatiite lava emplacement. Journal of Volcanology and Geothermal Research 118, 57-75.

Beresford, S., Stone, W.E., Cas, R.A.F., Lahaye, Y, Jane, M., 2005. Volcanological controls on the localisation of a komatiite-hosted Ni-Cu-(PGE) deposit, Coronet, Kambalda, Western Australia. Economic Geology 100, 1457-1467.

Bhattacharyya, P., Czeck, M., 2008. Using network analyses within geographic information system technologies to quantify geometries of shear zone networks. Geosphere 4, 640–656.

Blenkinsop, T.G., 2004. Applications of fractal geometry to mineral exploration, in: Muhling, J., Goldfarb, R., Vielreicher, N., Bierlein, F., Stumpfl, E., Groves, D., Kenworthy, S. (Eds.), Predictive Mineral Discovery Under Cover, Extended Abstracts. SEG 2004 Conference, 27 September-1 October 2004 Perth, Western Australia, p. 158-161.

Blenkinsop, T.G., Sanderson, D.J., 1999. Are gold deposits in the crust fractals? A study of gold mines in the Zimbabwean craton, in: McCaffrey, K.J.W., Lonergan, L.,Wilkinson, J.J. (Eds.), Fractures, fluid flow and mineralization. Geological Society Special Publication 155, 141-151.

Bratt, R.S., Bache, T.C., 1988. Locating events with a sparse network of regional arrays. Bulletin of the Seismological Society of America 78, 780-798.

Bultman, M.W., Force, E.R. Gettings, M. E., Fisher, F. S., 1992. Comments on the "three-step" method for quantification of undiscovered mineral resources. US Geological Survey Open-File Report 93–23, 59 pp.

Cowden, A.C., Roberts, D.E., 1990. Komatiite-hosted nickel sulphide deposits, Kambalda, in: Hughes, F.E. (Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy: Melbourne, Monograph 14, p. 567-581.

de Smith, M.J., Goodchild, M.F., Longley, P.A., 2007. Geospatial analysis. A comprehensive guide to principles, techniques and software tools. Matador, Leicester, U.K., 394 pp.

Diggle, P.J., 1983. Statistical analysis of spatial point patterns. Academic Press, London, 148 pp.

Ebdon, D., 1988. Statistics in Geography. Blackwell Publishing, Oxford, U.K., 232 pp.

ESRI (Environmental Systems Research Institute), 2009. Multi-Distance Spatial ClusterAnalysis (Ripley's *K*-function) (Spatial Statistics). http://webhelp.esri.com/arcgisdesktop/9.3/index.cfm?topicname=multi-distance_spatial_cluster_analysis_(ripley's_k-function)_(spatial_statistics). (accessed February 10, 2009).

Evernden, J. F., 1969. Precision of epicenters obtained by small numbers of worldwide stations. Bulletin of the Seismological Society of America 59, 1365-1398.

Finch, W.I, Grundy, W.D, Pierson, C.T., 1992. Statistical sampling of the Distribution of uranium deposits using geologic/geographic clusters. Nonrenewable Resources 1, 148-152.

Flinn, E.A., 1965. Confidence regions and error determinations for seismic event location. Reviews of Geophysics 3, 157-185.

Furfey, P.H., 1927. A note on Lefever's "standard deviational ellipse". The American Journal of Sociology 33, 94-98.

Gong, J., 2002. Clarifying the standard deviational ellipse. Geographical Analysis 34, 155-167.

Hwang, S., 1999. Temporal extensions of K function. http://www.ucgis.org/ucgisfall2004/studentpapers/files/Hwang.PDF (accessed September 22, 2008).

Gresham, J.J., 1986. Depositional environments of volcanic peridotite-associated nickelsulfide deposits with special reference to the Kambalda Dome, in: Friedrich, G.H., Genkin, A.D., Naldrett, A.J., Ridge, J.D., Sillitoe, R.H., Vokes, F.M. (Eds.), Geology and Metallogeny of Copper Deposits, Springer-Verlag, Berlin, p. 63-89.

Gresham, J.J., Loftus-Hills, G.D., 1981. The geology of the Kambalda nickel field, Western Australia. Economic Geology 76, 1373-1416.

GSWA (Geological Survey of Western Australia), 2008. 1:500 000 interpreted bedrock geology of Western Australia, 2008 update, Geological Survey of Western Australia.

Kent, J., Leitner, M., 2008. Efficacy of standard deviational ellipses in application of criminal geographic profiling. Journal of Investigative Psychology and Offender Profiling 4, 147-165.

Klausen, M.B., 2004. Geometry and mode of emplacement of the Thverartindur cone sheet swarm, SE Iceland. Journal of Volcanology and Geothermal Research 138, 185-204.

Knoring, L.D. and Dech, V.N., 1993. Mathematics for geologists, in: Zeidler, R.B., (Ed.), Geotechnika 10, Netherlands, A.A. Balkema, 200 pp.

Lefever, D.W., 1926. Measuring geographic concentration by means of the standard deviational ellipse. The American Journal of Sociology 32, 88-94.

Levine, N., 2007. CrimeStat® III. A spatial statistics program for the analysis of crime incident locations (v 3.1). Ned Levine & Associates and the National Institute of Justice, Washington, DC.

Mamuse, A., Powal, A., Kreuzer, O.P., and Beresford, S., 2009, A new method for centrographic analysis of mineral deposit clusters: Ore Geology Reviews 36, 293-305.

Mamuse, A., Porwal, A., Kreuzer, O., Beresford, S.W., 2010a. Spatial statistical analysis of the distribution of komatiite-hosted nickel sulfide deposits of the Kalgoorlie Terrane, Western Australia: clustered or not? Economic Geology 105, 229 – 242.

Marcon, E., Puech, F., 2009. Generalizing Ripley's K function to inhomogeneous. In: HAL / Working Papers. RePEc:hal:wpaper:halshs-00372631_v1. http://ideas.repec.org/p/hal/wpaper/halshs-00372631_v1.html (accessed May 12, 2009).

Marston, R.J., 1984. Nickel mineralization in Western Australia. Geological Survey of Western Australia Mineral Resources Bulletin, vol. 14, 271 pp.

McCuaig, T.C.M, Beresford, S.W., and Hronsky, J.M.A., 2010. Scale dependence of targeting criteria in light of recent advances in understanding mineral systems. Ore Geology Reviews (in press).

MINEDEX database. Western Australia Department of Mines and Petroleum http://mapserver.doir.wa.gov.au/meta/arcMetaPage.asp?Id=532 (accessed January 14, 2009)

MINMET database, Intierra Pty Ltd. http://www.intierra.com/ (accessed January 14, 2009).

Mitchell, A., 2005. The ESRI guide to GIS analysis (volume 2: spatial measurements and statistics). ESRI Press, California, 238 pp.

Myint, S.W., 2008. An exploration of spatial dispersion, pattern, and association of socio-economic functional units in an urban system. Applied Geography 28,168-188.

Singer, D.A., 2010. Progress in integrated quantitative mineral resource assessments. Ore Geology Reviews, doi:10.1016/j.oregeorev.2010.02.001

Stone, W.E. and Masterman, E.E., 1998. Kambalda nickel deposits, in: D.A. Berkman and D.H. Mackenzie (Eds.), Australian and Papa New Guinean Mineral Deposits. The Australasian Institute of Mining and Metallurgy: Melbourne, Monograph 22, p. 347-356.

Stone, W.E., Archibald, N.J., 2004. Structural controls on nickel sulphide oreshoots in Archaean komatiite, Kambalda, WA: the volcanic trough controversy revisited. Journal of Structural Geology 26, 1173-1194.

Tanaka, T, Ryu S., Nishigaki, M., Hashimoto, M., 1981. Methodological approaches on medical care planning from the view point of geographical allocation model: a case study on South Tama District. Social Science and Medicine 15D, 83-91.

Williams, R.I., Archibald, N.J., Miller, D.R., 1993. Nickel sulphide deposits of the Kambalda dome - a 3-dimensional perspective. Australian Geological Survey Organisation Geoscience Record 1993/54, p. 171-173.

Woolrich, P., Cowden, A., Giorgetta, N.E., 1981. The chemical and mineralogical variations in the nickel mineralization associated with the Kambalda Dome, Western Australia. Economic Geology 76, 1629-1644.

Yuill, R.S., 1971. The standard deviational ellipse; an updated tool for spatial description. Geografiska Annaler (Series B, Human Geography) 53, 28-39.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

6.1 Discussion

6.1.1 Introduction

In this thesis, concepts of geology, spatial analysis and mathematical-statistical modelling are integrated for estimating undiscovered mineral endowment. Mathematical-statistical modelling approaches are increasingly applied in geology and other natural sciences (Knoring and Dech, 1993; Thiergärtner, 2006). However, geological objects and phenomena are so complex that they require substantial abstraction to permit appropriate application of the mathematical-statistical modelling (Knoring and Dech, 1993). The quality of results from the model is determined by how well the abstraction captures the intrinsic properties of the modelled geological phenomena or processes (Knoring and Dech, 1993).

As the emphasis in this study is placed on showcasing procedures in spatial and mathematical-statistical methods in mineral resources assessment, an archetype mineral system and terrane are prerequisites. Komatiite-associated nickel sulphide deposits in the Kalgoorlie Terrane, Western Australia were selected for this purpose because: (i) the terrane is the world's best studied and richest nickel sulphide province, (ii) the komatiite-associated nickel system is distinct, well understood and it is geologically well-constrained (i.e. predominantly hosted by komatiites) and temporally well constrained (i.e. about c. 2.7 Ga old).

6.1.2 Application of spatial analysis and mathematical-statistical concepts in this study

As proposed in Chapter 3, nickel sulphide deposits in the Kalgoorlie Terrane can be regarded as point realizations of stochastic mineralization processes. The framework for spatial and mathematical-statistical analysis of these deposits is described in Chapter 1 (section 1.4.2; Fig. 1.1). Komatiites in the Kalgoorlie Terrane constitute the full sample space (Ord, 1990) or, equivalently, the permissive tract (Singer, 1993) for analyses in this study (Fig. 1.1). The spatial analysis units in this study are komatiite bodies, which are mappable, naturally bound and disjoint sub-regions of the sample space (Ord, 1990). Some komatiite bodies are favourable to nickel mineralization and others are not (Fig. 1.1; Mamuse et al., 2010a). Unlike artificial quadrats, naturally bound spatial analysis units are less prone to edge effects that can significantly affect spatial analyses (Diggle, 1983; Haining, 1990a; Ripley, 1990). However, the precision with which komatiite bodies or any spatial analysis units are delineated may be influenced by mapping scale, degree of exposure and level of geological knowledge (Singer and Menzie, 2008).

In Chapter 3, it is shown that in the Kalgoorlie Terrane, mineralised komatiite bodies are clustered whereas nickel sulphide deposits within individual mineralised komatiite bodies are randomly distributed or dispersed and not clustered. The random distribution of deposits within mineralised komatiite bodies indicates relative spatial stationarity of mineralisation processes within komatiite bodies. Spatial stationarity, which implies that replication is possible from different partitions a komatiite body, is generally a reasonable assumption to make especially over a restricted geographical range (Diggle, 1983; Haining 1990b). This is perhaps a direct consequence of Tobler's (1970) First law of geography: 'everything is related to everything else, near things are more related than distant things' (p. 236).

It can be said that the implicit spatio-statistical goal of delineation of permissive geological units is to obtain analysis units over which stationarity can be reasonably assumed. Properties of a deposit point pattern are restricted to within each stationary permissive geological unit (e.g. komatiite body) and are not assumed to hold for points outside the geological unit (Haining, 1990b). For example the deposit density (number of deposits per km^2) represents an estimate of the intensity of a mineralisation process under the assumption that the process is stationary throughout each individual komatiite body.

In economic geology, as in this thesis, the location of mineral deposits has a special meaning that may shape exploration philosophy. Carlson (1991) suggested that one meaning of the saying, 'gold is where you find it' is that a prospective place to look for gold is near known gold deposits. Evidence for widespread belief in the saying, which is a manifestation of Tobler's (1970) law, is exhibited by the various gold rushes throughout history and the spatial and temporal distribution of exploration tenements and tenement activity. The saying can also be interpreted as suggesting that the locations of gold deposits are unpredictable; one can only know with certainty where gold is after its discovery. Another insightful view is that the presence of a mineral deposit bears testimony that the required mineralisation processes have occurred, with the deposit representing the ultimate focal point of the larger scale processes critical in the formation of mineral deposits (Hronsky, 2004). Thus some information about mineral deposits is encoded in their spatial locations, although not all the information can be easily decoded. Hence the proposition that location may be a surrogate for inherent complexities which are not easily recognisable or measured (Fotheringham et al., 2002).

Although individual locations of mineral deposits are important, understanding of the mineral system (Wyborn et al., 1994) can be enhanced by analysing the configuration or pattern of deposits in totality. Individual deposits essentially represent a continuous surface of metal endowment that has been discretized using arbitrary cut off grades. By applying a suitable interpolator, it is theoretically possible to reconstruct the natural continuous metal endowment surfaces. The reconstructed surfaces are better descriptors of metal endowment than individual deposits because of greater statistical support. The centrographic approach which embodies this concept is applied in this thesis (Chapter 5) to characterize nickel sulphide endowment in the Kambalda region of the Kalgoorlie Terrane using statistical slices. This analysis shows that certain spatio-geometric slices derived from the distribution of nickel sulphide deposits are good proxies for the distribution of mineralised komatiite units. This kind of analysis is potentially useful in delineating mineralised rock packages in mineral systems wherein the host rock types are not as distinctive as they are in the komatiite-associated nickel system (e.g. orogenic gold systems).

6.1.3 Geological uncertainties in this thesis

Uncertainty, or the vagueness, ambiguity or lack of determinability of phenomena, is prevalent in many academic fields, including geology and spatial analysis, due to imperfect knowledge of the natural world, limited measurement technology, and approximated methods (Mann, 1993; Bardossy and Fodor, 2001; Shi, 2010). In this thesis, uncertainty arises from three main sources: (i) delineation of komatiite bodies, (ii) deposit grouping, and (iii) incomplete deposit discovery and delineation.

Although the komatiite-associated nickel sulphide system is geologically better defined than other mineral systems, the delineation of geological units is not entirely definitive. For example, komatiite rocks in the Honeymoon Well area are so complexly deformed and juxtaposed that the Mt. Keith, Cliffs and Monument ultramafic units cannot be separately identified in that area (Chapter 2), making detailed lithology-based delineation difficult. Because of such geological complexities the Honeymoon Well-Mt. Keith-Yakabindie area has been presented as one control area (Chapter 4).

In order to create a consistent sampling unit and to minimise deposit miscounting in quantitative resource assessments, radial distances are generally used to combine orebodies into deposits (Bliss and Menzie, 1993; Singer, 1993a, 2008, 2010; Singer et al., 2001). Komatiitic peridotite-associated nickel orebodies in the Kalgoorlie Terrane, exemplified by the Kambalda camp (Chapter 2), exhibit large aspect ratios and are interpreted to occur along magma pathways or lava channels (Fig. 4.8). In this thesis therefore the orebodies were grouped according to the magma pathways they occupy. This ensures that orebodies that are most closely related genetically are grouped into deposits. However, as not all magma pathways are known or mapped, not enough geological information was available for grouping some of the deposits. This could have introduced some uncertainty in the deposit density models which are based on the power-law relation between the areas of mineralized komattite bodies and the numbers of deposits (or deposit groups) per km^2. However, the effect of this uncertainty is expected to be diminished by the use of endowment density models which are based on the power-law relation between the areas of the mineralized komatiite bodies and the endowment per km^2. The endowment density models consider the aggregate endowment of the deposits, rather than their numbers, and hence are unaffected by the way the deposits are grouped. More weight is placed on the endowment models and estimates by noting that nickel endowment is the more intrinsic property of a terrane than individual deposits.

The issues of delineation of permissive geological units and deposit grouping raised above relate to what is known as the modifiable areal unit problem (MAUP) in spatial analysis. MAUP refers to the variation in statistical results under alternative aggregation or partitioning schemes of spatial analysis units (Openshaw and Taylor, 1981; Openshaw, 1984; O'Sullivan and Unwin, 2003). However there is an emerging opinion suggesting that the MAUP problem is a consequence of using unsuitable models and methods (Tobler, 1989; Anselin, 1992; Marble, 2000).

Due to incomplete deposit discovery, incomplete resource delineation, and resource economic truncation known deposits are invariably a subset of the true but unknown geologic deposit population (Bultman et al., 1993; Blenkinsop, 2004). How this is handled in spatial analyses merits discussion because it has implications for interpretations of the analyses. This issue is often addressed through two assumptions. One assumption is that all deposits and endowment in assessment areas have been discovered. The other assumption is that known deposits represent a random sample of the geologic distribution of deposits (Blenkinsop and Sanderson, 1999).

In terms of spatial statistical analysis theory, the assumption that all deposits have been discovered implies that the point pattern has been mapped (i.e. all individual point events in the analysis unit have been recorded) and the assumption of randomly distributed deposits implies that the point pattern has been sampled (Diggle, 1983; Ord, 1990). In Chapter 3 where the objective is to determine the current spatial distribution of mineral deposits, any of the two paradigms can be assumed. In Chapter 4 it may be preferable to assume a mapped point pattern (i.e. that all deposits in control areas have been discovered) in the application of deposit and endowment density models. However, in the application of Zipf's law in the same chapter it is not necessary to make either of the two assumptions. Rather the focus is on the size of the largest deposit and the question becomes one of whether the largest deposit has been fully delineated or not.

In Chapter 5, both paradigms may work well because the centrographic mathematical statistics group individual deposits into robust statistical slices which may not be significantly affected by changes in the number of individual deposits.

Regarding the assumption of randomness, Diggle (1983) points out that it is not essential for sampling points to be randomly located according to a uniform distribution; they need only be well separated so that observations from different points can be assumed to be independent. This may explain the close resemblance between Fig. 3.5 (based on randomly generated points in mineralised komatiite bodies) and Fig. 3.6 (based on relatively sparse deposit points in mineralised komatiite bodies) in Chapter 3.

6.1.4 Implications of this study to nickel exploration in the Kalgoorlie Terrane

The two methods used in this thesis (both in Chapter 4) to estimate undiscovered nickel endowment in the Kalgoorlie Terrane are (i) deposit and endowment density regression modelling, and (ii) Zipf's law. Application of these methods is based on concepts discussed in section 6.1.2 and is subject to uncertainties in section 6.1.3. A clear understanding of the concepts, limitations (including uncertainties) and assumptions underpinning these methods enhances interpretation of the estimates.

Regression modelling applied in this thesis assumes that there exist in the Kalgoorlie Terrane a sufficient number of well explored komatiite bodies wherein almost all nickel sulphide deposits and endowment are known (i.e. control areas). The estimates presented in Chapter 4 pertain only to demonstrably mineralised komatiites in the Kalgoorlie Terrane. As explained above more weight is placed on estimates of nickel endowment because estimates of deposit numbers are sensitive to the way deposits used in the model are grouped. Based on the nickel endowment density model, the estimated amount of undiscovered nickel metal in the terrane is 3.0 to 10.0 Mt nickel metal, or 27 to 91 % of the currently known 11 Mt nickel metal.

The spatial analysis units for regression estimates are the individual komatiite bodies and the estimates are derived for each komatiite body. This may be desirable for exploration purposes because it permits local targeting at the scale of a komatiite body. However, as shown in Chapter 3 nickel sulphide deposits at this scale tend to be randomly distributed and are therefore not easily predictable, necessitating application of direct detection methods. Mineralised komatiite bodies themselves are, however, clustered and therefore more easily predictable.

The other approach utilised in this study to estimate nickel endowment in the Kalgoorlie Terrane is Zipf's law. Unlike regression method, Zipf's law was applied to estimate the total nickel endowment for the entire Kalgoorlie Terrane. Key assumptions in application of Zipf's law are: (i) the size of the largest deposit in the population under consideration is known, (ii) the deposit population under consideration obeys Zipf law, that is the size distribution of deposits in that population follows the relations captured in Eq. 4.7, i.e. the size of the largest deposit is twice the size of the second largest, thrice the size of the third largest and *n* times the size of the n^{th} largest deposit, where n is any deposit rank. Based on the currently known size of the largest deposit, Mt. Keith (about 2.77 Mt nickel metal), application of Zipf's law predicted that about 3.0 Mt nickel metal remains to be discovered in the Kalgoorlie Terrane. Remarkably, this estimate corresponds to the lower bound of the regression estimate given above.

But was the first assumption met in this estimation? That is, assuming that Mt. Keith is the largest deposit, has it been fully delineated? The consensus among industry experts is that the actual size of the Mt. Keith deposit, which is currently only delineated to open-cuttable depth, may be at least twice as large as currently known. Based on a projected size of 4.15 Mt nickel metal, the total undiscovered nickel metal in the Kalgoorlie Terrane rises to 10.0 Mt nickel metal. This is once again equal to the upper regression estimate but this is superficial non-significant coincidence. This is because the regression estimate is based on the assumption that all deposits in control areas, including the Mt. Keith deposit, have been discovered and are fully delineated.

The remarkable fit of Kalgoorlie Terrane's known nickel endowment distribution to the Zipf curve (based on known resources; Fig. 4.17) suggests that the terrane may be approaching nickel exploration maturity with only 3.0 Mt nickel metal remaining to be discovered. On the other hand if the projected size of 4.15 Mt nickel for Mt. Keith deposit is assumed, 10.0 Mt nickel metal (91% of currently known resources) is yet to be discovered and the Kalgoorlie Terrane is far from maturity. How can this discrepancy between the two estimates be explained? One explanation would be to suggest that the projected size estimate of the Mt. Keith deposit is incorrect.

However, the projection is based on some drilling beyond open-cuttable and therefore the estimate cannot simply be dismissed altogether.

The speculation that the Kalgoorlie Terrane or parts of it might be approaching exploration maturity is not new. According to Stone (1998), there was limited opportunity for discovering additional deposits containing greater than 100 kt nickel metal at or near the surface on the Kambalda Dome. He pointed out that this justified the shift in exploration focus to the search for deeper deposits lacking obvious surface footprints. Deeper exploration probably constitutes opening up of a new exploration search space (Hronsky and Schodde, 2006; Hronsky, 2009). The concept of exploration search space refers to the set of conditions or variables (e.g. ore type, cover type, available detection technology, and economic and political regimes) that constrain economically effective outcomes of the search process (Hronsky, 2009). According to Hronsky and Schodde (2006:10), 'the next driver for creating a new parameter space in the Yilgarn might be associated with the development of innovative techniques that allow the explorer to "see" through deeper cover'. Projecting the size of Mt. Keith deposit to twice its current size (i.e. to 4.15 Mt nickel metal) based on deeper drilling beyond open-cuttable resources is probably equivalent to creating a new exploration search space.

Using the concept of exploration search space it can be suggests that the Kalgoorlie Terrane is probably approaching maturity in terms of the current search space epitomized by the current size of Mt. Keith deposit. The undiscovered 3.0 Mt nickel metal in the initial search space plus 7.0 Mt nickel metal in the next search space make up the 10.0 Mt nickel metal predicted by projecting Mt. Keith to 4.15 Mt nickel metal. Therefore, the designation of a terrane or camp as mature is relative to the extent to which the exploration search space has been explored. This is because even in a mature camp, a new search space can be opened up leading to new discoveries that may even surpass earlier ones (Hronsky, 2009).

Thus the 3.0 Mt and10.0 Mt undiscovered nickel metal estimated using Zipf's law can be considered as separate estimates unlike the 3.0 to 10.0 Mt nickel metal estimated using regression analysis. The latter is a range based on a 95% prediction interval wherein there is a 95 % chance that the undiscovered nickel endowment is

3.0 Mt or more, a 5% chance that it is 10.0 Mt or more, and a 50% chance that it is 5.5 Mt or more. In other words, the lower the estimate, the higher the chance of its attainability. The lower estimate is further corroborated by the 3.0 Mt nickel metal estimated using Zipf's analysis based on the currently known resources at Mt Keith.

In the final analysis therefore it can be stated that in the current exploration search space, the Kalgoorlie Terrane is approaching nickel exploration maturity with only about 3.0 Mt nickel metal remaining to be discovered. All of the 3.0 Mt nickel metal is accounted for by demonstrably mineralised komatiites in the Kalgoorlie Terrane, suggesting that no significant nickel endowment exists in known komatiites that are not currently demonstrably mineralised. This strongly supports the hypothesis of Hronsky and Schodde, 2006 that, 'the only realistic opportunities for finding entire new belts (mineralised komatiites) in the Yilgarn province are where such belts are largely covered' (p.10).

6.1.5 Guidelines for application to other mineral systems

Although best demonstrated by a well defined mineral system such as komatiite-associated nickel sulphide system, methods presented in this thesis are potentially applicable to any mineral system (*sensu* Wyborn et al., 1994) anywhere in the world where the geology can be abstracted with some fidelity and which is relatively mature in terms of exploration. The general framework for application of the methodology is presented in Fig. 6.1.

A spatial analysis framework, such as Figure 1.1, constitutes a key component of the general framework (Fig. 6.1). As shown in Figure 6.1, whether the deposits within the selected spatial analysis unit are clustered or not affects the methods available for subsequent analyses. Statistical models such as the Poisson, Neyman-Scott and binomial models can be applied, but they do not take into account the well established variability between size of analysis units and mineral deposit density or mineral endowment density. Therefore, regression models are generally preferred. For non-clustered deposit patterns, deposit density (deposits/ km^2) is an appropriate estimator of intensity of the pattern. Although this formulation of deposit density can be applied to clustered patterns, more appropriate estimators such as those listed in Ord (1990) apply in this case.

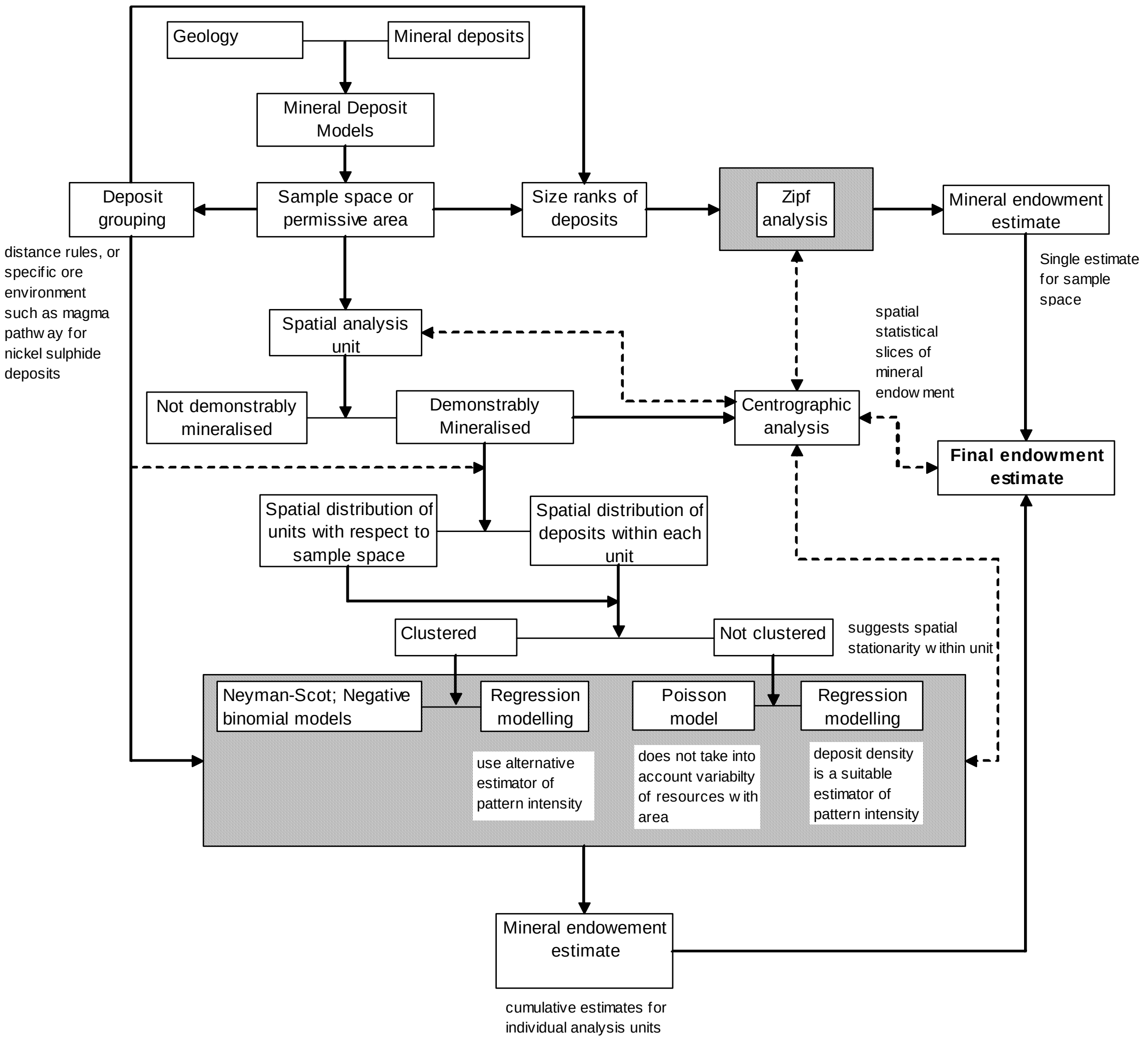


Fig. 6.1 General framework for application of the mineral resources assessment methodology proposed in this thesis. Solid lines denote the sequencing of processes as applied in this thesis whereas the dashed lines denote alternative sequencing or potential applications.

As regression endowment estimates are cumulated over selected analysis units of the sample space, they may be complemented with endowment estimates for the entire terrane to give an indication of the size of endowment outside the selected units. If it is considered that the parent endowment distribution follows Zipf's law, and that the largest deposit within the sample space has been fully delineated, Zipf's law constitutes an effective method of estimating the global endowment of the sample space. Comparative analysis of the Zipf's and regression endowment estimates provides the final endowment estimate (Fig. 6.1). The figure also highlights the potential role of centrographic analyses in spatially apportioning endowment and delineation of analysis units.

6.2 Conclusions

This thesis has the following major conclusions.

1. The komatiite-associated nickel sulphide system is amenable to spatio-mathematical-statistical manipulation because it is geologically and temporally relatively well defined.

2. A workable spatial-statistical framework for analysis of the komatiite-associated nickel sulphide system in the Kalgoorlie Terrane is as follows. Komatiites in the terrane constitute the full sample space or the permissive tract. Disjoint, naturally bound individual komatiite bodies that make up the sample space are appropriate spatial analysis units. These analysis units can be divided into those that are favourable to nickel mineralization and those that are not. These spatial analysis units can be used to determine the spatial pattern of deposits and to calculate deposit density for predictive purposes.

3. Spatial point pattern analyses show that although the host komatiite bodies in the Kalgoorlie Terrane are clustered within the sample space, deposits in these host komatiite bodies are not clustered. Thus models that assume clustering at the scale of komatiite bodies in the Kalgoorlie Terrane would tend to overestimate the number of nickel sulphide deposits and/ or endowment. Although mineral deposits on most maps appear clustered, assessing clustering this way is commonly illusory (Diggle, 1983; Ford and Blenkinsop, 2008; Singer and Menzie, 2008) and must be explicitly tested as discussed in Chapter 3.

4. Using the exemplar komatiite-associated nickel sulphide system of the Kalgoorlie Terrane, this study has shown that deposit density models hitherto based on well explored regions (control areas) distributed worldwide, can be usefully adapted to the local terrane scale using local control areas. In this case 12 most explored komatiite bodies were selected as the local control areas against which deposit

estimates for the less explored control areas are estimated using control area-based regression models.

5. Endowment density can be directly used to estimate mineral endowment. In fact, endowment density may be the more fundamental property of a terrane than deposit density.

6. Spatial centrographic methods presented in this thesis offer an alternative delineation method based on statistical geometries rather than geological units. The close match between the two in the case of komatiite-hosted nickel sulphide deposits on the Kambalda Dome attests to potential reliability of the centrographic technique.

7. Regression modelling of nickel endowment densities suggests that there is a 95 % chance that the undiscovered nickel endowment in less explored demonstrably mineralised komatiite bodies in the Kalgoorlie Terrane is 3.0 Mt or more. Zipf's law predicts that the total undiscovered nickel endowment for the entire terrane, based on the current size of Mt. Keith deposit, is about 3.0 Mt nickel metal. Collectively, these results suggest that virtually all the undiscovered nickel endowment in the Kalgoorlie Terrane is contained in komatiites that are already known to be mineralised. In other words, there may not be significant undiscovered nickel endowment in known komatiite bodies in the Kalgoorlie Terrane that are not at present demonstrably mineralised. If the projected size of Mt. Keith (4.15 Mt nickel metal) is applied, the Zipf estimate jumps to 10.0 Mt nickel metal. This can be explained in terms of a new exploration search space.

8. Although best demonstrated by a well defined mineral system such as komatiite-associated nickel sulphide system, methods presented in this thesis are potentially applicable to any mineral system anywhere in the world where the geology can be abstracted with some fidelity and which are relatively mature in terms of exploration. More generally, amenability of the geological system to mathematical modelling is attributable to the fact that geological phenomena and processes are subject to physical, chemical and biological processes that are themselves governed by inherently mathematical-statistical natural laws. The

major drawbacks are limitations in human cognition capabilities which escalate with system complexity, thus introducing uncertainties.

The regression models developed in this study can be directly applied to less mature komatiite-associated nickel sulphide provinces that are geologically similar to the Kalgoorlie Terrane to derive first approximations of the nickel sulphide endowment. Such areas include Southern Africa and Brazil. In more mature komatiite-associated nickel sulphide provinces such as those in Canada and Finland, models similar to those developed for the Kalgoorlie Terrane may be locally derived and applied.

References

Anselin, L. 1990. What is special about spatial data? Alternative perspectives on spatial data analysis, in: Griffith, D.A. (Ed.), Spatial Statistics, Past, Present and Future. Institute of Mathematical Geography, Ann Arbor, ML, pp. 63-77.

Anselin, L. 1992. Spatial data analysis with GIS: an introduction to application in the social sciences. Technical Report 92-10, University of California, 53 pp.

Bardossy, G., Fodor, J., 2001. Traditional and new ways to handle uncertainty in geology. Natural Resources Research 10, 179-187.

Blenkinsop, T. G., 2004, Applications of fractal geometry to mineral exploration. Extended abstracts, in: SEG 2004 Conference, Predictive Mineral Discovery Under Cover, Extended Abstracts. SEG 2004 Conference, 27 September-1 October 2004 Perth, Western Australia.

Blenkinsop, T.G., Sanderson, D.J., 1999. Are gold deposits in the crust fractals? A study of gold mines in the Zimbabwean craton, in: McCaffrey, K.J.W., Lonergan, L.,Wilkinson, J.J. (Eds.), Fractures, Fluid Flow and Mineralization. Geological Society Special Publication 155, pp. 141-151.

Bliss, J.D., Menzie W.D., 1993. Spatial mineral-deposit models and the prediction of undiscovered mineral deposits, in: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), Mineral deposit modeling. Geological Association Canada Special Paper 40, 693-706.

Carlson, C.A., 1991. Spatial distribution of mineral deposits. Geology 19, 111- 114.

Diggle, P.J., 1983. Statistical analysis of spatial point patterns. Academic Press, London, 148 pp.

Fotheringham, A.S., Brundson, C., Charlton, M., 2002. Geographically weighted regression: the analysis of spatially varying relationships. John Willey and Sons, West Sussex, UK, 269 pp.

Haining, R., P. 1990a. Models in human geography: problems in specifying, estimating and validating models for spatial data. in: Griffith, D.A. (Ed.), Spatial Statistics, Past, Present and Future. Institute of Mathematical Geography, Ann Arbor, ML, pp. 83-102.

Haining, R. 1990b. Spatial data analysis in the social and environmental sciences. Cambridge University Press, Cambridge, 409 pp.

Hronsky, J.M.A., 2004. The science of exploration targeting, in: Muhling, J., Goldfarb,R., Vielreicher, N., Bierlein, F., Stumpfl, E., Groves, D., Kenworthy, S. (Eds.), Predictive Mineral Discovery Under Cover, Extended Abstracts. SEG 2004 Conference, 27 September-1 October 2004, Perth, Western Australia Perth, pp. 129-133.

Knoring, L.D. and Dech, V.N., 1993. Mathematics for geologists, in: Zeidler, R.B., (Ed.), Geotechnika 10, Netherlands, A.A. Balkema, 200 pp.

Mamuse, A., Porwal, A., Kreuzer, O.P., and Beresford, S., 2009. A new method for centrographic analysis of mineral deposit clusters. Ore Geology Reviews 36, 293-305.

Mamuse, A., Porwal, A., Kreuzer, O., Beresford, S.W., 2010a. Spatial statistical analysis of the distribution of komatiite-hosted nickel sulfide deposits of the Kalgoorlie Terrane, Western Australia: clustered or not? Economic Geology 105, 229-242.

Mann, C.J., 1993. Uncertainty in geology, in: Davis, J.C., Herzfeld, U.C. (Eds.), Computers in geology – 25 years of progress. Oxford University Press, pp. 241-254.

Marble, D.S. 2000. Some thoughts on the integration of spatial analysis and geographic information systems. Journal of Geographical Systems 2, 31-35.

Openshaw, S. 1984. The modifiable areal unit problem. Concepts and Techniques in Modern Geography 38 Geo Books, Norwich, 41 pp.

Openshaw, S. and Taylor, P.J. 1981. The modifiable areal unit problem, in: Wrigley, N. and Bennett, R.J. (Eds.), Quantitative Geography: a British view. Routledge and Kegan Paul, pp. 60-69.

Ord, J.K. 1990. Statistical methods for point pattern data. in: Griffith, D.A. (Ed.), Spatial Statistics, Past, Present and Future. Institute of Mathematical Geography, Ann Arbor, ML, pp. 31-53.

O'Sullivan, D and Unwin, D. J. 2003. Geographic information analysis. John Willey and Sons, New Jersey, 436 pp.

Ripley, 1990. Gibbsian Interaction models, in: Griffith, D.A. (Ed.), Spatial Statistics, Past, Present and Future. Institute of Mathematical Geography, Ann Arbor, ML, pp. 3-25.

Shi, W., 2010. Principles of modeling uncertainties in spatial data and spatial analyses. CRC Press, Taylor & Francis Group, Boka Raton, 412 pp.

Singer, D.A., 1993a. Basic concepts in three-part quantitative assessments of undiscovered mineral resources. Nonrenewable Resources 2, 69–81.

Singer, D.A. and Menzie, W.D., 2008. Map scale effects on estimating the number of undiscovered mineral deposits. Natural Resources Research 17, 79-86.

Thiergärtner, H., 2006. Theory and Practice in Mathematical Geology-introduction and discussion. Mathematical Geology 38, 659-665.

Tobler, W. 1970. A computer movie simulating urban growth in the Detroit region. Economic Geography 46, 234-240.

Tobler, W., 1989. Frame independent analysis, in: Goodchild, M and Gopal, S. (Eds.), The Accuracy of Spatial Databases, London, Taylor and Francis, pp115-122.

Wyborn L.A.I., Heinrick C.A., Jaques A.L. 1994. Australian Proterozoic mineral systems: essential ingredients and mappable criteria. 1994 AusIMM Annual Conference, The Australasian Institute of Mining and Metallurgy Publication Series 5/95, 109–115.

APPENDICES

APPENDIX 1

List of nickel sulphide deposits and prospects utilised in this study

	Komatiite body			Nickel sulphide deposits								
				Deposit groups[2]			Deposits					
Domain	Serial number	Name (D, P)[1]	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	Longitude[3]	Latitude[4]
Boorara	1	Amy Ricks (P)			-		1	Amy Ricks			120.8897	-28.1961
	2	Antioch (P)			-		2	Antioch			120.9510	-28.4523
	3	Antioch East (P)			-		3	Antioch East			120.9591	-28.4776
	4	Black Swan (D)	374.0	1	Black Swan	296.0	4	Black Swan	0.8	296.0	121.6343	-30.3990
				2	Cygnet	40.0	5	Cygnet	1.3	40.0	121.6323	-30.3956
				3	Silver Swan	38.0	6	Silver Swan	9.4	38.0	121.6319	-30.3933
	5	Blair (P)	23.0	4	Blair	22.0	7	Blair	1.0	22.0	121.7150	-30.9110
				5	Blair South	1.0	8	Blair South	1.4	1.0	121.7105	-30.9456
	6	Carnilya Hill (P)	88.9	6	Carnilya East	65.3	9	Carnilya East	3.7	65.3	121.8622	-31.0544
				7	Dunlop	5.8	10	Dunlop	1.9	5.8	121.8017	-31.0386
				8	Goodyear	16.0	11	Goodyear	4.1	16.0	121.7965	-31.0367
				9	Zone 29	1.8	12	Zone 29	3.0	1.8	121.8105	-31.0491

Notes

[1]D stands for komatiitic dunites and P for komatiitic peridotites (see Chapter 2)

[2]Deposits in the Kambalda, Tramways and Black Swan camps have been grouped according to the magma pathway in which they occur (See chapters 2 and 4). komatiites for which magma pathways have not been mapped, each deposit is assumed to be within a magma pathway and, therefore, constituting a 'group'. Only deposit groups within control areas (Appendix B) have been named and numbered in this list.

[3]Longitude and [4]latitude are deposit coordinates in decimal degrees (GDA 1994 datum).

[5]The Wroth nickel sulphide resources are incorporated in the Gellatly resources.

APPENDIX 1 **(continued)**

List of nickel sulphide deposits and prospects utilised in this study

	Komatiite body			Nickel sulphide deposits								
				Deposit groups[2]			Deposits					
Domain	Serial number	Name (D, P)[1]	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	Longitude[3]	Latitude[4]
Boorara	7	Carthage (P)			-		13	Carthage			120.9132	-28.1866
	8	Cliffs (P)	127.0		-	127.0	14	Cliffs	2.3	127.0	120.5510	-27.3129
					-		15	Spinifex Park			120.5589	-27.3243
	9	Deep South (P)			-		16	Deep South			120.9326	-28.2159
	10	Delphi (P)			-		17	Delphi			120.8491	-28.4512
	11	Fly Bore (P)			-		18	Fly bore			120.9282	-28.1939
	12	Golden Valley (P)			-		19	Golden Valley			121.6100	-30.5700
	13	Harmony (P)	74.0		-		20	Harmony	2.3	74.0	120.6883	-27.7729
	14	Hayes (D)			-		21	Hayes			120.1597	-26.5658
	15	Honeymoon Well-Mt Keith-Yakabindie (D)	5,912.4	10	Corella	322.9	22	Corella	0.7	322.9	120.3800	-26.8787
				11	Hannibals	290.0	23	Hannibals	0.7	290.0	120.3780	-26.9200
				12	Harakka	29.6	24	Harakka	0.8	29.6	120.3760	-26.9190
				13	Harrier	379.3	25	Harrier	0.6	379.3	120.3960	-26.9450

Notes

[1]D stands for komatiitic dunites and P for komatiitic peridotites (see Chapter 2)

[2]Deposits in the Kambalda, Tramways and Black Swan camps have been grouped according to the magma pathway in which they occur (See chapters 2 and 4). In komatiites for which magma pathways have not been mapped, each deposit is assumed to be within a magma pathway and, therefore, constituting a 'group'. Only deposit groups within control areas (Appendix B) have been named and numbered in this list.

[3]Longitude and [4]latitude are deposit coordinates in decimal degrees (GDA 1994 datum).

[5]The Wroth nickel sulphide resources are incorporated in the Gellatly resources.

APPENDIX 1 **(continued)**

List of nickel sulphide deposits and prospects utilised in this study

				Nickel sulphide deposits								
	Komatiite body			[2]Deposit groups			Deposits					
Domain	Serial number	Name [1](D, P)	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	[3]Longitude	[4]Latitude
Boorara	15	Honeymoon Well-Mt Keith-Yakabindie (D)	5,912.4	14	Jericho	207.0	26	Jericho	0.6	207.0	120.4468	-27.0376
				15	Kingston		27	Kingston			120.4140	-26.9660
				16	Wedgetail	260.6	28	Wedgetail	1.0	260.6	120.3450	-26.8746
				17	Fortuna		29	Fortuna			120.5660	-27.3973
				18	Betheno		30	Betheno			120.5769	-27.4191
				19	David		31	David			120.5821	-27.4425
				20	Goliath Central		32	Goliath Central			120.5882	-27.4565
				21	Goliath North	458.0	33	Goliath North	0.6	458.0	120.5888	-27.4504
				22	Goliath South		34	Goliath South			120.5927	-27.4690
				23	Six Mile	1198.0	35	Six Mile	0.6	1198.0	120.5765	-27.4277
				24	Mt. Keith - MKD5	2767.0	36	Mt. Keith-MKD5	0.6	2767.0	120.5430	-27.2300
				25	Mt. Keith - MKD49		37	Mt. Keith-MKD49			120.5422	-27.2186
				26	Sarah's Find		38	Sarahs Find			120.5337	-27.1983

Notes

[1]D stands for komatiitic dunites and P for komatiitic peridotites (see Chapter 2)

[2]Deposits in the Kambalda, Tramways and Black Swan camps have been grouped according to the magma pathway in which they occur (See chapters 2 and 4). In komatiites for which magma pathways have not been mapped, each deposit is assumed to be within a magma pathway and, therefore, constituting a 'group'. Only deposit groups within control areas (Appendix B) have been named and numbered in this list.

[3]Longitude and [4]latitude are deposit coordinates in decimal degrees (GDA 1994 datum).

[5]The Wroth nickel sulphide resources are incorporated in the Gellatly resources.

APPENDIX 1 **(continued)**

List of nickel sulphide deposits and prospects utilised in this study

				Nickel sulphide deposits								
	Komatiite body			[2]Deposit groups			Deposits					
Domain	Serial number	Name [1](D, P)	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	[3]Longitude	[4]Latitude
Boorara	15	Honeymoon Well-Mt Keith-Yakabindie (D)	5,912.4	27	East Spinifex Park		39	Spinifex Park East			120.5595	-27.3240
	16	Horn (P)	8.3		-	8.3	40	Horn	1.4	8.3	120.9253	-28.1661
					-		41	Roadside			120.9081	-28.1459
	17	Jungle Jewel (P)			-		42	Jungle Jewel			120.8991	-28.3565
	18	Longbow (D)			-		43	Longbow			120.1597	-26.5658
	19	Marshall (P)			-		44	Marshall			121.6913	-30.8893
	20	Melon-11 Mile Well (D)	11.0		-		45	11 Mile Well	2.0	11.0	120.7373	-27.8778
					-		46	Melon			120.7232	-27.8477
	21	Menzies (P)			-		47	Menzies			121.1040	-29.7442
	22	Mt. Clifford (D)	9.4	28	Mariott's	9.4	48	Marriott's	1.1	9.4	120.9910	-28.4510
				29	Randal's Find		49	Randals Find			120.9903	-28.4714
				30	Salute		50	Salute			121.0323	-28.4585
	23	Mt. Jewel (P)	1.7		-		51	Mt Jewel	2.0	1.7	121.4405	-30.1918

Notes

[1]D stands for komatiitic dunites and P for komatiitic peridotites (see Chapter 2)

[2]Deposits in the Kambalda, Tramways and Black Swan camps have been grouped according to the magma pathway in which they occur (See chapters 2 and 4). In komatiites for which magma pathways have not been mapped, each deposit is assumed to be within a magma pathway and, therefore, constituting a 'group'. Only deposit groups within control areas (Appendix B) have been named and numbered in this list.

[3]Longitude and [4]latitude are deposit coordinates in decimal degrees (GDA 1994 datum).

[5]The Wroth nickel sulphide resources are incorporated in the Gellatly resources.

APPENDIX 1 **(continued)**

List of nickel sulphide deposits and prospects utilised in this study

	Komatiite body			Nickel sulphide deposits								
				[2]Deposit groups			Deposits					
Domain	Serial number	Name [1](D, P)	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	[3]Longitude	[4]Latitude
Boorara					-		52	Ringlock			121.3964	-30.1434
	24	Mt. Martin (P)			-		53	Mt. Martin			121.6800	-31.0100
	25	Mt. Newman (D)			-		54	Mt Newman			121.0844	-28.4972
	26	Perseverance (D)	1,055.0	31	A1		55	A1			120.7055	-27.8141
				32	Perseverance	1055.0	56	Perseverance	0.9	1055.0	120.7077	-27.8205
				33	Progress		57	Progress			120.7063	-27.8117
	27	Perseverance East (P)			-		58	Perseverance East			120.7128	-27.8186
	28	Quinn Hills (P)			-		59	Quinn Hills			120.5165	-28.9989
	29	Rocky's Reward (P)	334.0		-		60	Rocky's Reward	2.1	334.0	120.6969	-27.7915
	30	Saints (P)	5.0		-		61	St. Andrew's			121.2251	-30.0580
					-		62	St. Patrick's	3.7	5.0	121.2288	-30.0660
	31	Schmitz Well (D)			-		63	Schmitz Well			120.8350	-28.5320
	32	Schmitz Well South (D)			-		64	Schmitz Well South			120.8303	-28.5869

Notes

[1]D stands for komatiitic dunites and P for komatiitic peridotites (see Chapter 2)

[2]Deposits in the Kambalda, Tramways and Black Swan camps have been grouped according to the magma pathway in which they occur (See chapters 2 and 4). In komatiites for which magma pathways have not been mapped, each deposit is assumed to be within a magma pathway and, therefore, constituting a ‘group’. Only deposit groups within control areas (Appendix B) have been named and numbered in this list.

[3]Longitude and [4]latitude are deposit coordinates in decimal degrees (GDA 1994 datum).

[5]The Wroth nickel sulphide resources are incorporated in the Gellatly resources.

APPENDIX 1 **(continued)**

List of nickel sulphide deposits and prospects utilised in this study

	Komatiite body			Nickel sulphide deposits								
				[2]Deposit groups			Deposits					
Domain	Serial number	Name [1](D, P)	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	[3]Longitude	[4]Latitude
Boorara	33	Scotia (P)	37.2		-		65	Scotia	2.9	37.2	121.2611	-30.2030
	34	Serp Hill (D)			-		66	Serp Hill North			120.5805	-27.4567
					-		67	Serp Hill South			120.5826	-27.4619
	35	Sinclair (P)	47.3		-		68	Sinclair	2.9	47.3	120.8670	-28.3640
					-		69	Skye			120.8657	-28.3699
	36	Sir Samuel (D)			-		70	Sir Samuel			120.6573	-27.6965
	37	Weebo (D)	88.0		-		71	Weebo	0.7	88.0	120.8203	-28.0474
Coolgardie	38	Nepean (P)	45.6		-		72	Bouchers			121.1022	-31.0536
					-		73	Miriam			121.0870	-31.0890
					-		74	Nepean	2.7	45.6	121.0895	-31.1933
	39	Riverina (P)			-		75	Riverina			120.5608	-29.7522
Depot	40	Widgiemooltha- outer (P)	137.2	34	Mariners	58.9	76	Mariners	3.0	58.9	121.6580	-31.6300
				35	Miitel	39.9	77	Miitel	3.6	39.9	121.6482	-31.5856

Notes

[1]D stands for komatiitic dunites and P for komatiitic peridotites (see Chapter 2)

[2]Deposits in the Kambalda, Tramways and Black Swan camps have been grouped according to the magma pathway in which they occur (See chapters 2 and 4). In komatiites for which magma pathways have not been mapped, each deposit is assumed to be within a magma pathway and, therefore, constituting a 'group'. Only deposit groups within control areas (Appendix B) have been named and numbered in this list.

[3]Longitude and [4]latitude are deposit coordinates in decimal degrees (GDA 1994 datum).

[5]The Wroth nickel sulphide resources are incorporated in the Gellatly resources.

APPENDIX 1 **(continued)**

List of nickel sulphide deposits and prospects utilised in this study

	Komatiite body			Nickel sulphide deposits								
				[2]Deposit groups			Deposits					
Domain	Serial number	Name [1](D, P)	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	[3]Longitude	[4]Latitude
Depot	40	Widgiemooltha-outer (P)		36	Redross	37.0	78	Redross	3.3	37.0	121.6474	-31.6852
				37	Unmin 1	1.4	79	Unmin 1	1.5	1.4	121.6424	-31.5735
	41	Widgiemooltha-inner (P)	171.1	38	132N	8.4	80	132N	1.7	8.4	121.5410	-31.4550
				39	14N	3.0	81	14N		3.0	121.5390	-31.4920
				40	26N-Mt Edwards	26.0	82	26N-Mt Edwards	2.7	26.0	121.5380	-31.4830
				41	332N	7.0	83	332N		7.0	121.5183	-31.4092
				42	Dordie Rocks North	2.2	84	Dordie Rocks North	1.5	2.2	121.6344	-31.5936
				43	Spargoville 5D	23.8	85	Spagoville 5D	2.5	23.8	121.4990	-31.3590
				44	Armstrong	12.0	86	Armstrong	2.0	12.0	121.5242	-31.4236
				45	Cooke-166N	2.5	87	Cooke-166N	1.3	2.5	121.5410	-31.4450
				46	McEwen-360N	11.0	88	McEwen-360N		11.0	121.5153	-31.4009
				47	Munda	5.0	89	Munda	1.9	5.0	121.5278	-31.5029
				48	Spagoville 5A	1.1	90	Spargoville 5A	3.7	1.1	121.5010	-31.3580

Notes

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[2]Deposits in the Kambalda, Tramways and Black Swan camps have been grouped according to the magma pathway in which they occur (See chapters 2 and 4). In komatiites for which magma pathways have not been mapped, each deposit is assumed to be within a magma pathway and, therefore, constituting a 'group'. Only deposit groups within control areas (Appendix B) have been named and numbered in this list.

[3]Longitude and [4]latitude are deposit coordinates in decimal degrees (GDA 1994 datum).

[5]The Wroth nickel sulphide resources are incorporated in the Gellatly resources.

APPENDIX 1 **(continued)**

List of nickel sulphide deposits and prospects utilised in this study

	Komatiite body			Nickel sulphide deposits								
				[2]Deposit groups			Deposits					
Domain	Serial number	Name [1](D, P)	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	[3]Longitude	[4]Latitude
Depot	41	Widgiemooltha-inner (P)		49	Spargoville 1A	0.0	91	Spargoville 1A			121.4910	-31.3200
				50	Spargoville 2 or 5B	4.9	92	Spargoville 2 or 5B	1.9	4.9	121.5041	-31.3672
				51	Wannaway	38.9	93	Wannaway	2.4	38.9	121.5164	-31.6087
				52	Wannaway North	4.3	94	Wannaway North		4.3	121.5021	-31.5679
				53	Widgie 3	10.5	95	Widgie 3	1.5	10.5	121.5857	-31.5181
				54	Widgie Townsite	0.0	96	Widgie Townsite			121.5754	-31.5041
				55	Zabel-384N	10.5	97	Zabel-384N	1.8	10.5	121.5110	-31.3880
Kambalda	42	Bluebush (P)	23.4		-		98	Cameron	1.5	2.6	121.8290	-31.6380
					-		99	Lawry			121.8158	-31.6308
					-		100	Stockwell-Grimsby	3.0	20.8	121.7650	-31.5830
	43	Silver Lake/ Kambalda (P)	1,134.7	56	Beta	22.0	101	Alpha Island			121.6906	-31.2377
							102	Beta		22.0	121.7007	-31.2465
				57	Coronet-Loreto	2.4	103	Coronet	2.5	2.0	121.6457	-31.1774

Notes

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[2]Deposits in the Kambalda, Tramways and Black Swan camps have been grouped according to the magma pathway in which they occur (See chapters 2 and 4). In komatiites for which magma pathways have not been mapped, each deposit is assumed to be within a magma pathway and, therefore, constituting a 'group'. Only deposit groups within control areas (Appendix B) have been named and numbered in this list.

[3]Longitude and [4]latitude are deposit coordinates in decimal degrees (GDA 1994 datum).

[5]The Wroth nickel sulphide resources are incorporated in the Gellatly resources.

APPENDIX 1 **(continued)**

List of nickel sulphide deposits and prospects utilised in this study

				Nickel sulphide deposits								
	Komatiite body			[2]Deposit groups			Deposits					
Domain	Serial number	Name [1](D, P)	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	[3]Longitude	[4]Latitude
Kambalda	43	Silver Lake/ Kambalda (P)	1,134.7				104	Loreto	1.9	0.4	121.6505	-31.1801
				58	Durkin North-Gibb-Victor	82.5	105	Durkin North	5.0	18.8	121.6651	-31.1620
							106	Gibb	3.6	0.9	121.6800	-31.1757
							107	Gibb South			121.6833	-31.1816
							108	McLeay	5.4	28.6	121.6932	-31.2036
							109	Victor	3.7	19.5	121.6890	-31.1940
							110	Victor South	3.7	14.7	121.6920	-31.1993
				59	Fisher	43.8	111	Fisher	2.7	43.8	121.6615	-31.2027
				60	Gellatly		112	Gellatly[5]	3.4	7.0	121.6416	-31.1677
				61	Gordon-Wroth	8.0	113	Gordon	1.6	1.0	121.6453	-31.1669
							114	Wroth[5]	-	-	121.6403	-31.1614
				62	Hunt	33.0	115	Hunt	2.6	33.0	121.6867	-31.2264
				63	Long	241.4	116	Long	4.6	241.4	121.6874	-31.1823

Notes

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[2]Deposits in the Kambalda, Tramways and Black Swan camps have been grouped according to the magma pathway in which they occur (See chapters 2 and 4). In komatiites for which magma pathways have not been mapped, each deposit is assumed to be within a magma pathway and, therefore, constituting a 'group'. Only deposit groups within control areas (Appendix B) have been named and numbered in this list.

[3]Longitude and [4]latitude are deposit coordinates in decimal degrees (GDA 1994 datum).

[5]The Wroth nickel sulphide resources are incorporated in the Gellatly resources.

APPENDIX 1 **(continued)**

List of nickel sulphide deposits and prospects utilised in this study

				Nickel sulphide deposits								
	Komatiite body			[2]Deposit groups			Deposits					
Domain	Serial number	Name [1](D, P)	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	[3]Longitude	[4]Latitude
Kambalda	43	Silver Lake/ Kambalda (P)	1,134.7	64	Lunnon	186.2	117	East Alpha	4.5	24.7	121.6997	-31.2353
							118	Lunnon	3.0	161.5	121.6880	-31.2154
				65	McMahon-Ken	75.0	119	Ken	4.3	20.0	121.6427	-31.1854
							120	McMahon	3.4	39.8	121.6388	-31.1732
							121	McMahon Deeps	4.1	15.2	121.6357	-31.1699
				66	Otter Juan-Durkin	440.4	122	Durkin	3.9	135.2	121.6647	-31.1666
							123	Otter Juan	3.8	305.2	121.6541	-31.1649
	44	St. Ives (P)	144.3	67	East Cooee	5.5	124	East Cooee	2.2	5.5	121.7962	-31.3488
				68	Foster	86.9	125	Foster	2.8	86.9	121.7511	-31.3473
				69	Jan	49.4	126	Jan	2.7	49.4	121.8030	-31.3760
				70	NW Foster	2.4	127	NW Foster	2.3	2.4	121.7458	-31.3442
	45	Talbot Island (P)					128	Talbot Island			121.8578	-32.0525
	46	Tramways (P)	263.3	71	Cruikshank	28.4	129	Cruikshank	1.4	28.4	121.8865	-31.4694

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[3]Longitude and [4]latitude are deposit coordinates in decimal degrees (GDA 1994 datum).

[5]The Wroth nickel sulphide resources are incorporated in the Gellatly resources.

APPENDIX 1 **(continued)**

List of nickel sulphide deposits and prospects utilised in this study

	Nickel sulphide deposits											
	Komatiite body			[2]Deposit groups			Deposits					
Domain	Serial number	Name [1](D, P)	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	[3]Longitude	[4]Latitude
	46	Tramways (P)	263.3	72	Edwin	9.0	130	Edwin	5.2	9.0	121.8303	-31.5077
				73	Edwin West	0.0	131	West Edwin			121.8278	-31.5106
				74	Ham	0.8	132	Ham	1.2	0.8	121.8253	-31.5096
				75	Helmut-Deacon	106.2	133	Deacon	2.9	63.6	121.8600	-31.5056
							134	Helmut	2.6	26.6	121.8601	-31.5003
							135	Helmut South	2.4	16.1	121.8610	-31.5048
				76	John-McComish	18.6	136	John	1.5	2.6	121.8729	-31.4938
							137	McComish	1.3	16.0	121.8724	-31.4978
				77	Joy		138	Joy			121.8452	-31.4864
				78	Lanfranchi	47.4	139	Lanfranchi	2.5	47.4	121.8367	-31.5069
				79	Martin	2.0	140	Martin	2.0	2.0	121.8356	-31.5114
				80	Winner-Schmitz-Skinner	50.9	141	Schimitz	4.8	29.1	121.8542	-31.5005
							142	Skinner	5.2	13.3	121.8540	-31.5027
							143	Winner	4.7	8.6	121.8523	-31.4958

Notes

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APPENDIX 1 **(continued)**

List of nickel sulphide deposits and prospects utilised in this study

	Komatiite body			Nickel sulphide deposits								
				Deposit groups[2]			Deposits					
Domain	Serial number	Name [1](D, P)	Ni ('000 t)	Serial number	Name	Ni ('000 t)	Serial number	Deposit Name	% Ni	Ni ('000 t)	[3]Longitude	[4]Latitude
Ora Banda	47	Acacia Ridge (P)					144	Acacia Ridge				
	48	Cosmos (D)	649.9	81	Alec Mairs	88.6	145	Alec Mairs	6.6	88.6	120.5752	-27.6034
				82	Anomaly 1	120.0	146	Anomaly 1	1.0	120.0	120.5769	-27.6048
				83	Anomaly 3		147	Anomaly 3			120.5776	-27.6472
				84	Anomaly 6		148	Anomaly 6			120.5737	-27.6074
				85	Anomaly 9		149	Anomaly 9			120.5752	-27.6290
				86	Cosmos	351.5	150	Cosmos	0.9	351.5	120.5762	-27.6000
				87	Mercury		151	Mercury			120.5764	-27.5737
				88	North Cosmos		152	North Cosmos			120.5722	-27.5930
				99	Prospero	79.2	153	Prospero	6.0	79.2	120.5797	-27.6374
				90	Tapinos	10.5	154	Tapinos	7.4	10.5	120.5760	-27.6350
				91	Venus		155	Venus			120.5746	-27.5848
				92	West Cosmos		156	West Cosmos			120.5723	-27.6000

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APPENDIX 2

Brief background to simple linear regression

This Appendix is drawn from Walpole et al. (2002). The simple linear regression model is stated as:

$$Yi = \mu_{Y|x_i} + E_i = \alpha + \beta x_i + E_i \qquad \text{(A4.1)}$$

where x_i is an independent regressor variable and Y_i a dependent random variable with mean $\mu_{Y|x_i}$ and model error E_i, and α and β are regression coefficients. Each sample observation (x_i, y_i) satisfies:

$$y_i = \alpha+\beta x_i+\varepsilon_i \qquad \text{(A4.2)}$$

where ε_i is the value assumed by E_i when Y_i takes on the value y_i. Denoting estimates of α and β by a and b, respectively, $\mu_{Y|x_i}$ may be estimated by $\hat{y}$ from the sample regression line (also known as the fitted or estimated regression line):

$$\hat{y} = a + bx. \qquad \text{(A4.3)}$$

Each pair of observations satisfies the relation,

$$y_i = a + bx_i + e_i, \qquad \text{(A4.4)}$$

where $e_i = y_i - \hat{y}_i$ is a residual denoting the error in the fit of the model at the i^{th} data point. The residual sum of squares, usually known as sum of squares of the errors (*SSE*) may be expressed as:

$$SSE = \sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n} (y_i - \hat{y})^2 \qquad \text{(A4.5)}$$

A related quantity s^2, known as the mean squared error, is an unbiased estimator of the model error variance, δ^2, and is given by:

$$s^2 = \frac{\sum_{i=1}^{n} (y_i - \hat{y})^2}{n-2} \qquad \text{(A4.6)}$$

where n-2 are the degrees of freedom, the subtracted two having been lost due to estimation of two regression parameters, α and β by a and b.

Estimating the regression coefficients

Given a sample $\{(x_i, y_i), i = 1, 2, \dots, n\}$, a and b are computed as follows:

$$b = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sum_{i=1}^{n} (x_i - \overline{x})^2}, \qquad \text{(A4.7)}$$

and

$$a = \frac{\sum_{i=1}^{n} y_i - b\sum_{i=1}^{n} x_i}{n} = \overline{y} - b\overline{x} \qquad \text{(A4.8)}$$

where $\overline{x}$ and $\overline{y}$ are the mean values of the sample's x and y variables, respectively.

Regression confidence and prediction intervals

The interval about the predicted values which contains the true relationship between the dependent and independent variables for a specified level of confidence is known as the confidence interval. A (1 - α) 100% confidence interval for the mean response $\mu_{Y|x_0}$ is given by:

$$\hat{y}_0 - t_{\alpha/2} S \sqrt{\frac{1}{n} + \frac{(x_0 - \bar{x})^2}{S_{xx}}} < \mu_{Y|x_0} < \hat{y}_0 + t_{\alpha/2} S \sqrt{\frac{1}{n} + \frac{(x_0 - \bar{x})^2}{S_{xx}}}, \qquad \text{(A4.9)}$$

The interval about the predicted values which contains the population from which the observations were drawn for a specified level of confidence is known as the prediction interval. A (1 - α) 100% prediction interval for a single response y_0 is given by:

$$\hat{y}_0 - t_{\alpha/2} S \sqrt{1 + \frac{1}{n} + \frac{(x_0 - \bar{x})^2}{S_{xx}}} < y_0 < \hat{y}_0 + t_{\alpha/2} S \sqrt{1 + \frac{1}{n} + \frac{(x_0 - \bar{x})^2}{S_{xx}}}. \quad \text{(A4.10)}$$

Assessing the quality of the regression model

The quality of fit of the estimated regression line is usually measured using the quantity R^2, known as the coefficient of determination, which measures the proportion of variability explained by the model. Apart from the perfection of fit as represented by R^2, the significance of the fit is another important attribute of the quality of fit. The significance of fit may be determined using the analysis of variance approach. Again taking from Walpole et al. (2002), we briefly describe the analysis of variance approach to regression significance testing, and show the relationship between R^2 and the significance of model fit.

The total corrected sum of squares (*SST*), representing the variation in the response that would ideally be explained by the model consists of two components, namely the regression sum of squares (*SSR*) and the error sum of squares (*SSE*). *SRR* reflects the amount of variation in the response (y) values that are explained by the regression model, whereas *SSE* is the variation about the regression line, representing variation due to error or variation unexplained. These relationships may be stated as:

$$SST = SSR + SSE \qquad \text{(A4.11)}$$

For purposes of computation, Eq. A 11 is written as:

$$\sum_{i=1}^{n}(y_i - \overline{y})^2 = \sum_{i=1}^{n}(\hat{y}_i - \overline{y})^2 + \sum_{i=1}^{n}(y_i - \hat{y})^2 \qquad \text{(A4.12)}$$

To analyse the significance of the linear relationship between variables y and x in the regression model, we state the hypothesis:

$H_{0:}\ \beta = 0$

$H_{1:}\ \beta \neq 0.$

The null hypothesis implies that the model is $\mu_{Y|x_i} \alpha$, that is, the variation in the response variable y results from chance or random fluctuations which are independent of variable x. To test the above hypothesis, we compute the F- statistic:

$$f = \frac{SSR/1}{SSE/(n-2)} \quad , \qquad \text{(A4.13)}$$

where devisors 1 and n-2 are degrees of freedom, based on well established mathematical theorems. We reject H_0 at the α-level of significance if $f > f_\alpha$ (1, n-2). The analysis-of-variance table (Table A1) is used to summarise the analysis.

Table A1 Analysis of variance approach to significance testing in regression

Source of variation	Sum of squares	Degrees of freedom	Mean squares	Computed *f*
Regression	SSR	1	SSR/1	SSR/(n-2)
Error	SSE	n-2	SSE/ (n-2)	
Total	SST	n-1		

The relationship of the coefficient of determination, R^2, components of variation in regression models is given by:

$$R^2 = 1 - \frac{SSE}{SST} \qquad \text{(A4.14)}$$

For a perfect fit, $R^2 = 1.0$, and for a poor fit $R^2 \sim 0$. For example $R^2 = 0.7$ suggests that the regression model explains 70 % of the variability observed in the response variable.

APPENDIX 3.

Quality and significance of nickel sulphide deposit and endowment density regression models for the Kalgoorlie Terrane, Yilgarn Craton, Western Australia

Table A2 Quality and significance of nickel sulphide deposit density models

Nickel sulphide deposit density

Regression equation**:** $\hat{y} = a + bx$, where $a = 0.4676$ and $b = -0.7276$,

Komatiite body	x_i	y_i	$\hat{y}_i$	$(y_i - \bar{y})^2$	$(\hat{y}_i - \bar{y})^2$	$(y_i - \hat{y}_i)^2$
Black Swan	0.4111	0.0660	0.1684	0.1525	0.2430	0.0105
Honeymoon-Well-Mt.-Keith-Yakabindie	1.7624	-0.5071	-0.8147	0.0333	0.2403	0.0946
Perseverance	0.3727	0.1044	0.1964	0.1840	0.2714	0.0085
Blair	1.2984	-0.9974	-0.4771	0.4527	0.0233	0.2707
Carnilya Hill	1.1620	-0.5599	-0.3778	0.0554	0.0028	0.0331
Cosmos	0.5273	0.5519	0.0839	0.7681	0.1668	0.2190
Kambalda	1.3825	-0.3411	-0.5383	0.0003	0.0457	0.0389
Mt. Clifford	1.5235	-1.0464	-0.6409	0.5210	0.1001	0.1644
St. Ives	0.5930	0.0091	0.0361	0.1113	0.1301	0.0007
Tramways	0.9457	0.0543	-0.2205	0.1435	0.0108	0.0755
Widgiemooltha outer	1.2342	-0.6322	-0.4304	0.0946	0.0112	0.0407
Widgiemooltha inner	1.8512	-0.5960	-0.8794	0.0737	0.3078	0.0803
		$\bar{y} = -0.3245$		SST = 2.5905	SSR = 1.5534	SSE = 1.0369

Hypothesis testing

H_0: $\beta = 0$ (The variation in the number of nickel deposits/ km^2 results from chance or random fluctuations which are independent of the area of komatiite bodies (x)

H_1: $\beta \neq 0$ (There is significant amount of variation in the number of nickel deposits/ km^2 (y) that is accounted for by the relationship of y to the area of komatiite bodies (x) as postulated in the straight line regression model).

To test the above hypothesis, compute:

$$f = \frac{SSR/1}{SSE/(n-2)} = \frac{1.5534}{1.0369/10} = 14.9809,$$

and reject H_0 at the 5% level of significance if $f > f_{0.05}(1, 10)$. From tables, $f_{0.05}(1, 10) = 4.96$

Decision: Since 14.9809 > 4.96, we reject H_0 and conclude that there is a significant amount of variation in the number of nickel deposits/ km^2 that is related to the variation in the area of komatiite bodies via the regression model.

Coefficient of determination, R^2

$$R^2 = \frac{SSE}{SST} = 1 - \frac{1.0369}{2.5905} = 0.5997$$

Notes.

Subscript $_i$ denotes each komatiite body

x_i represents the area of each komatiite body ($\log_{10}$ km^2) and y_i the nickel deposit density ($\log_{10}$ deposits/ km^2) in each komatiite body

$\hat{y}_i$ is the nickel deposit density predicted from the regression model for each komatiite body

$\bar{y}$ is the average nickel deposit density the listed komatiite bodies

SST = $\sum_{i=1}^{n}(y_i - \bar{y})^2$ is the total corrected sum of squares of y

SSR = $\sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2$ is the regression sum of squares reflecting the amount of variation in the y valued explained by the model

SSE = $\sum_{i=1}^{n}((y_i - \hat{y}_i)^2$ is the error sum of squares reflecting the amount of variation about the regression line

TABLE A 3. Quality and significance of nickel sulphide endowment density models

Nickel metal endowment density

Regression Equation**:** $\hat{y} = a + bx$, *where* $a = 2.5944$, $b = -1.2039$

Komatiite body	x_i	y_i	$\hat{y}_i$	$(y_i - \bar{y})^2$	$(\hat{y}_i - \bar{y})^2$	$(y_i - \hat{y}_i)^2$
Black Swan	0.4111	2.1617	2.0994	0.7708	0.6653	0.0039
Honeymoon Well_Mt. Keith-Yakabindie	1.7624	2.0094	0.4727	0.5265	0.6579	2.3615
Perseverance	0.3727	2.6505	2.1457	1.8681	0.7429	0.2549
Blair	1.2984	0.0633	1.0312	1.4895	0.0638	0.9369
Carnilya Hill	1.1620	0.7874	1.1955	0.2463	0.0078	0.1665
Cosmos	0.5273	2.2855	1.9596	1.0035	0.4567	0.1063
Kambalda	1.3825	1.6723	0.9300	0.1510	0.1252	0.5511
Mt. Clifford	1.5235	-0.5504	0.7603	3.3640	0.2740	1.7178
St. Ives	0.5930	1.5654	1.8805	0.0793	0.3561	0.0993
Tramways	0.9457	1.4747	1.4559	0.0365	0.0296	0.0004
Widgiemooltha outer	1.2342	0.9031	1.1085	0.1449	0.0307	0.0422
Widgiemooltha inner	1.8512	0.3821	0.3657	0.8131	0.8428	0.0003
		$\bar{y} = 1.2838$		SST = 10.4936	SSR = 4.2528	SSE = 6.2409

Hypothesis testing

H_0: $\beta = 0$ (The variation in the amount nickel metal/ km^2 results from chance or random fluctuations which are independent of the area of komatiite bodies (x)

H_1: $\beta \neq 0$ (There is significant amount of variation in the amount of nickel metal/ km^2 (y) that is accounted for by the relationship of y to the area of komatiite bodies (x) as postulated in the straight line regression model).

To test the above hypothesis, compute:

$$f = \frac{SSR/1}{SSE/(n-2)} = \frac{4.2528}{6.2409/10} = 6.8144,$$

and reject H_0 at the 5% level of significance if $f > f_{0.05}(1, 10)$. From tables, $f_{0.05}(1, 10) = 4.96$

Decision: Since 6.8344 > 4.96, we reject H_0 and conclude that there is a significant amount of variation in nickel metal/ km^2 that is related to the variation in the area of komatiite bodies via the regression model.

Coefficient of determination, R^2

$$R^2 = \frac{SSR}{SST} = 1 - \frac{6.2409}{10.4936} = 0.4053$$

Notes.

Subscript $_i$ denotes each komatiite body

x_i represents the area of each komatiite body ($\log_{10} km^2$) and y_i the nickel metal endowment density ($\log_{10}$ metal/ km^2) for each komatiite body

$\hat{y}_i$ is the value of nickel endowment density predicted from the regression model for each komatiite body

$\bar{y}$ is the average nickel metal endowment density for the listed komatiite bodies.

SST = $\sum_{i=1}^{12}(y_i - \bar{y})^2$ is the total corrected sum of squares of y

SSR = $\sum_{i=1}^{12}(\hat{y}_i - \bar{y})^2$ is the regression sum of squares reflecting the amount of variation in the y valued explained by the regression model

SSE = $\sum_{i=1}^{12}((y_i - \hat{y}_i)^2$ is the error sum of squares reflecting the amount of variation about the regression line

APPENDIX 4

95 % confidence interval and prediction interval regression estimates for the number of nickel sulphide deposits and amount of nickel sulphide endowment in demonstrably mineralized komatiite bodies in the Kalgoorlie Terrane, Western Australia.

				[1]Estimates of number of deposits and nickel metal endowment (kt Ni metal)											
				95% confidence interval estimates						95% prediction interval estimates					
Komatiite body				No. of deposits			Nickel metal (kt)			No. of deposits			Nickel metal (kt)		
Serial number	Name	Area (km^2)	Ref. map	Lower	mean	Upper	Lower	mean	Upper	Lower	mean	Upper	Lower	mean	Upper
Favourable komatiite bodies with at least one nickel sulphide deposit with published resources															
1	Rocky's Reward (P)	0.01	Fig. 3d	-	-	-	-	-	-	-	-	-	-	-	-
2	Perseverance East (P)	0.01	Fig. 3d	-	-	-	-	-	-	-	-	-	-	-	-
3	Harmony (P)	0.05	Fig. 3d	-	-	-	-	-	-	-	-	-	-	-	-
4	Melon-11 Mile Well (D)	0.33	Fig. 3d	-	-	-	-	-	-	-	-	-	-	-	-
5	Mt. Jewel (P)	2.94	Fig. 3l	3	4	5	247	316	404	2	4	7	176	316	567
6	Saints (P)	3.45	Fig. 3l	3	4	5	243	305	384	2	4	7	171	305	545
7	Weebo (D)	3.75	Fig. 3e	3	4	5	241	300	375	2	4	7	169	300	534
8	Sinclair (P)	3.89	Fig. 3e, 3f	3	4	5	240	298	370	2	4	8	168	298	529
9	Horn (P)	6.32	Fig. 3e	4	5	6	226	270	322	3	5	8	154	270	473
10	Cliffs (P)	7.21	Fig. 3c	4	5	6	222	263	311	3	5	9	150	263	459
11	Nepean (P)	24.43	Fig. 3m	6	7	8	171	205	245	4	7	12	117	205	359
12	Bluebush (P)	27.14	Fig. 3o, 3p	6	7	9	166	200	242	4	7	13	114	200	352
13	Scotia (P)	104.24	Fig. 3l, 3n	-	-	-	-	-	-	-	-	-	-	-	-
Favourable komatiite bodies for which significant drill-intersected nickel sulphides have been reported															
14	Serp Hill (D)	0.13	Fig. 3c	-	-	-	-	-	-	-	-	-	-	-	-
15	Marshall (P)	0.42	Fig. 3n	-	-	-	-	-	-	-	-	-	-	-	-
16	Fly Bore (P)	0.66	Fig. 3e	-	-	-	-	-	-	-	-	-	-	-	-
17	Mt. Newman (D)	1.03	Fig. 3f	-	-	-	-	-	-	-	-	-	-	-	-

Notes

[1] ‘Mean’ denotes estimates based on the regression equations (Eq. 1 and Eq. 2). ‘Lower’ and ‘upper’ estimates are the lower and upper estimates for the 95% confidence and prediction intervals about the mean. Estimates for komatiite bodies that are too small or too large (Scotia) to be analysed with models of Mamuse et al. (2010b) in Chapter 4 are not included and are denoted by dashes (-) in the table.

APPENDIX 4 **(continued)**

				[1]Estimates of number of deposits and nickel metal endowment (kt Ni metal)											
				95% confidence interval estimates						95% prediction interval estimates					
Komatiite body				No. of deposits			Nickel metal (kt)			No. of deposits			Nickel metal (kt)		
Serial number	Name	Area (km^2)	Ref. map	Lower	mean	Upper	Lower	mean	Upper	Lower	mean	Upper	Lower	mean	Upper
Favourable komatiite bodies for which significant drill-intersected nickel sulphides have been reported															
18	Deep South (P)	1.03	Fig. 3e	-	-	-	-	-	-	-	-	-	-	-	-
19	Quinn Hills (P)	1.37	Fig. 3h	-	-	-	-	-	-	-	-	-	-	-	-
20	Carthage (P)	1.56	Fig. 3e	-	-	-	-	-	-	-	-	-	-	-	-
21	Sir Samuel (D)	1.58	Fig. 3d	-	-	-	-	-	-	-	-	-	-	-	-
22	Schmitz Well (D)	1.98	Fig. 3f	-	-	-	-	-	-	-	-	-	-	-	-
23	Riverina (P)	2.16	Fig. 3j	-	-	-	-	-	-	-	-	-	-	-	-
24	Delphi (P)	2.67	Fig. 3f	3	4	5	249	322	416	2	4	7	178	322	580
25	Schmitz Well South (D)	3.35	Fig. 3f	3	4	5	243	307	388	2	4	7	172	307	549
26	Jungle Jewell (P)	3.87	Fig. 3e, 3f	3	4	5	240	298	371	2	4	8	168	298	530
27	Antioch (P)	6.20	Fig. 3f	4	5	6	227	271	324	3	5	8	155	271	475
28	Talbot Island (P)	8.59	Fig. 3p	4	5	6	216	254	298	3	5	9	145	254	442
29	Mt. Martin (P)	9.88	Fig. 3n	5	5	6	211	246	288	3	5	10	141	246	429
30	Longbow (D)	11.51	Fig. 3a	5	6	7	205	239	278	3	6	10	137	239	415
31	Golden Valley (P)	13.30	Fig. 3l, 3n	5	6	7	199	232	270	3	6	10	133	232	403
32	Hayes (D)	14.14	Fig. 3a	5	6	7	196	229	267	3	6	11	132	229	398
33	Amy Ricks (P)	14.66	Fig. 3e	5	6	7	195	227	266	4	6	11	131	227	396
34	Antioch East (P)	21.48	Fig. 3e, 3f	6	7	8	177	210	250	4	7	12	120	210	368
35	Menzies (P)	40.02	Fig. 3i	6	8	10	148	185	231	5	8	14	104	185	330
36	Acacia Ridge (P)	59.76	Fig. 3i	7	9	12	131	171	222	5	9	16	94	171	309
Estimates for parts of komatiites under cover															
37	Kambalda (P)	21.68	Fig. 3n, 3o	6	7	8	177	210	249	4	7	12	120	210	367
38	Cosmos (D)	2.53	Fig. 3d	3	4	5	250	325	423	2	4	7	180	325	589

Notes

[1] 'Mean' denotes estimates based on the regression equations (Eq. 1 and Eq. 2). 'Lower' and 'upper' estimates are the lower and upper estimates for the 95% confidence and prediction intervals about the mean. Estimates for komatiite bodies that are too small or too large (Scotia) to be analysed with models of Mamuse et al. (2010b) in Chapter 4 are not included and are denoted by dashes (-) in the table.

APPENDIX 5

Written statements of contribution by co-authors to journal papers included as part of this PhD thesis

I, **Antony Mamuse**, contributed 90% or more to idea development, database compilation, data analysis and write up of the paper entitled: **Spatial statistical analysis of the distribution of komatiite-hosted nickel sulphide deposits of the Kalgoorlie Terrane, Western Australia: clustered or not?** This paper, published by *Economic Geology* (Mamuse et al., 2010a), forms the basis of Chapter 3 of this thesis.

I, as Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate. My own contribution was supervisory and which primarily involved reviewing the candidate's work and providing guidance on content and structure.

Co-Author 1.

Full Name: Alok Porwal Signature

Co-Author 2.

Full Name: Oliver Kreuzer Signature

Co-Author 3.

Full Name: Steve Beresford Signature

I, **Antony Mamuse**, contributed 90% or more to idea development, database compilation, data analysis and write up of the paper entitled: **A new method for spatial centrographic analysis of mineral deposit clusters.** This paper, published by *Ore Geology Reviews* (Mamuse et al., 2009), forms the basis of Chapter 5 of this thesis.

I, as Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate. My own contribution was supervisory and which primarily involved reviewing the candidate's work and providing guidance on content and structure.

Co-Author 1.

Full Name: Alok Porwal Signature

Co-Author 2.

Full Name: Oliver Kreuzer: Signature

Co-Author 3.

Full Name: Steve Beresford Signature

I, **Antony Mamuse**, contributed 90% or more to idea development, database compilation, data analysis and write up of the paper entitled: **Assessment of undiscovered nickel sulphide resources, Kalgoorlie Terrane, Western Australia. Part 1. Deposit and endowment density models.** This paper, published by *Ore Geology Reviews* (Mamuse et al., 2010b), is one of three that constitute Chapter 4 of this thesis.

I, as Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate. My own contribution was supervisory and which primarily involved reviewing the candidate's work and providing guidance on content and structure.

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I, **Antony Mamuse**, contributed 90% or more to idea development, database compilation, data analysis and write up of the paper entitled **Assessment of undiscovered nickel sulphide resources, Kalgoorlie Terrane, Western Australia. Part 2. Estimates from deposit and endowment density models.** This manuscript, submitted to *Ore Geology Reviews* (Mamuse et al., submitted), is one of three that constitute Chapter 4 of this thesis.

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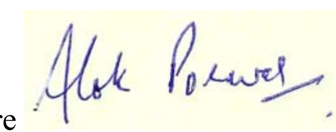
Full Name: Alok Porwal Signature 

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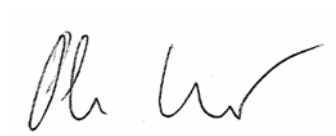
Full Name: Oliver Kreuzer Signature 

I, **Antony Mamuse**, contributed 90% or more to database compilation, idea development data analysis and write up of Chapter 4 which partly draws from a manuscript currently in review with *Mineralium Deposita* (Mamuse & Guj, 2010, in review). The manuscript is entitled: **Rank Statistical analysis of nickel sulphide resources of The Norseman-Wiluna Greenstone Belt, Western Australia.**

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I, as Co-Author endorse, that this level of contribution by the candidate indicated above is appropriate. My own contribution was supervisory and which primarily involved reviewing the candidate's work and providing guidance on content and structure.

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Bibliography

Anselin, L. 1990. What is special about spatial data? Alternative perspectives on spatial data analysis, in: Griffith, D.A. (Ed.), Spatial Statistics, Past, Present and Future. Institute of Mathematical Geography, Ann Arbor, ML, pp. 63-77.

Anselin, L. 1992. Spatial data analysis with GIS: an introduction to application in the social sciences. Technical Report 92-10, University of California, 53 pp.

Archibald, N. J., Bettenay, L. F., Binns, R. A., Groves, D. I., Gunthorpe, R. J., 1978. The evolution of Archaean greenstone terrains, Eastern Goldfields province, Western Australia. Precambrian Research 6, 105-151.

Arndt, N.T., Jenner, G.A.,1986. Crustally contaminated komatiites and basalts from Kambalda, Western Australia. Chemical Geology 56, 229-255.

Australian Mines Limited. http://www.australianmines.com.au/operations.29.html (accessed September 20, 2009)

Australian Mines Limited, 2007. Quarterly report on activities for the period ended 30th June 2007. Australian Mines Limited, Perth, 20 pp.

Ahrens, L.H., 1954. The log-normal distribution of the elements (A fundamental law of geochemistry and its subsidiary). Geochimica et Cosmochimica Acta 5, 49-73.

Bachi, R., 1957. Statistical analysis of geographical series. Bulletin de l’Institut International de Statistique 36, 229-240.

Barnes, S.J., 2006a. Komatiite-hosted nickel sulphide deposits: geology, geochemistry, and genesis, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, p. 51-97.

Barnes, S.J., 2006b. Komatiites: petrology, volcanology, metamorphism, and Geochemistry, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists, Special Publication 13, p. 13-49.

Barnes, S.J., Gole, M.J., Hill, R.E.T., 1988. The Agnew nickel deposit, Western Australia. Part I. Stratigraphy and structure. Economic Geology 83, 524-536.

Barnes, S.J., Hill, R.E.T., Perring, C.S., and Dowling, S.E., 2004. Lithogeochemical exploration for komatiite associated Ni-sulphide deposits: strategies and limitations: Mineralogy and Petrology 82, 259-293.

Barnes, S.J., Lesher, C.M. and Keays, R.R., 1995. Geochemistry of mineralised and barren komatiites from the Perseverance Nickel Deposit, Western Australia. Lithos 34, 209-234.

Barnes, S.J., Perring, C.S., 2006. Appendix. Summary of geological features of nickel sulphide deposits of the Yilgarn craton, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, 99-118.

Baddeley, A., 2008. Analysing spatial point patterns in R. Workshop Notes, version

3. Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, 199 pp. http://www.csiro.au/resources/pf16h.html (accessed August 14, 2009).

Baddeley, A. and Turner, R., 2005. Spatstat: an R package for analysing spatial point patterns. Journal of Statistical Software, 12(6):1–42, URL: www.jstatsoft.org, ISSN: 1548-7660.

Bailey, C.T. and Gatrell, A.C., 1995. Interactive spatial data analysis. Longman, Harlow, 413 pp.

Bardossy, G., Fodor, J., 2001. Traditional and new ways to handle uncertainty in geology. Natural Resources Research 10, 179-187.

Barley, M. E., Brown, S. J. A., Cas, R. A. F., Cassidy, K. F., Champion, D. C., Gardoll,S. J., Krapež, B., 2003. An integrated geological and metallogenic framework for the eastern Yilgarn Craton: developing geodynamic models of highly mineralized Archaean granite-greenstone terranes. Amira International Limited, AMIRA Project no. P624 (unpublished report).

Bavinton, O.A., 1981. The nature of sulfidic metasediments at Kambalda and their broadrelationships with associated ultramafic rocks and nickel ores. Economic Geology 76, 1606-1628.

Beresford, S.W., Cas, R.A.F., 2001. Komatiitic invasive flows, Kambalda, Western Australia. Canadian Mineralogist 39, 525-535.

Beresford, S.W., Cas, R., Lahaye, Y., Jane, M., 2002. Facies architecture of an

Achaean komatiite-hosted Ni-sulphide ore deposit, Victor, Kambalda, Western Australia: implications for komatiite lava emplacement. Journal of Volcanology and Geothermal Research 118, 57-75.

Beresford, S.W., Stone, W.E., Cas, R.A.F., Lahaye, Y, Jane, M., 2005. Volcanological controls on the localisation of a komatiite-hosted Ni-Cu-(PGE) deposit, Coronet, Kambalda, Western Australia. Economic Geology 100, 1457-1467.

Beresford, S, During, P., Florentine, M., Rosengren, N., Bleaker, W., Barley, M., CAS,R., Tait, M., Wallace, H., 2004. The Structural and Stratigraphic Architecture of the Agnew/Wiluna Belt, WA, Project P710 Project Final Report. AMIRA International Limited (unpublished report), 511 pp.

Beresford, S.W., Fiorentini, M., Hronsky, J.M.A., Rosengren, N., Bertuch, D.I., Saleem, A., Cas, R.A.F., Stone, W.E., Duuring, P., Bekker, A., Barley, M., 2007. Komatiite-hosted Ni-Cu-(PGE) deposits: understanding deposit and camp footprints, in: Bierlein F.P. and Knox-Robinson C.M., (eds.), 2007. Proceedings of Geoconferences (WA) Inc. Kalgoorlie '07 Conference, 25-27 September 2007, Kalgoorlie, Western Australia. Geoscience Australia Record 2007/14, 249 pp.

Berger, R.B., Drew, L.J., Singer, D.A. 1999. Quantifying mineral-deposit models for resource assessment, in: Deposit modeling and mining-induced environmental risks, Geologica-Hungarica Series Geologica, Tomus 24: 41-54.

Bhattacharyya, P., Czeck, M., 2008. Using network analyses within geographic information system technologies to quantify geometries of shear zone networks. Geosphere 4, 640-656.

Blenkinsop, T.G. 1995. Fractal measures for the size and spatial distributions of gold mines: economic applications, in: T.G. Blenkinsop and P.L. Tromp (Eds.), Sub-Saharan Economic Geology. Geological Society of Zimbabwe Special Publication 3, Balkema, Rotterdam, p.177-186.

Blenkinsop, T.G., 2004, Applications of fractal geometry to mineral exploration, in: Muhling, J., Goldfarb, R., Vielreicher, N., Bierlein, F., Stumpfl, E., Groves, D., Kenworthy, S. (Eds.), Predictive Mineral Discovery Under Cover, Extended Abstracts. SEG 2004 Conference, 27 September-1 October 2004 Perth, Western Australia, p. 158-161.

Blenkinsop, T.G., Sanderson, D.J., 1999, Are gold deposits in the crust fractals? A studyof gold mines in the Zimbabwean craton, in: McCaffrey, K.J.W., Lonergan, L.,Wilkinson, J.J. (Eds.), Fractures, fluid flow and mineralization. Geological Society Special Publication 155, 141-151.

Bliss, J.D., Menzie, W.D., 1993. Spatial mineral-deposit models and the prediction of undiscovered mineral deposits, in: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), Mineral deposit modeling. Geological Association Canada Special Paper 40, p. 693-706.

Bliss, J.D., Menzie, W.D., Orris, G.J., Page, N.J., 1987. Mineral deposit density – a useful tool for mineral-resource assessment, in: Sachs, J.S. (Ed.), U.S. Geological Survey Research of Mineral Resources - 1987 Program and Abstracts, U.S. Geological Survey Circular 995, p. 6.

Bonham-Carter, G.F., 1994. Geographic Information Systems for geoscientists – modelling with GIS. Elsevier Science, New York, 398 pp.

Biondini, R. 1976. Cloud motion and rainfall statistics. Journal of Applied Meteorology 15, 205-224.

Brand, N.W., 1999. Element ratios in nickel sulphide exploration: vectoring towards ore environments. Journal of Geochemical Exploration 67, 145-165.

Bratt, R.S., Bache, T.C., 1988. Locating events with a sparse network of regional arrays. Bulletin of the Seismological Society of America 78, 780-798.

Brilliant Mining Corp, 2007. 5.4% Ni delivered from winner during first month production, Lanfranchi Nickel Mine, Kambalda District of Western Australia. News releases, November 29, 2007, TSX Venture Exchange, Vancouver.

Brilliant Mining Corp, 2008a. Production commences 18 months after discovery at high-grade Deacon orebody, Lanfranchi Nickel Mine, Kambalda District of Western News releases, Australia March 31, 2008, TSX Venture Exchange, Vancouver.

Brilliant Mining Corp, 2008b. Tramways Dome Drill Program to Commence Lanfranchi Nickel Mine, Kambalda District of Western Australia. News releases, March 13 2008, TSX Venture Exchange, Vancouver.

Bultman, M.W., Force, E.R. Gettings, M. E., Fisher, F. S., 1992. Comments on the "three-step" method for quantification of undiscovered mineral resources. US Geological Survey Open-File Report 93–23, 59 pp.

Cas, R.A.F., Self, S., Beresford, S.W., 1999. The behaviour of the fronts of komatiite lavas in medial to distal settings. Earth and Planetary Science Letters 172, 127-139.

Carlson, C.A., 1991. Spatial distribution of mineral deposits. Geology 19, 111- 114.

Cassidy, K.F., Champion, D.C., Krapez, B., Barley, M.E., Brown, S.J.A., Blewett, R.S., Groenewald, P.B., Tyler, I.M., 2006. A revised tectonic framework for the Yilgarn craton, Western Australia. Geological Survey of Western Australia, Record 2006/ 8, 8 pp.

Chung, C.F., Singer, D.A., and Menzie, W.D., 1992. Predicting sizes of undiscovered mineral deposits - an example using mercury deposits in California. Economic Geology 87, 1174-1179.

Clark, P.J. and Evans, F.C., 1954. Distance to nearest neighbour as a measure of spatial relationships in populations. Ecology 35, 445-453.

Cliff, A.D. and Ord, J.K., 1981. Spatial processes-models and applications. Pion, London, 266 pp.

Cliff, A.D., Ord, P., Bassett, K., Davies, R., 1975. Elements of spatial structure: a quantitative approach. Cambridge University Press, Cambridge, UK, 258 pp.

Cowden, A.C., Roberts, D.E., 1990. Komatiite-hosted nickel sulphide deposits, Kambalda, in: Hughes, F.E. (Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 14, Melbourne, pp. 567-581.

Cox, D., 1993. Estimation of undiscovered quantitative mineral resource assessments-Examples from Venezuela and Puerto Rico, Nonrenewable Resources 2, 82-91.

Cox, D.P., Singer, D.A., eds., 1986. Mineral deposit models. U.S. Geological Survey Bulletin 1693, 379 pp.

Cressie, N.A.C., 1993, Statistics for spatial data. John Willey & Sons, New York, 900 pp.

Crow, E.L., Shimizu, K., 1988. Log-normal Distributions: Theory and Application. Dekker, New York.

Curtin University of Technology, 2009. Guidelines for Thesis by publication (series of published papers), version date: 30/092009. http://research.curtin.edu.au/local/docs/graduate/GS-ThesisByPubGuidelines.pdf. Accessed January 17, 2010.

Daddow, B., McCuaig, T., C., Mappleson, D.B., 2003. Structural controls of the Wannaway nickel-sulfide deposit, Widgiemooltha, Western Australia. 5th International Mining Geology Conference, Bendigo, Victoria, Australia, 17-19 November, 2003, pp. 101-112.

Dale, M. R. T., Dixon, P., Fortin, M. J., Legendre, P., Myers, D. E. and Rosenberg, M. S. 2002. Conceptual and mathematical relationships among methods for spatial analysis. Ecography 25: 558-577.

de Smith, M.J., Goodchild, M.F., Longley, P.A., 2007. Geospatial analysis. A comprehensive guide to principles, techniques and software tools. Matador, Leicester, U.K., 394 pp.

De Vitry, C., Libby, J. W., Langworthy, P. J., 1998, Rocky's Reward nickel deposit, in: Berkman, D.A., and Mackenzie, D.H. (Eds.), Geology of Australian and Papua New Guinean mineral deposits. The Australasian Institute of Mining and Metallurgy Monograph 22, Melbourne, pp. 315-319.

Diggle, P.J., 1983. Statistical analysis of spatial point patterns. Academic Press, London, 148 pp.

Donaldson, M.J., Lesher, C.M., Groves, D.I., Gresham, J.J., 1986. Comparison of Archaean dunites and komatiites associated with nickel mineralisation in Western Australia: implications for dunite genesis. Mineralium Deposita 21, 296-305.

Drew, L.J. Singer, D.A., Menzie, W.D., Berger, B.R. 1999. Mineral resource assessment-state of the art. Geologica Hungarica Series Geologica, Tomus 24, 31-40.

Duuring P., Bleeker, W., Beresford S.W., 2004. Major folding and remobilization of nickel sulphides at Perseverance, Leinster, Western Australia, in: Beresford, S.W., Duuring, P., Fiorentini, M., Rosengren, N., Bleeker, W., Barley, M., Cas, R., Tait, M., Wallace, H. 2004. The Structural and Stratigraphic Architecture of the Agnew/Wiluna Belt, WA AMIRA Project P710. AMIRA International Limited (unpublished report), pp. 317-346.

Duuring P., Bleeker, W. and Beresford S.W., 2008. Structural Modification of the Komatiite-Associated Harmony Nickel Sulfide Deposit, Leinster, Western Australia. Economic Geology 102, 277-297.

Duuring, P., Bleeker, W., Beresford, S.W. and Hayward, N., 2010. Towards a volcanic-structural balance: relative importance of volcanism, folding, and remobilisation of nickel sulphides at the Perseverance Ni–Cu–(PGE) deposit, Western Australia. Mineralium Deposita 45, 281-311.

Ebdon, D., 1988. Statistics in Geography. Blackwell Publishing, Oxford, U.K., 232 pp.

Eisenlohr, B.N., 1988. The structural development and controls on mineralisation of the northern sector of the Norseman-Wiluna Belt, Western Australia. PhD thesis, University of Western Australia, Perth, 187 pp.

ESRI (Environmental Systems Research Institute), 2009. Multi-Distance Spatial ClusterAnalysis (Ripley's *K*-function) (Spatial Statistics). http://webhelp.esri.com/arcgisdesktop/9.3/index.cfm?topicname=multi-distance_spatial_cluster_analysis_(ripley's_k-function)_(spatial_statistics). (accessed February 10, 2009).

Evernden, J. F., 1969. Precision of epicenters obtained by small numbers of world-wide stations. Bulletin of the Seismological Society of America 59, 1365-1398.

Fagan, R.K., 2006. Modelling how much gold is left to be found in the Eastern Goldfields of W.A. Outcrop to orebody: innovative geoscience in exploration and mining, Abstract Volume. Kalgoorlie 2006 Conference, 30 April to 4 May 2006, Kalgoorlie. Australian Institute of Geoscientists Bulletin 44, 23-25.

Finch, W.I, Grundy, W.D, Pierson, C.T., 1992. Statistical sampling of the distribution of uranium deposits using geologic/geographic clusters. Nonrenewable Resources 1, 148-152.

Fiorentini, M.L., Beresford, S.W. and Barley, M.E., 2008. Ruthenium-chromium variation: a new lithogeochemical tool in the exploration for komatiite-hosted Ni-Cu-(PGE) deposits, Economic Geology 103, 431-477.

Fiorentini, M.L., Rosengren, N., Beresford, S.W., Grguric, B., Barley, M.E. 2007. Controls on the emplacement and genesis of the MKD5 and Sarah's Find Ni–Cu–PGE deposits, Mount Keith, Agnew–Wiluna Greenstone Belt, Western Australia. Mineralium Deposita 42, 847-877.

Flinn, E.A., 1965. Confidence regions and error determinations for seismic event location. Reviews of Geophysics 3, 157-185.

Folinsbee RE., 1977. World's view-from Alph to Zipf. Geological Society of America Bulletin 88, 897-907.

Ford, A., Blenkinsop, T.G., 2008. Combining fractal analysis of mineral deposit clustering with weights of evidence to evaluate patterns of mineralisation: application to copper deposits of the Mt. Isa inlier, NW Queensland, Australia. Ore Geology Reviews 33, 435-450.

Fotheringham, A.S., Brundson, C., Charlton, M., 2002. Geographically weighted regression: the analysis of spatially varying relationships. John Willey and Sons, West Sussex, UK, 269 pp.

Furfey, P.H., 1927. A note on Lefever's "standard deviational ellipse". The American Journal of Sociology 33, 94-98.

Gatrell, Bailey, T.C., Diggle, P.J., Rowlinson, B.S., 1996. Spatial point pattern analysis and its application in geographical epidemiology: Transactions of the Institute of British Geographers NS 21, 256-274.

Getis, A. and Boots, B., 1978. Models of spatial processes. An approach to the study of point, line and area patterns. Cambridge University Press, London, 198 pp.

Gettings, M. E., Bultman, M.W., Fisher, F.S. 2004**.** A Complex systems model approach to quantified mineral resource appraisal. Environmental Management 33, 87-98.

Gemuts, I., Theron, A. C., 1975. The Archaean between Coolgardie and Norseman- Stratigraphy and mineralization, in: Knight, C.L. (Ed.), Economic Geology of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 5, Melbourne, pp. 66-74.

Gong, J., 2002. Clarifying the standard deviational ellipse. Geographical Analysis 34, 155-167.

Gresham, J.J., 1986. Depositional environments of volcanic peridotite-associated nickel sulfide deposits with special reference to the Kambalda Dome, in: Friedrich, G.H., Genkin, A.D., Naldrett, A.J., Ridge, J.D., Sillitoe, R.H., Vokes, F.M. (Eds.), Geology and Metallogeny of Copper Deposits. Springer-Verlag, Berlin, pp. 63-89.

Gresham, J.J., Loftus-Hills, G.D., 1981. The geology of the Kambalda nickel field, Western Australia. Economic Geology 76, 1373-1416.

Grguric, B.A., Rosengren, N.M., Fletcher, C.M., and Hronsky, J.M.A. 2006. Type 2 deposits: geology, mineralogy, processing of the Mount Keith and Yakabindie orebodies, Western Australia, in: Barnes, S.J. (Ed.), Nickel deposits of the Yilgarn craton: geology, geochemistry and geophysics applied to exploration. Society of Economic Geologists Special Publication 13, 119-138.

Groenewald, P.B., Riganti, A., 2004. East Yilgarn 1:100,000 geological information series-an explanatory note. Geological Society of Western Australia Report 95, 58 pp.

GSWA (Geological Survey of Western Australia), 2008. 1:500 000 Interpreted bedrock geology of Western Australia, 2008 update. http://mapserver.doir.wa.gov.au/datacentre/ (accessed April 24, 2009).

Guj, P., Fallon, M., McCuaig T.C., Fagan R., in review. A time-series audit of the Zipf's law as a measure of terrane endowment and maturity in mineral exploration. Economic Geology.

Guj P., McCuaig, T.C., Garzon, R. 2007. Can the petroleum industry's probabilistic approach to targeting and resources definition be applied in predicting mineral discoveries?. Conference Proceedings, Mineral Exploration and Research: Digging Deeper. 9th Biennial SGA Meeting.

Haggett, P., Cliff, A.D. and Frey, A. 1977. Locational methods. Edward Arnold, London, 605 pp.

Haining, R., P. 1990a. Models in human geography: problems in specifying, estimating and validating models for spatial data. in: Griffith, D.A. (Ed.), Spatial Statistics, Past, Present and Future. Institute of Mathematical Geography, Ann Arbor, ML, pp. 83-102.

Haining, R. 1990b. Spatial data analysis in the social and environmental sciences. Cambridge University Press, Cambridge, 409 pp.

Hill, R.E.T., Gole, M.J., 1990. Nickel sulphide deposits of the Yilgarn Block, in: Hughes, F.E. (Ed.), Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 14, Melbourne, pp. 557-559.

Hill, R.E.T., Barnes S.J., Gole M.J., Dowling, S.E. 1990. Physical volcanology of komatiites. A field guide to the komatiites of the Norseman-Wiluna Greenstone Belt, Eastern Goldfields Province, Yilgarn Block, Western Australia. Excursion guide book no. 1. Geological Survey of Western Australia, Perth, 100 pp.

Hill, R.E.T., Barnes, S.J., Gole, M.J., Dowling, S.E., 1995. The volcanology of komatiites as deduced from field relationships in the Norseman-Wiluna greenstone belt, Western Australia. Lithos 34, 159-188.

Hill R.E.T., Barnes S.J., Dowling, S.E., Thordarson, T. 2004. Komatiites and nickel sulfide orebodies of the Black Swan area, Yilgarn Craton, Western Australia. Part 1. Petrology and volcanology of host rocks. Mineralium Deposita 39, 684-706.

Hirano, S.S., Nordheim, E.V., Arny, D.C., Upper, C.D., 1982. Log-normal distribution of epiphytic bacterial populations on leaf surfaces. Applied and Environmental Microbiology 44, 695-700.

Hoatson, D.M., Subhash, J., Jaques, A.L., 2006. Nickel sulphide deposits in Australia: characteristics, resources and potential. Ore Geology Reviews 29, 177-241.

Hronsky, J.M.A., 2004. The science of exploration targeting, in: Muhling, J., Goldfarb,R., Vielreicher, N., Bierlein, F., Stumpfl, E., Groves, D., Kenworthy, S. (Eds.), Predictive Mineral Discovery Under Cover, Extended Abstracts. SEG 2004 Conference, 27 September-1 October 2004, Perth, Western Australia Perth, pp. 129-133.

Hronsky, J.M.A., 2009. The exploration search space concept: key to a successful exploration strategy. CET Quarterly Newsletter 8, June 2009.

Hronsky, J.M.A. and Groves, D.I., 2008. Science of targeting: definitions, strategies, targeting and performance measurement. Australian Journal of Earth Sciences 55, 3-12.

Hronsky, J.M.A., Schodde, R.C. 2006. Nickel exploration of the Yilgarn Craton: from the nickel boom to today. Society for Economic Geologists Special Publication 13: 1-11.

Hwang, S., 1999. Temporal extensions of K function. http://www.ucgis.org/ucgisfall2004/studentpapers/files/Hwang.PDF (accessed September 22, 2008).

Independence Group N.L., 2009. Growing a great company, Annual General Meeting, 25November, 2009. http://www.independencegroup.com.au/IRM/content/investor/presentations.htm (accessed December 18, 2009).

Intierra Pty Ltd. MINMET database. http://www.intierra.com/ (accessed January 14, 2009).

Jubilee Mines N.L., 2005. Quarterly report for the period ended June 30, 2005. Jubilee Mines N.L., Sydney, 13 pp.

Jubilee Mines N.L., 2007a. Bannockburn Project-new nickel discovery and Exploration update. Announcement, April 18 2007. Australian Stock Exchange, Sydney, 3 pp.

Jubilee Mines N.L., 2007b. Significant increase to Sinclair resource. Announcement, September 24, 2007. Australian Stock Exchange, Sydney, 2pp.

Keays, R.R., 1995. The role of komatiitic and picritic magmatism and S-saturation in the formation of ore deposits. Lithos 34, 1-18.

Kent, J., Leitner, M., 2008. Efficacy of standard deviational ellipses in application of criminal geographic profiling. Journal of Investigative Psychology and Offender Profiling 4, 147-165.

Knoring, L.D. and Dech, V.N., 1993. Mathematics for geologists, in: Zeidler, R.B., (Ed.), Geotechnika 10, Netherlands, A.A. Balkema, 200 pp.

Koch, A.L., 1966. The logarithm in biology. I. Mechanisms generating the log-normal distribution exactly. Journal of Theoretical Biology 23, 276-290.

Klausen, M.B., 2004. Geometry and mode of emplacement of the Thverartindur cone sheet swarm, SE Iceland. Journal of Volcanology and Geothermal Research 138, 185-204.

Knoring, L.D. and Dech, V.N., 1993. Mathematics for geologists, in: Zeidler, R.B.

(ed.), Geotechnika 10: Netherlands, A.A. Balkema, 200 p.

Krapez, B., Brown, S.J.A., Hand, J., Berley, M.E., Cas, R.A.F., 2000. Age constraints on recycled crustal and supracrustal sources of Archaean metasedimentary sequences, Eastern Goldfields Province, Western Australia: evidence from SHRIMP zircon dating. Tectonophysics 322, 89-133.

Krige, D.G., 1966. A study of gold and uranium distribution patterns in the Klerksdorp Gold Field. Geoexploration 4, 43-53.

Langworthy, P. 2004. Cosmos nickel project, Kathleen Valley, in: Neumayr, P., Harris, M., Beresford, S.W (Eds.), Gold and Nickel Deposits in the Archean Norseman-Wiluna Greenstone Belt, Yilgarn Craton, Western Australia – a field guide. Geological Survey of Western Australia, Perth, pp.109-116.

Lefever, D.W., 1926. Measuring geographic concentration by means of the standard deviational ellipse. The American Journal of Sociology 32, 88-94.

Lesher, C.M., Burnham, O.M., Keays, R.R., Barnes, S.J., Hulbert, L., 2001. Geochemical discrimination of barren and mineralized komatiites associated with magmatic Ni-Cu-(PGE) sulfide deposits. Canadian Mineralogist 39, 673-696.

Lesher, C.M.and Keys, R.R., 2002. Komatiite-associated Ni-Cu-PGE deposits: geology, mineralogy, geochemistry and genesis, in: Cabri L.J. (Ed.), The geology, geochemistry mineralogy and mineral beneficiation of platinum group elements. Canadian Institute of Mining Metallurgy and Petroleum Special Publication 54, 579-617.

Levine, N., 2007. CrimeStat® III. A spatial statistics program for the analysis of crime incident locations (version 3). Ned Levine & Associates and the National Institute of Justice.

Limpert, E., Abbt, M., Asper, R., Graber, W.K., Godet, F., Stahel, W.A., Windhab, E.J., 2000. Life is log normal: Keys and clues to understand patterns of multiplicative interactions from the disciplinary to the transdisciplinary level, in: Klein, J.T., Grossenbacher-Mansuy, W., Häberli, R., Scholz, R.W., Bill, A.,Welti., M. (Eds.), Transdisciplinarity: Joint Problem-Solving among Science, Technology and Society. Haffmans, Zurich, Switzerland, p. 20-24.

Limpert, E., Wener, A.S., Markus, A., 2001. Log-normal distributions across the sciences. Bioscience 51, 341-352.

Loper, J.E., Suslow, T.V., Schroth, M.N., 1984. Log-normal distribution of bacterial populations in the rhizosphere. Phytopathology 74, 1454-1460.

Lloyd, C.D., 2007. Local Models for spatial analysis. , CRC/ Taylor and Francis, Boca Raton, USA, 260 pp.

Magurran, A.E. 1988. Ecological Diversity and its Measurement. Croom Helm, London, 179 pp.

Malanca, A., Gaidolfi, L., Pessina, V., Dallara, G., 1996. Distribution of 226-Ra, 232-Th, and 40-K in soils of Rio Grande do Norte (Brazil). Journal of Environmental Radioactivity 30, 55–67.

Mamuse, A., Guj, P., submitted. Rank statistical analysis of nickel sulphide resources of the Norseman-Wiluna Greenstone Belt, Western Australia. Mineralium Deposita.

Mamuse, A., Porwal, A., Kreuzer, O.P., and Beresford, S., 2009, A new method for centrographic analysis of mineral deposit clusters: Ore Geology Reviews, v. 36, 293-305.

Mamuse, A., Porwal, A., Kreuzer, O., Beresford, S.W., 2010a. Spatial statistical analysis of the distribution of komatiite-hosted nickel sulfide deposits of the Kalgoorlie Terrane, Western Australia: clustered or not? Economic Geology 105, 129-142.

Mamuse, A., Beresford, S., Porwal, A., and Kreuzer, O.P., 2010b. Assessment of undiscovered nickel sulphide resources, Kalgoorlie Terrane, Western Australia. Part 1. Deposit and endowment density models. Ore Geology Reviews 37, 141-157.

Mamuse, A., Beresford, S., Porwal, A., Kreuzer, O.P., 2010, submitted. Assessment of undiscovered nickel sulphide resources, Kalgoorlie Terrane, Western Australia. Part 2. Estimates from local deposit and endowment density models. Ore Geology Reviews.

Mapleson, D.B, Bewsher, A.W., Bayley, J. 2007. Technical report on the Lanfrachi nickel project, Kambalda, Western Australia. BM Geological Services Pty Ltd., Perth, 137 pp.

Mandelbrot B.B., 1983. The fractal geometry of nature. W.H. Freeman and Company, New York, 468 pp.

Mann, C.J., 1993. Uncertainty in geology, in: Davis, J.C., Herzfeld, U.C. (Eds.), Computers in geology – 25 years of progress. Oxford University Press, pp. 241-254.

Marble, D.S. 2000. Some thoughts on the integration of spatial analysis and geographic information systems. Journal of Geographical Systems 2, 31-35.

Marcon, E., Puech, F., 2009. Generalizing Ripley's K function to inhomogeneous, in: HAL / Working Papers. RePEc:hal:wpaper:halshs-00372631_v1. http://ideas.repec.org/p/hal/wpaper/halshs-00372631_v1.html (accessed May 12, 2009).

Marston, R.J., 1984. Nickel mineralization in Western Australia. Mineral Resources Bulletin 14. Geological Survey of Western Australia, Perth, 271 pp.

Marston, R.J., Groves, D.I., Hudson, D.R., Ross, J.R., 1981. Nickel sulphide mineralisation of Western Australia: a review. Economic Geology 76, 1330-1363.

Martin, J. E., Allchurch, P. D., 1975. Perseverance nickel deposit, Agnew. Economic Geology of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 5, Melbourne, pp.149-155.

McCall, L.M., Dentith, M.C., Li, Z.X., Trench, A., 1995. The magnetic signature of komatiitic peridotie-hosted nickel sulphide deposits in the Widgiemooltha area, Western Australia. Exploration Geophysics 26, 66-77.

McQueen, K.G., 1981. Volcanic-associated nickel deposits from around the Widgiemooltha dome, Western Australia. Economic Geology 76, 1417-1448.

McCuaig, T.C.M, Beresford, S.W., and Hronsky, J.M.A., 2010. Translating the mineral systems approach into an effective exploration targeting system. Ore Geology Reviews, in press, doi:10.1016/j.oregeorev.2010.05.008.

McCuaig, T.C., and Guj, P., 2006. Balancing risk and reward in the face of increasing global exploration maturity. Outcrop to orebody: innovative geoscience in exploration and mining, Abstract Volume. Kalgoorlie 2006 Conference, 30 April to 4 May 2006, Kalgoorlie. Australian Institute of Geoscientists Bulletin 44, 3-8.

Merriam, D.F., Drew, L.J., Schuenemeyer, J.H., 2004. Zipf's Law: a viable geological paradigm? Natural Resources Research 13, 265-271.

Mincor Resources NL, 2008. Annual Report 2008. http://mincor.ice4.interactiveinvestor.com.au/Mincor0802/Annual%20Report%202008/EN/body.aspx?z=1&p=-1&v=2&uid=# (accessed September 22, 2009)

Mincor Resources NL, 2007. Profits and growth in nickel, Diggers and Dealers, Kalgoorlie, August 2007. http://www.mincor.com.au/images/mincor-46--foubi.pdf (accessed August 13, 2009).

Mitchell, A., 2005. The Esri guide to GIS analysis (volume 2: spatial measurements and statistics). ESRI Press, California, 238 pp.

Mosier, D.L., Singer, D.A., Berger, V.I., 2007. Volcanogenic massive sulfide deposit density. US Geological Survey Scientific Investigations Report 2007-5082, 21 p. Available http://pubs.usgs.gov/sir/2007/5082/ (accessed August 29, 2009).

Myers, J. S., 1990. Precambrian tectonic evolution of part of Gondwana, southwestern Australia. Geology 18, 537-540.

Myers, J. S., 1995. The generation and assembly of an Archaean supercontinent: evidence from the Yilgarn Craton, Western Australia, in: Coward, M.P., Ries, A.C. (Eds.), Early Precambrian processes, The Geological Society Special Publication 95, 143-154.

Myers, J. S., 1997. Preface: Archaean geology of the Eastern Goldfields of Western Australia-a regional overview. Precambrian Research 83, 1-10.

Myers, J.S. and Hickman, A.H., 1990. Pilbara and Yilgarn cratons-regional geology and Mineralization, in: Hughes, F.E. (Ed.), Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy Monograph 14, Melbourne, pp. 129-133.

Myint, S.W., 2008. An exploration of spatial dispersion, pattern, and association of socio-economic functional units in an urban system. Applied Geography 28,168-188.

Naldrett, A.J., 2004. Magmatic ore deposits. Geology, geochemistry and exploration. Springer-Verlag, Berlin, 727 pp.

Naldrett, A.J., Turner, A.R., 1977. The geology and petrogenesis of a greenstone belt and related nickel sulfide mineralization at Yakabindie, Western Australia, Precambrian Research 5, 43-103.

Nelson, D.R., 1998. Granite-greenstone crust formation on the Archaean earth-a consequence of two superimposed processes. Earth and Planetary Science Letters 158, 109-119.

Onley, P., Stephenson, W., Miller, A., Payne, P., Mappleson, D., Woodward, G., 2006. Technical Report: Lanfranchi Nickel Project, Western Australia. Golder Associates, Perth, 88 pp.

Openshaw, S. 1984. The modifiable areal unit problem. Concepts and Techniques in Modern Geography 38 Geo Books, Norwich, U.K., 41 pp.

Openshaw, S., Taylor, P.J. 1981. The modifiable areal unit problem, in: Wrigley, N., Bennett, R.J. (Eds.), Quantitative Geography: a British view. Routledge and Kegan Paul, London, p. 60-69.

O'Sullivan, D and Unwin, D. J, 2003. Geographic information analysis. John Willey and Sons, New Jersey, 436 pp.

Ord, J.K. 1990. Statistical methods for point pattern data, in: Griffith, D.A. (Ed.), Spatial Statistics, Past, Present and Future. Institute of Mathematical Geography, Ann Arbor, ML, pp. 31-53.

Ott, W.R., 1978. Environmental Indices. Ann Arbor (MI), Ann Arbor Science.

Paliwal, H.V., Bhatnagar, S.N., Haldar, S.K., 1986. Lead-zinc resource prediction in India: an application of Zipf's law. Mathematical Geology 18, 539-549.

Page, M.L., Schmulian, M.L., 1981. The proximal volcanic environment of the Scotia nickel deposit. Economic Geology 76, 1981-1479.

Panoramic Resources Limited, undated. Geology.

http://www.panoramicresources.com/go/operations/lanfranchi/geology (accessed September 22, 2009)

Panoramic Resources Limited, undated. Geology. http://www.panoramicresources.com/go/operations/lanfranchi/geology (accessed September 22, 2009)

Panoramic Resources Limited, 2009. Site visit Review, 29 June 2009. http://www.panoramicresources.com/files/090625_Stonebridge.pdf (accessed September 22, 2009).

Porwal, A., 2006. Mineral potential mapping with mathematical geological models. PhD dissertation, ITC , The Netherlands, 289 pp.

Quirk, D.G., Ruthrauff, R., 2006. Analysis of reserves discovered in petroleum exploration. Journal of Petroleum Geology, 29, 125 -146.

Razumovsky, N.K., 1940. Distribution of metal values in ore deposits. Comptes Rendus (Doklady) de l'Académie des Sciences de l'URSS 9, 814-816.

Reliance Mining Limited, 2004. Quarterly report for the period ended 31 March 2004. Reliance Mining Limited, Perth, 11 pp.

Reliance Mining Limited, 2005. Beta Hunt Project Update. Company Announcements, 12 January 2005. Australian Stock Exchange, Sydney, 3 pp.

Rice, A., Moore, J., 2001. Physical modelling of the formation of komatiite-hosted nickel deposits and a review of the thermal erosion paradigm. Canadian Mineralogist 39, 491-503.

Ripley, B.D., 1977. Modeling spatial patterns: Journal of the Royal Statistical Society B, 39, 172-192.

Ripley, B.D.,1981. Spatial statistics. John, Willey and Sons, New York, 252 pp.

Ripley, B.D., 1990. Gibbsian Interaction models, in: Griffith, D.A. (Ed.), Spatial Statistics, Past, Present and Future. Institute of Mathematical Geography, Ann Arbor, ML, pp. 3-25.

Root, D.H., Menzie, W.D. and Scott, W.A., 1992. Computer Monte Carlo simulation in quantitative resources estimation. Natural Resources Research 1, 125-138.

Rosengren, N.M., Beresford, S.W., Grguric, B.A., Cas, R.A.F., 2004. Flow focusing in a large komatiite sill: implications for the assembly and genesis of the Mt. Keith Ultramafic and associated NiS mineralization, in: Rosengren, N.C. 2004. Architecture and emplacement origin of an Archaean komatiitic dunite and associated NiS mineralization: Mt. Keith, Agnew-Wiluna Greenstone Belt, Yilgarn craton, Western Australia. PhD thesis, Monash University, Australia, pp. 155-194.

Rosengren, N.M., Beresford, S,W., Grguric, B.A., Cas, R.A.F., 2005. An intrusive origin for the komatiitic dunite-hosted Mount Keith nickel sulfide deposit, Western Australia. Economic Geology 100, 149-156.

Rosengren, N.M., Grguric, B.A., Beresford, S.W., Fiorentini, M.L., Cas, R.A.F. 2007. Internal stratigraphic architecture of the komatiitic dunite-hosted MKD5 disseminated nickel sulfide deposit, Mount Keith Domain, Agnew-Wiluna Greenstone Belt, Western Australia. Mineralium Deposita 42, 821-845.

Ross, J. R., Travis, G. A., 1981. The nickel sulfide deposits of Western Australia in global perspective: Economic Geology 76, 1291-1329.

Rowlands. N.J., Sampey, D., 1977. Zipf's law-an aid to resource inventory prediction in partially explored areas. Mathematical Geology 9, 383-391.

Sahu, B.K., 1982. Stochastic Modeling of Mineral Deposits. Mineralium Deposita. 17, 99-105.

Schuenemeyer, J.H., Drew, L.J., 1983. A procedure to estimate the parent population of the size of oil and gas fields as revealed by a study of economic truncation. Mathematical Geology 15, 145-161.

Scott, M., Dimitrakopoulos, R., 2001. Quantitative analysis of Mineral Resources for Strategic Planning: Implications for Australia Geological Survey. Natural Resources Research 10, 159-177.

Shi, W., 2010. Principles of modeling uncertainties in spatial data and spatial analyses. CRC Press, Taylor & Francis Group, Boka Raton, 412 pp.

Singer, D.A., 1993a. Basic concepts in three-part quantitative assessments of undiscovered mineral resources. Nonrenewable Resources 2, 69-81.

Singer, D.A., 1993b. Development of grade and tonnage models for different Deposit types, in: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), Mineral deposit modeling. Geological Association Canada Special Paper 40, p. 21-30.

Singer, D.A., 1994. Conditional estimates of the number of podiform chromite deposits. Nonrenewable Resources 3, 200–204.

Singer, D.A., 2008. Mineral deposit densities for estimating mineral resources, Mathematical Geosciences 40, 33-46.

Singer, D.A., 2010. Progress in integrated quantitative mineral resource assessments. Ore Geology Reviews, doi:10.1016/j.oregeorev.2010.02.001

Singer, D.A., Menzie, W.D., 2008. Map scale effects on estimating the number of undiscovered mineral deposits. Natural Resources Research 17, 79-86.

Singer, D.A., Mosier, D.L. 1981. Review of regional mineral resource Assessment methods. Economic Geology 76, 1006-1015.

Singer, D.A., Menzie, W.D., Sutphin, D., Mosier, D.L., Bliss, J.D. 2001. Mineral deposit density - an update, in: Schulz, K.J. (Ed.), Contributions to global mineral resource assessment research. US Geological Survey Professional Paper 1640-A, A1–A13. (also available online at http://pubs.usgs.gov/prof/p1640a/)

Singer D.A., Berger, V.I., Menzie, W.D., Berger, B.R., 2005. Porphyry copper density. Economic Geology 100, 491–514.

Stolz, G. W., Nesbitt, R. W., 1981. The komatiite nickel sulfide association at Scotia: a petrochemical investigation of the ore environment. Economic Geology 76, 1480-1502.

Stone, W.E. and Masterman, E.E., 1998. Kambalda nickel deposits, in: Berkman, D.A., Mackenzie, D.H. (Eds.), Australian and Papa New Guinean Mineral Deposits. The Australasian Institute of Mining and Metallurgy Monograph 22, Melbourne, pp. 347-356.

Stone, W.E., Archibald, N.J., 2004. Structural controls on nickel sulphide oreshoots in Archaean komatiite, Kambalda, WA: the volcanic trough controversy revisited. Journal of Structural Geology 26, 1173-1194

Stone, W.E., Beresford, S.W., Archibald, N.J., 2005. Structural setting and shape analysis of nickel sulfide shoots at the Kambalda Dome, Western Australia: implications for deformation and remobilization. Economic Geology 100, 1441-1455.

Stone, W.E., Rutter, J.B., Stone, M.S., Archibald, N.J., Ketelaar, P.B., 1998. Three-dimensional GIS and nickel exploration at Kambalda. Annual conference of the Australian academy of technological sciences. Proceedings of the 1998 symposium, Fremantle, pp. 97–111.

Sugihara, G. 1980. Minimal community structure: An explanation of species abundance patterns. American Naturalist 116, 770-786.

Sulway, R.M., Glacken, A.M., Earl, A. 2005. LionOre Mining International Ltd: Independent Technical Report, Black Swan Nickel Project 4966. Snowden, Perth, 57 pp.

Swager, C. P., 1995. Geology of the greenstone terranes in the Kurnalpi-Edjudina region, southeastern Yilgarn Craton. Geological Survey of Western Australia Report 47, Perth, 31 pp.

Swager, C.P., 1997. Tectono-stratigraphy of late Archaean greenstone terranes in the southern Eastern Goldfields, Western Australia. Precambrian Research 83, 11-42.

Swager, C. P., Griffin, T. J., 1990. An early thrust duplex in the Kalgoorlie-Kambalda greenstone belt, Eastern Goldfields Province, Western Australia. Precambrian Research 48, 63-73.

Swager, C.P., Griffin, T.J., Witt, W.K., Wyche, S., Ahmat, A.L., Hunter, W.M., McGoldrick, P.J., 1995. Geology of the Archaean Kalgoorlie Terrane-an explanatory note. Geological Survey of Western Australia Report 48 (reprint of Record 1990/12), Perth, 26 pp.

Tanaka, T, Ryu S., Nishigaki, M., Hashimoto, M., 1981. Methodological approaches on medical care planning from the view point of geographical allocation model: a case study on South Tama District. Social Science and Medicine 15D, 83-91.

Thiergärtner, H., 2006. Theory and Practice in Mathematical Geology - Introduction and Discussion. Mathematical Geology 38, 659-665.

Tobler, W. 1970. A computer movie simulating urban growth in the Detroit region. Economic Geography 46, 234-240.

Tobler, W., 1989. Frame independent analysis, in: Goodchild, M and Gopal, S. (Eds.), The Accuracy of Spatial Databases, London, Taylor and Francis, pp115-122.

Trofimovs, J., 1999. Facies architecture of the tri-modal volcanic succession of the southern portion of the Archaean Agnew-Wiluna greenstone belt, Leinster, Western Australia. BSc Honours Thesis, Monash University, Melbourne, 121 pp.

Trofimovs, J., Tait, M. A., Cas, R. A. F., McArthur, A., Beresford, S. W., 2003. Can the role of thermal erosion in strongly deformed komatiite-Ni-Cu-(PGE) deposits be determined? Perseverance, Agnew-Wiluna Belt, Western Australia: Australian Journal of Earth Sciences 50, 199-214.

Turcotte D.L., 1986. A fractal approach to the relationship between ore grade and tonnage. Economic Geology 81, 1528-1532.

Turcotte D.L., 1992. Fractals and chaos in geology and geophysics. Cambridge University Press, 221 pp.

Walpole, R.E., Myers, R.H., Myers, S.L., Ye, K., 2002. Probability and statistics for engineers and scientists, 7th edition. Prentice Hall, New Jersey, 730 pp.

Williams, R.I., Archibald, N.J., Miller, D.R., 1993. Nickel sulphide deposits of the Kambalda dome - a 3-dimensional perspective. Australian Geological Survey Organisation Geoscience Record 1993/54, pp. 171-173.

Woolrich, P., Cowden, A., Giorgetta, N.E., 1981. The chemical and mineralogical variations in the nickel mineralization associated with the Kambalda Dome, Western Australia. Economic Geology 76, 1629-1644.

Wong, D.W.S. and Lee, J., 2005. Statistical analysis of geographic information with ArcView and ArcGIS. John Willey & Sons, New Jersey, 441 pp.

Wyborn L.A.I., Heinrick C.A., Jaques A.L. 1994. Australian Proterozoic mineral systems: essential ingredients and mappable criteria. 1994 AusIMM Annual Conference, The Australasian Institute of Mining and Metallurgy Publication Series 5/95, 109–115.

Yuill, R.S., 1971. The standard deviational ellipse; an updated tool for spatial description. Geografiska Annaler (Series B, Human Geography) 53, 28-39.

Zipf, G.K. 1949. Human behaviour and the principle of least effort: an introduction to human ecology. Addison-Wesley, Reading, MA, 573 pp.

Zuo, R., Cheng, Q, Agterberg, F.P., Xia, Q., 2009. Evaluation of the uncertainty in estimation of skarn tin in Southern China. Ore Geology Reviews 35, 415-422.