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# A MINERAL SYSTEMS APPROACH TO THE DEVELOPMENT OF STRUCTURAL TARGETING CRITERIA FOR OROGENIC GOLD DEPOSITS IN THE ASANKRANGWA GOLD BELT OF THE KUMASI BASIN, SOUTH-WEST GHANA

by

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**A thesis submitted in partial fulfillment of the requirements for the degree of**
**MASTER OF SCIENCE (Economic Geology)**

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March 2018

# Acknowledgements

I would like to thank my supervisors Professor Jock Harmer and Dr. David Khoza, both of whom provided excellent guidance and inspiration during my studies. Without the continued support from Professor Harmer I would not have completed this project on time, and for that I am grateful. Dr. Khoza generously donated much of his time to help me with data interpretation and guidance.

I would like to thank my mentor Phil Bentley, who completed the same program in 1985 and was a major source of inspiration to enroll in the Rhodes Economic Geology MSc. program. Mr. Bentley taught me to think on multiple scales and was a major source of inspiration for this project. As a result of his mentorship I am a much better geologist.

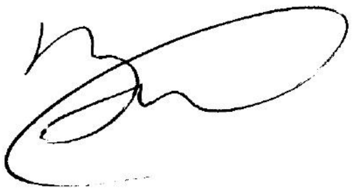
In addition, I would like to thank my employer Asanko Gold Inc. for allowing me the time off, data, and freedom to complete the project.

I would like to thank my family and friends for their continued support and encouragement. In particular I would like to thank my beautiful fiancé Giorgia Mariucci for her patience, love and support, and wonderful Italian cooking through this process. It wasn’t always easy, but it was worth it.

# Declaration

I, Benjamin D.J. Gelber declare this dissertation to be my own work. It is submitted in fulfilment of the Degree of Master of Science, Economic Geology, at Rhodes University.

It has not been submitted before for any degree of examination on any other University or tertiary institution.

Signature of candidate: 

Date: 17 March 2018

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## Acronyms and Abbreviations

| | |
|---|---|
| AMIRA | Australian Mineral Industries Research Association Limited |
| CET | Centre for Exploration Targeting |
| EM | Electromagnetic |
| HEM | Helicopter Electromagnetic and Magnetic |
| MPM | Mineral Prospectivity Mapping |
| MRA | Mineral Resource Assessment |
| PMCDC | Predictive Mineral Discovery Cooperative Research Centre |
| SCLM | Sub-continental Lithospheric Mantle |
| VTEM | Versatile Time-domain Electromagnetic |
| WAC | West African Craton |
| WAXI | West African Exploration Initiative |

## ABSTRACT

The Kumasi Basin in South-west Ghana lies at the centre of the best-endowed Paleoproterozoic gold province in the world. The Kumasi Basin and margins of the adjacent volcanic belts are host to six world class gold camps: (1) 62 Moz Obuasi camp, (2) 22 Moz Prestea-Bogoso camp, (3) 11 Moz Asanko Gold Mine camp, (4) 9 Moz Edikan camp, (5) 7 Moz Bibiani camp, (6) 5 Moz Chirano camp, as well as several additional minor gold camps and many more prospects. Cumulatively these camps account for >116 Moz of endowment and contribute to making south-west Ghana the greatest Paleoproterozoic gold province in the world.

Gold deposits in the Kumasi Basin are shear zone hosted and mineralisation ranges from disseminated to massive sulphide refractory deposits, to free milling quartz vein style deposits. Structural relationships and age dating indicate that most deposits are genetically related and were formed during a single episode of gold mineralisation during the D4 NNW-SSE crustal shortening deformation event of the Eburnean Orogeny (2125 – 1980 Ma). The understanding of structural controls on mineralisation is critical for exploration success as it allows exploration to focus on areas where these structural controls exist.

This study uses a mineral systems approach to understand the relationship between the geodynamic history and structural controls on gold mineralisation in the Kumasi Basin at various scales, and define targeting criteria which can be applied for the purpose of developing predictive exploration models for making new discoveries in the Asanko Gold Mine camp located in the Asankrangwa Belt. The study used a quantitative analysis to establish residual endowment potential in the Asankrangwa Belt, providing the basis for a business model and resulting exploration strategy. Once established, a Fry autocorrelation analysis was applied to identify trends in deposit and camp spatial distribution to which critical geological processes were ascribed. Observed trends were mapped from multi-scale geophysical data sets and through interpretation of existing geophysical structure models, and structural criteria for targeting orogenic gold deposits at the regional and camp scales were developed.

Results show that different structural controls on mineralisation act at the regional and camp scale. At the regional scale the distribution of gold camps was found to be controlled by fundamental N-S and NW-SE basement structures with gold camps forming where they intersect NE-SW first and second order structural corridors. At the Asanko Gold Mine camp scale, deposit distribution was found to be related to the intersection between major second order D3 NE-SW shear zones, minor third order D4 NNE-SSW brittle faults, and cryptic NW-SE upward propagating basement structures. In addition to these structural criteria, deposits in the Asanko Gold Mine camp were found to be aligned along a NNE-SSW lineament caused by the interaction between the N-S basement structure and the NE-SW trending Asankrangwa Belt shear corridor.

# 1 INTRODUCTION

The aim of economic geology is to provide a framework for the understanding of ore deposits that can be used by exploration geologists to efficiently discover and delineate new major mineral resources that remain economic through commodity price cycles. Mineral exploration is essentially comprised of three sequential steps:

(1) Development of a business strategy.

(2) Creation and application of targeting models.

(3) Follow-up with direct detection methodologies of defined high priority target areas (Hronsky & Groves, 2008).

In order to justify exploration expenditure one must be sure that there is the potential to make significant discoveries in a particular area of interest and this forms the foundation on which a robust business strategy can be built. A Zipf's Law quantitative study is an effective way of quantifying the residual endowment of a search area in terms of the number and size of as yet undiscovered orebodies (Fallon, et al., 2010). The result of a Zipf's Law analysis allows realistic geological models of residual endowment to be generated and provides the basis for building a business case on which initial investment or further exploration expenditure in the Asankrangwa Belt can be based. This can be applied at multiple scales in any commodity and is particularly important in moderate to mature districts in order to satisfy that there is a reasonable potential for making additional significant discoveries.

This study aims to use a Zipf's Law quantitative analysis to draw a strong link between prospectivity and the residual endowment of a camp or district. A mineral system approach is adopted whereby critical geological processes identified in the geodynamic history are related to trends in the spatial distribution of ore deposits identified using a Fry analysis. Structural features corresponding to these trends are modelled by interpreting geophysical data to develop structural criteria for targeting gold deposits in the Asanko Gold Mine camp. As the gold deposits of the Kumasi Basin, and in West Africa in general, are structurally controlled, understanding the underlying structural controls that dictate mineral deposit location at different scales is key to developing an effective exploration targeting criteria.

The minerals system concept is based on understanding the combination of geological processes that are required to form and preserve ore deposits at all scales (Wyborn, et al., 1994). It is based on the concept that although individual mineral deposits are relatively small and rare, they are formed by exceptional interaction of geological processes which are mappable on a much larger, district to regional scale, and constitute a mineral system of which the deposit is the central feature (McCuaig & Hronsky, 2014). This study uses a mineral systems approach to understand the structural controls on gold mineralisation in the Kumasi Basin at various scales by relating them to critical geological processes in the geodynamic history. By drawing the link between geological processes and mappable features, robust structural targeting criteria are defined which can be applied for the purpose of making new discoveries in the Asanko Gold Mine camp located in the Asankrangwa Belt.

Creating robust, multi-scale targeting models for ore deposits is the most critical task for exploration geologists, as well as the most challenging. Effectively translating geological processes critical for ore formation at various scales into mappable criterion is not always straight forward. This requires a clear understanding of the geodynamic history and ability to relate the critical processes to mappable features (Hronsky & Groves, 2008). At some scales, critical features may have no surface expression and only be visible in large regional datasets which may, or may not be readily available. If critical features are misidentified and non-critical features are focused on, many false positives can be introduced into resulting prospectivity and targeting exercises reducing the efficiency of exploration programs based on them (McCuaig, et al., 2010). Central to this process is the concept of scale. Scale is a fundamental principle of the mineral systems concept, which states that deposits are small expressions of much larger systems. As such, in order to be effective, multi-scale targeting models must be created in order to fully understand the structural controls on mineralization at the scale being observed. Only then can truly predictive models be generated.

Fry auto-correlation analyses are effective for illuminating relationships between structure and mineralisation and can be used to examine preferred trends in deposit location data at all scales (Austin & Blenkinsop, 2009). Trends can then be related to both the geodynamic deformation history and underlying structural architecture indicating the dominant controls on gold camp or deposit location at different scales (McCuaig & Hronsky, 2014). This is a critical step in translating geological processes into mappable features on which the mineral systems concept is based. Trends identified in the Fry analysis are related to critical geological processes and mapped using geophysical data sets and existing models. At the regional and district scale the Kumasi Basin Fry analysis indicated four distinct spatial trends in deposit location point data. Two trends could be attributed to observed structural features related to D3 and D4 deformation events of the Eburnean Orogeny. Two trends were more cryptic, however, and are not expressed as mappable features on surface. At the camp scale, three distinct spatial distribution trends in deposit point data were observed of which one could be related to the D4 deformation event of the Eburnean Orogeny, and the other two to more cryptic geological processes. The most dominant trend at the camp scale was not observed at either the regional, or district scales indicating that the controls on mineralisation are different depending on the scale being observed. This is a very important observation and critical for the development of multi-scale targeting models.

Interpretation of geophysical data sets was used to map geological features at different scales. This is the methodology by which this study translated critical geological processes identified in the geodynamic history and confirmed by observed trends in the Fry analysis, into mappable features. Geophysical data sets are most often proprietary and notoriously closely guarded. Such is the case for high density regional gravity and regional magnetic data covering SW Ghana and the Kumasi Basin. As such, publicly accessible regional gravity survey data was used in this study and although somewhat lacking in definition was suitable to illustrate the cryptic basement structure architecture of the Kumasi basin. At the scale of the Asankrangwa Belt and Asanko Gold Mine camp, 2D and 3D structure models created from airborne electromagnetic (EM) and magnetic data of the surficial and upward propagating basement structure architecture were analyzed.

The result of this work is the development of a fully integrated, robust, multi-scale structural model over the Kumasi Basin and Asankrangwa Belt study area. The model successfully translates the critical geological processes identified from the geodynamic history and corroborated by spatial distribution trends observed in the Fry analysis, into 2D structural targeting criteria for orogenic gold deposits in the Asankrangwa Belt study area.

Geological and structural models used in this report are products of the collaborative efforts of the author, Asanko geologists, and external consultants as part of Asanko Gold Inc.'s ongoing exploration activities in the Asanko Gold Mine Camp. The current study synthesizes and interprets these models to identify those elements of the models that correspond to critical geological processes in order to generate the targeting criteria. As such, all of the interpretations and conclusions presented in this study were derived by the Author.

# 2 QUANTITATIVE MINERAL RESOURCE ASSESSMENT

## 2.1 Introduction

Before embarking on expensive and time-consuming exploration programs in either the brownfield, or greenfield spaces, it is important to have a business model for the targeted mineral deposit type. The mineral system concept provides a fantastic framework for understanding the structural controls on mineralisation and predicting where deposits are likely to occur. What the mineral system theory does not do however, is provide a framework for the quantity, or size of deposits that are likely to be found. In order to do this one must be able to assess with some accuracy the potential endowment in a greenfield environment, and the residual endowment in a brownfield environment. This provides information that is essential in strategic planning of any first time investment, or follow-up exploration program. This process is also very important for managing expectations regarding the potential outcomes of exploration programs.

The Asanko Gold Mine camp, located within the Asankrangwa Belt (see Figure 20) is primarily a brownfield environment. The principal aim of exploration in this environment is to find, or acquire, new deposits within economic transport distances of the existing mine infrastructure in order to add materially to shareholder value through:

(a) Mine capacity extension.

(b) Displacement of lower value ore.

(c) Extension of mine life.

(d) Understand and realise full potential value as it relates to future development, or exit strategy (Whiting & Schodde, 2006).

A key aspect of this is a full and informed understanding of the potential residual resource endowment in the area of interest. This section demonstrates the residual endowment potential of the Asankrangwa Belt study area in order to make the business case for continued investment in exploration programs to discover new deposits.

Mineral Prospectivity Mapping (MPM) uses criteria deemed to be fundamental for deposit formation in order to identify areas where deposits have the highest potential of occurring. Mineral Resource Assessment (MRA) has a slightly different focus in that it aims to:

(1) Identify areas where the geology is permissible for deposit formation.

(2) Estimate the amount of residual metal within an area of interest.

(3) Estimate the number of undiscovered mineral deposits within the area of interest (Carranza, et al., 2009).

This section focuses on (2) and (3) above; estimating the amount of residual metal and number of residual deposits in the Asakrangwa Belt in the Kumasi Basin. Mineral prospectivity mapping was not undertaken as part of this study and would be a logical follow up project.

There are two primary methodologies for predicting both residual metal content and number of residual deposits in an area of geologically permissive host rocks. The first is a probabilistic approach such as that applied by Lisitsin, et al., (2010) and Singer & Kouda, (2011). The second uses Zipf's Law power-law relationship such as that applied by Guj, et al., (2011) and Hunt & Ozcan, (2016).

The probabilistic approach uses the area of geologically permissive regions and the concept that the total ore tonnage in a particular area is proportional to the median size of the known deposits in that area (Lisitsin, et al., 2010) and (Singer & Kouda, 2011). Regressions of the size of geologically permissive areas against median tonnage of known deposits allow an estimation of the number of total residual deposits and tonnages to be made. Estimates are usually represented as 90%, 50% and 10% confidence limits for the number of deposits and total tonnage. This methodology was devised from the study of 10 different deposit types from 109 districts and camps worldwide (Singer & Kouda, 2011).

This methodology works reasonably well when applied to relatively mature districts where existing deposits have been well explored. It also works well in districts where well-explored, permissive geological terrains disappear under cover. Using this methodology can be effective for business investment decision points by quantifying the probabilities of making significant discoveries in a target area. This type of analysis is commonly done as a precursor to deciding whether it was worthwhile investing in geophysics or other methods. required to understand the structural architecture necessary for targeting, or even whether to search in a particular district at all. As previously mentioned: this methodology is dependent on substantial grade tonnage information and so is not generally appropriate for greenfield, or juvenile districts.

When there is little grade tonnage data a one–level prediction analysis can be used to predict the number of potential residual deposits, as was done in a study of the SW Ashanti belt, Ghana, by Carranza, et al., (2009). One-level prediction involves dividing an area into a grid of equal-area unit cells and calculating a favourability value for each area based on the extent of exploration and known endowment in each cell. A fractal analysis can also be applied for the purpose of estimating residual endowment as applied by Kreuzer, et al., (2007) in their study of the Charters Towers goldfield, NE Australia. While these methodologies can be useful for estimating the number of potential residual deposits, they are ineffective in accurately predicting the size of deposits likely to be found.

An alternative method for calculating number and size of residual deposits is a Zipf's Law distribution analysis. Although somewhat controversial, Zipf's Law is a method that enables the potential and residual endowment to be calculated with some degree of certainty. As opposed to area and median grade tonnage, Zipf's Law operates on the assumption that in any given prospective search area, the larger deposits are generally found first because they have the most obvious surficial expression. When used correctly it is the perfect accompaniment to the mineral system concept which is a predictive methodology for deposit detection.

There is substantial evidence that many natural systems, including the size and distribution of mineral and petroleum deposits, are controlled by some sort of a power law (Guj, et al., 2011). Zipf's Law is one such power law that was initially devised to predict the frequency of words used in various languages. It was then applied to other natural systems such as income distribution, immune system responses, city populations and then to the size petroleum and mineral deposits (Guj, et al., 2011). Zipf's Law is a modified Pareto distribution, which is also referred to as a power law distribution, 80/20 rule, or heavy-tailed distribution (Seigrist, 2017). In Zipf's Law the distribution decreases at a power rate rather than an exponential rate meaning that there are few large deposits accounting for the majority of the metal endowment and many smaller deposits training off in size in a given population distribution. Points along the Zipf's curve are generated by the following formula:

$$y = C \cdot r^{-k}$$

Where *C* is the value of the largest member of the population at rank 1, *r* is the rank of a point with value y, and k is a constant that under stable conditions of geological equilibrium has a value of approaching 1 (Guj, et al., 2011). As a result, in natural systems abiding by this relationship the product of the rank and the size of each deposit is approximately constant, and dictated by the largest deposit in the system (rank 1) (Guj, et al., 2011). The Zipf's distribution predicts that rank 1 (the largest deposit) is twice as large as rank 2, three times as large as rank 3, and so on (Guj, et al., 2011).

Table 1 is an example of a Zipf's Law application in an immature or emerging district in which three gold deposit discoveries were made: (1) 1 Moz, (2) 0.25 Moz, and (3) 0.1 Moz. By using the largest deposit as rank 1, Zipf's Law calculates from the top 20 largest deposits that there should be 3.6 Moz of total endowment in the example district of which 1.35 Moz has been discovered and 2.25 Moz is residual in 17 deposits. This represents a 37.5% maturity for the example district. Zipf's Law is powerful because not only does it predict the total quantum of potential residual endowment, it also predicts the size and number of deposits it will occur in.

**Table 1: Example Zipf's Law Distribution**

| Deposit | Deposit Name | Known Au | Calculated Zipf | Residual Au |
|---|---|---|---|---|
| 1 | Example Deposit 1 | 1,000,000 | 1,000,000 | 0 |
| 2 | Undiscovered Deposit | | 500,000 | 500,000 |
| 3 | Undiscovered Deposit | | 333,333 | 333,333 |
| 4 | Example Deposit 2 | 250,000 | 250,000 | 0 |
| 5 | Undiscovered Deposit | | 200,000 | 200,000 |
| 6 | Undiscovered Deposit | | 166,667 | 166,667 |
| 7 | Undiscovered Deposit | | 142,857 | 142,857 |
| 8 | Undiscovered Deposit | | 125,000 | 125,000 |
| 9 | Undiscovered Deposit | | 111,111 | 111,111 |
| 10 | Example Deposit 3 | 100,000 | 100,000 | 0 |
| 11 | Undiscovered Deposit | | 90,909 | 90,909 |
| 12 | Undiscovered Deposit | | 83,333 | 83,333 |
| 13 | Undiscovered Deposit | | 76,923 | 76,923 |
| 14 | Undiscovered Deposit | | 71,429 | 71,429 |
| 15 | Undiscovered Deposit | | 66,667 | 66,667 |
| 16 | Undiscovered Deposit | | 62,500 | 62,500 |
| 17 | Undiscovered Deposit | | 58,824 | 58,824 |
| 18 | Undiscovered Deposit | | 55,556 | 55,556 |
| 19 | Undiscovered Deposit | | 52,632 | 52,632 |
| 20 | Undiscovered Deposit | | 50,000 | 50,000 |
| **Total for Largest 20 Ranked Deposits** | | **1,350,000** | **3,597,740** | **2,247,740** |

Figure 1 is a graphical representation of Table 1. The calculated Zipf distribution curve is shown as the dashed black line and the three known deposits as histograms. Gaps in the histograms represent potential residual endowment. The Zipf's distribution shows that the largest 5 discoveries in an area of interest represent 63% of the total potential endowment and the largest 10 deposits represent 81%. As a general rule, the more deposits that are discovered between rank 1 and 20, the more mature a district is.

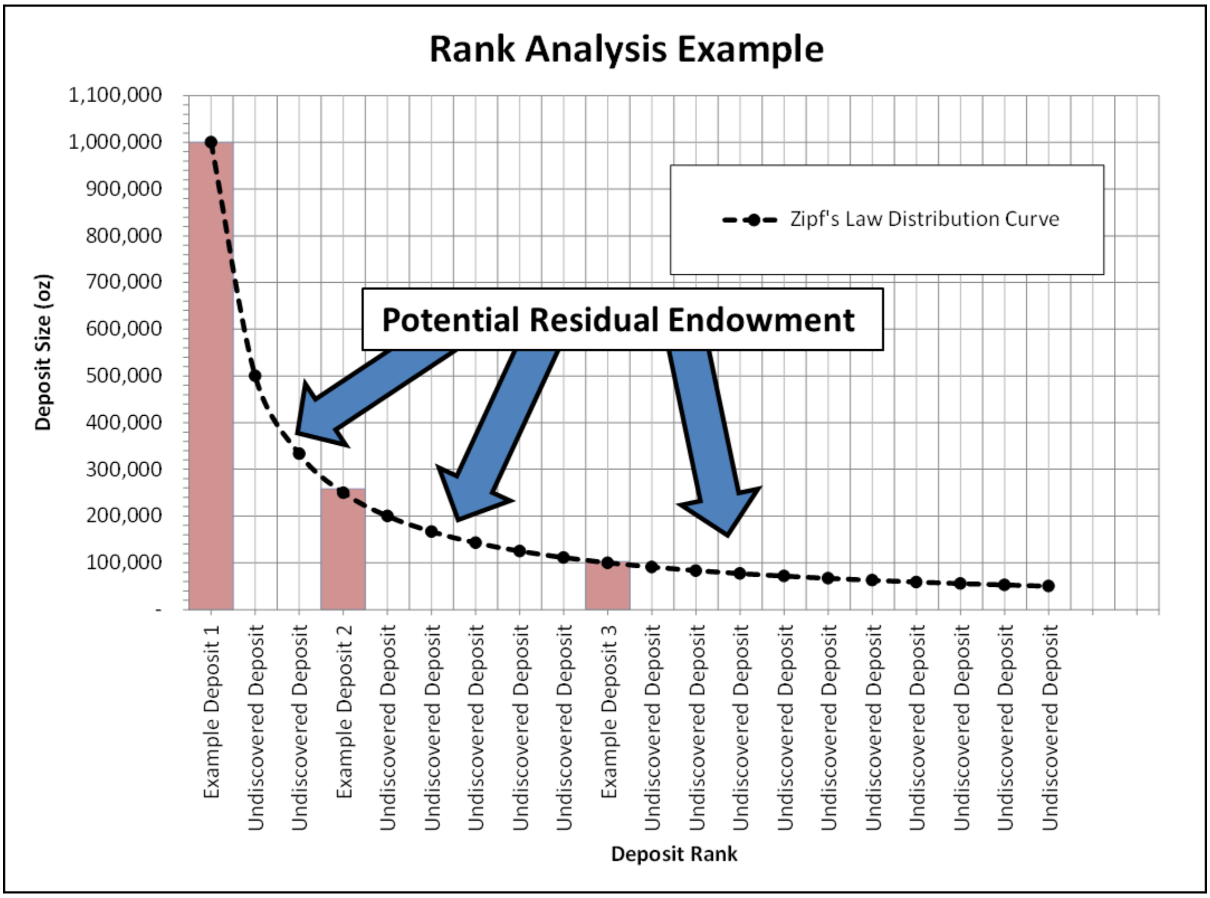


**Figure 1: Example Zipf's Law Rank Analysis Distribution Plot**

This estimation of the number and size of undiscovered gold resources is important in quantifying prospectivity and prioritizing exploration activity. Zipf's Law is an effective tool for managing expectation levels regarding the quantity and size of deposits that are likely to be made in a particular district. Zipf's Law is also effective as it updates the model with information from all new discoveries, or as deposits grow in size through further exploration quickly and easily.

Calculating expected residual gold resources at various stages of region, district, or camp, maturity can demonstrate the improvement in knowledge of resources and the diminishing residual potential (Hunt & Ozcan, 2016). Important investment decisions can then be made based on the potential endowment that is likely to be found, or residual in a particular district, or camp. When investing money into exploration in a particular project it is important to have a realistic idea of the potential discovery outcomes. This has major implications on the decision making process regarding whether to invest in a in a project, or area.

Previous methodologies for predicting endowment were typically based on subjective criteria applied to genetic, structural, geological and economic models generated by the geologist (Fallon, et al., 2010). History has shown that this methodology has led geologists to be overly optimistic in their predictions of deposit size resulting in low probabilities of success when executing their exploration programs and this directly contributes to the boom and bust nature of the minerals exploration industry. Companies with low discovery costs per ounce are generally rewarded in the market. In this day and age deposits are more difficult to find, either deeper or under cover. In order to drive successful exploration programs a pragmatic approach to potential mineral endowment must be adopted and a dedication to good science is essential.

In measuring potential or residual endowment of a district of camp, Zipf's Law is by default assessing the relative measure of prospectivity and maturity within an area of interest. This methodology has been applied successfully to exploration in the petroleum industry for decades in order to assess prospectivity and maturity of a particular oil field. The petroleum industry faced a similar problem with overestimating endowment and under delivering on discovery, destroying shareholder and company value. This trend forced the petroleum industry to apply a statisticl and probabilistic approach to the evaluation and targeting of residual endowment in oil basins and fields (Fallon, et al., 2010). By analysing the size and number of oil deposits in hydrocarbon producing areas around the world, it was recognised that the size and number of deposits within a particular basin followed a logarithmic distribution (Fallon, et al., 2010). Zipf's Law has since been successfully adapted to the natural distribution of mineral systems. Lisitsin, et al., (2010) estimated undiscovered orogenic gold endowment in Northern Victoria, Australia using several methods, including a Zipf's Law analysis and Hunt and Ozcan, (2016) estimated residual gold endowment of various terranes of different maturity in South Africa, Zimbabwe, and Turkey using Zipf's Law. Two case studies included below include a Zipf's Law analysis of the Plutonic/Marymia Greenstone belt in Western Australia by Fallon, et al., (2010), chosen for its similarity in size and total endowment to the Asanko Gold Mine camp, and perhaps the most comprehensive study which retrospectively applied Zipf's Law to calculate residual endowment of the Yilgarn Craton through time by Guj, et al., (2011).

It is important to note that some gold districts do not follow a power law distribution. Factors that could contribute to a significant deposit existing in relative isolation could be caused by lack of exposure, variable amounts of erosion, or simply a lack of effective exploration. This type of situation appears to be quite rare, but needs to be kept in mind when developing a business case in a particular district. It is up to the geologist to critically assess these factors with respect to the Fry analysis results. In the Kumasi Basin, exposure of permissible rocks is consistent through the basin, and all deposits are deemed to have experienced similar amounts of erosion.

## 2.2 Zipf's Law Applications in Mineral Systems

One of the reason why Zipf's Law works remarkably well is that in any given district, or camp, is because generally the largest deposits are commonly discovered early in the exploration history (Hronsky & Groves, 2008). This is because the largest deposits usually have the largest alteration and geochemical footprint. Large deposits often take up much of the exploration focus of a particular company and residual endowment isn't sometimes fully realised until much later. In addition, many companies are only interested in finding the next 'elephant'. While this is commonly the case, it should be noted that large discoveries can also be made in districts that have had previous exploration success. This was the case in the study Asanko Gold Mine camp with the >6 Moz Esaase deposit being discovered 15 years after the discovery of the >3 Moz Nkran deposit. The explanation in this case is due to the fact that the concession area containing the Esaase deposit was held by an alluvial mining company with no interest in hard rock exploration or discovery. The hard rock source was discovered immediately following the onset of hard rock exploration activities. A similar example is the Subika deposit in the Ahafo district in the adjacent Sefwi Gold Belt in SW Ghana. Due to a weak surface geochemistry anomaly, this giant deposit was not discovered until later in the maturity of the belt as it was low on the priority list for drill testing. In general the reasons contributing to large deposits being discovered later in the maturity of a belt can be due to lack of access or deposits can be blind to surface or under cover.

Using Zipf's Law within a district or camp allows expectations to be managed the prospect of significant discovery to be rationally assessed in a particular district, or camp and lead to well informed business model and investment decision benchmarks. This can help avoid unnecessary and futile exploration programs in areas districts little prospectivity, or in fully mature camps where all significant deposits have been.

Several comprehensive studies have been carried out to test the application of Zipf's Law at various scales and on various commodities. Mamuse, Porwal, Kreuzer, & Beresford, (2010) have written several papers on Ni endowment in the Kalgoorlie Terrane in Western Australia. Here, by studying 12 different control areas, they found that the size (as surface area, in $km^2$) of the control areas had power law relationships with (1) nickel sulphide deposit density, and (2) nickel endowment density (Ni metal/$km^2$). Regression analysis showed that both power law relationships were statistically significant suggesting that Ni sulphide deposit and endowment density models could be used to estimate the number of undiscovered Ni deposits and amount of Ni metal endowment in less explored Komatiite host rocks (Mamuse, et al., 2010).

Guj, et al., (2011) use a time audited Zipf's Law analysis to track the maturity of the Yilgarn craton through time and Fallon et al., (2010) in the paper titled "Prospectivity analysis of the Plutonic Marymia Greenstone Belt, Western Australia" use Zipf's Law to estimate residual gold endowment at the camp-scale. These are the two case studies examined in this current study.

### *2.2.1 Case Study 1: "A time-series audit of Zipf's Law as a measure of terrane endowment and maturity in mineral exploration" by Guj, et al., (2011).*

A comprehensive Zipf's Law study was carried out on the Yilgarn Craton in Western Australia and detailed in the 2011 paper titled "A time-series audit of Zipf's Law as a measure of terrane endowment and maturity in mineral exploration" by Guj, et al., (2011). This study assessed, with the benefit of hindsight, the accuracy of predictions that could have been made at selected points in time about the number and size of lode gold deposits yet to be discovered in the Archean Yilgarn craton.

The study looked at the gold endowment that Zipf's Law was predicting for this terrane based on the available knowledge at the time and calculated the residual endowment in 1973, 1989, 2003, and 2008.

Using production data from 1973, a Zipf's Law curve was used to estimate the total and residual endowment at that time (see Figure 2). Records at this time focussed on production and little is known about resource values. At this time the total gold production for the Yilgarn was calculated at 43.2 Moz, the residual endowment estimated at 186.1 Moz, and the total endowment estimated at 229.2 Moz (Guj, et al., 2011). Based on these numbers, the total production at this time represented only 19% of the total estimated endowment of the craton. The Zipf's Law distribution estimated that there would be 27 more ore bodies containing >1 Moz of gold and of these deposits (6) six were predicted to exceed 5 Moz of gold (Guj, et al., 2011).

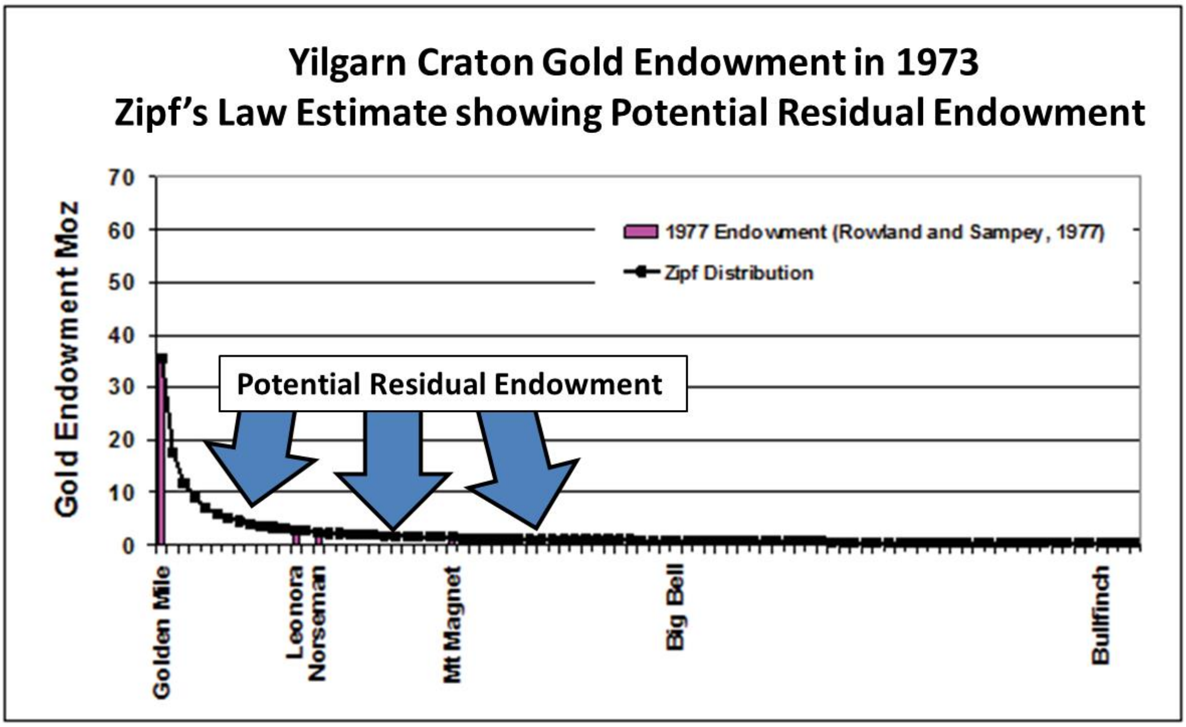


**Figure 2: Yilgarn Craton gold endowment in 1973 on a Zipf's Law distribution curve. Modified from Guj, et al., (2011)**

In Figure 3, the Zipf curve generated in 1989 shows a number of new greenfield and brownfield discoveries starting to fill the gaps. In addition to this, significant increase in the size of the rank 1 deposit had increased from 35.4 Moz to 43.1 Moz, lifting the entire curve and creating new gaps for possible discovery (Guj, et al., 2011). As a result of this total known endowment in the Yilgarn increased to 75.5 Moz, the residual endowment increased to 151.4 Moz, and the total endowment was now estimated at 226.9 Moz indicating that 33.3% of the total gold endowment had been discovered (Guj, et al., 2011). Of the residual orebodies remaining, 29 were estimated to contain in excess of 1 Moz and of these (7) seven were estimated to exceed 5 Moz (Guj, et al., 2011). Of the 27 undiscovered deposits in excess of 1 Moz predicted in 1973, 13 had been discovered by 1989 and even more were now predicted (Guj, et al., 2011).

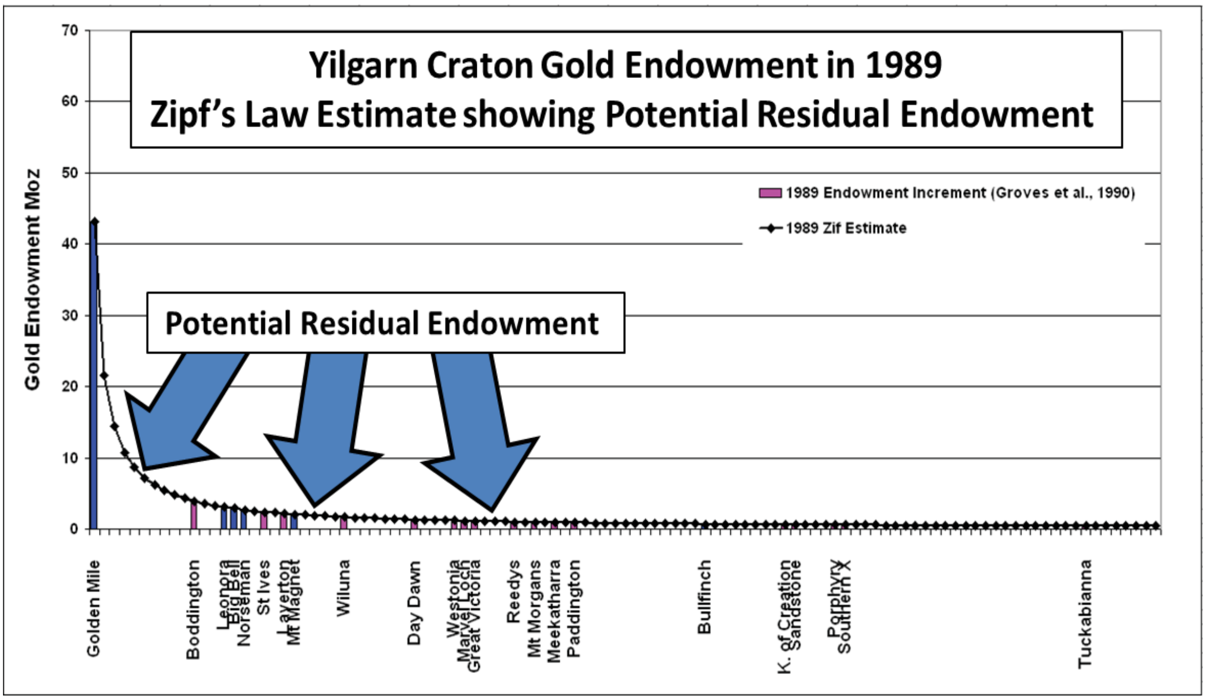


**Figure 3: Yilgarn Craton gold endowment in 1989 on a Zipf's Law distribution curve. Modified from Guj, et al., (2011)**

Figure 4 shows that by the end of 2003, 62.5% of the total predicted endowment had been discovered, with 35 deposits each containing more than 1 Moz having been found (Guj, et al., 2011). Again, the total endowment of the rank 1 deposit had increased significantly, raising the overall predicted endowment, opening up new gaps under the curve and increased the number of predicted residual deposits and hence the residual endowment (Guj, et al., 2011)

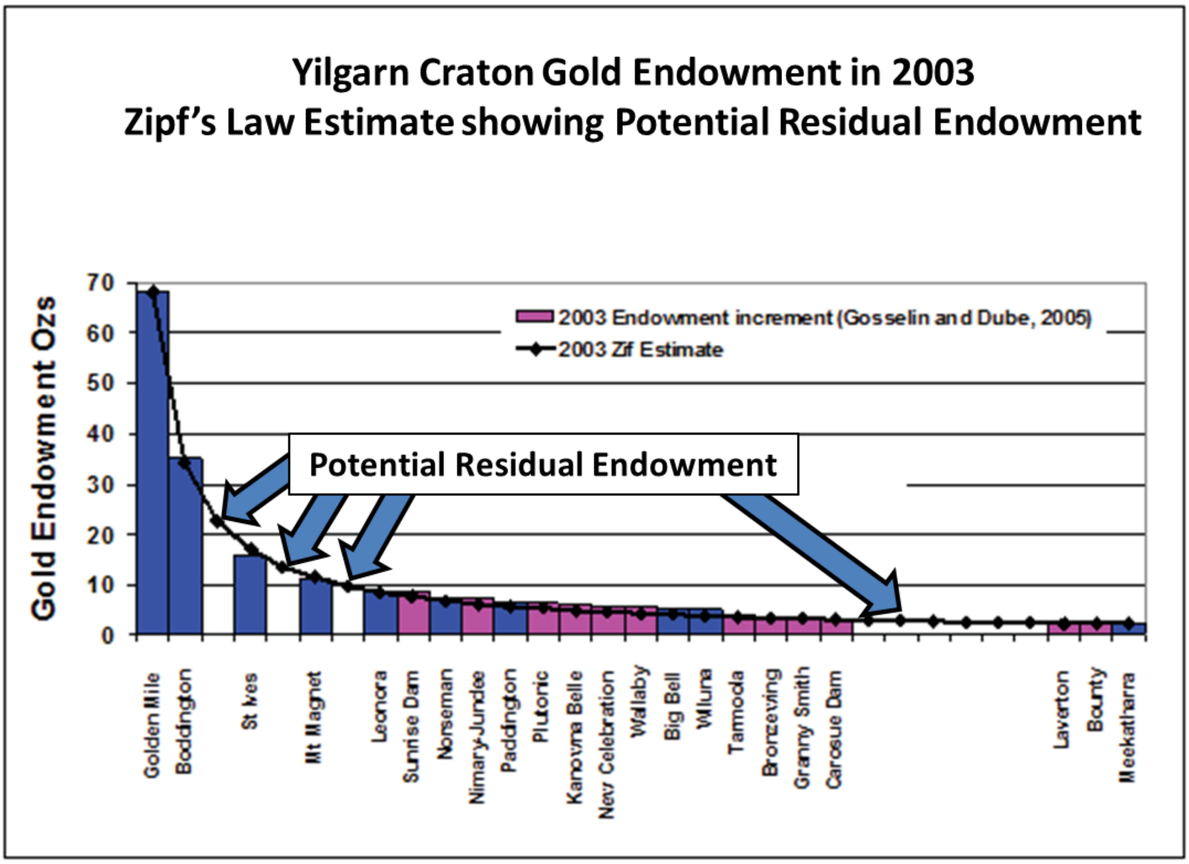


**Figure 4: Yilgarn Craton gold endowment in 2003 on a Zipf's Law distribution curve. Modified from Guj, et al., (2011)**

Figure 5 shows that by the end of 2008 it was estimated that 75% of the gold endowment of the Yilgarn had been discovered and that no new major gold camps were discovered between 2003 and 2008 (Guj, et al., 2011). This study showed that the residual endowment steadily decreased with the increase in known resources and new discoveries. As of 2008, apart from two large and at this stage highly unlikely camps predicted in the rank 3 and 4 spots, the gaps in the known mineralisation contained <1.6 Moz (Guj, et al., 2011). Considering the total endowment of the Yilgarn craton was 328 Moz in 2008 this represents 0.5% of the total known endowment, or conversely the Yilgarn could be considered to be 99.5% mature. Although the probability of discovering the rank 3 and 4 deposits is extremely low, if you assume it is possible then the maturity drops to 75%. This then provides the bases on which a business case can be made for exploration expenditure in the Yilgarn.

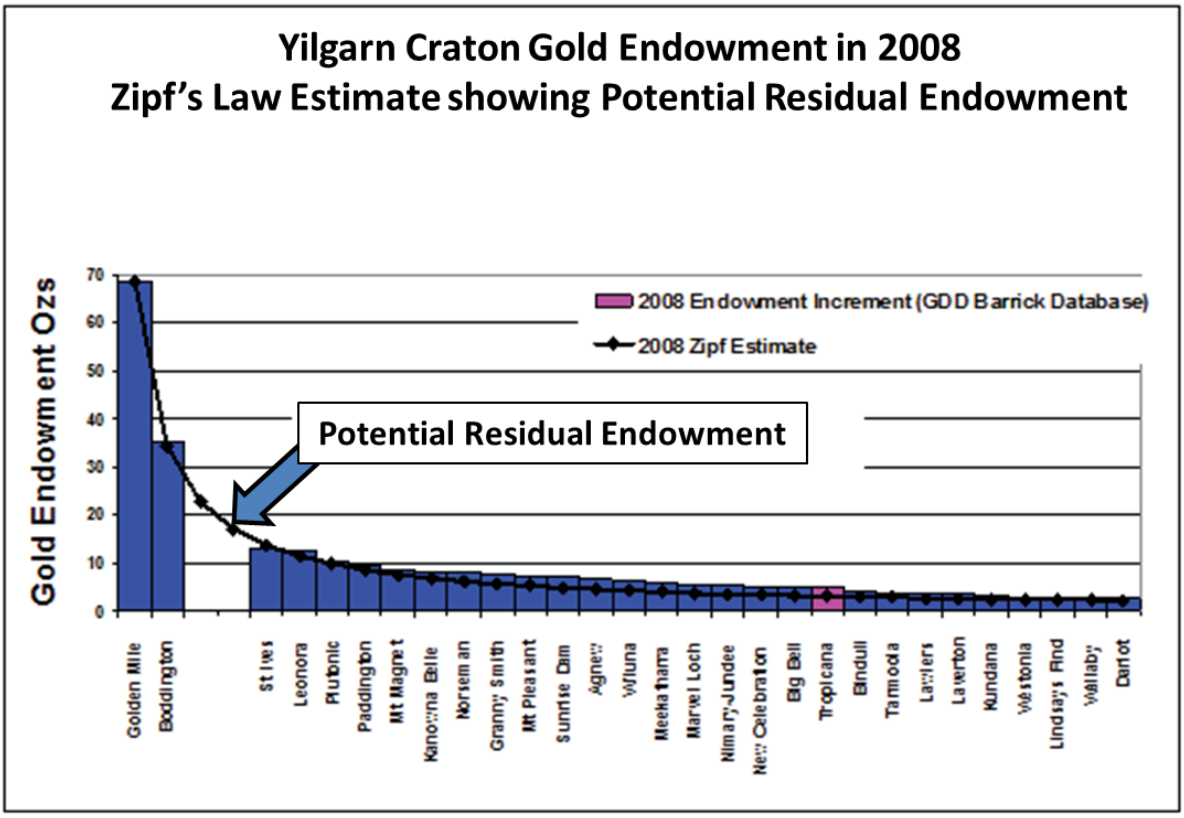


**Figure 5: Yilgarn Craton gold endowment on a Zipf's Law distribution curve. in 2008 Modified from Guj, et al., (2011)**

An important observation made in this Zipf's analysis is that for any study area, through time known deposits can be enlarged and new discoveries can be made. This is largely a function of better delineation of known deposits, discovery of additional near mine satellite deposits, and development of large, low-grade, previously uneconomical deposits (Guj, et al., 2011). In addition, new exploration technologies and exploitation methodologies can have an impact and spur the expansion of known assets and/or the discovery of new assets (Guj, et al., 2011). As a result, size ranking of deposits can change which will, in turn, change the Zipf's distribution curve, which, in turn, has major implications on accurately assessing the residual prospectivity of a region. Progressive increases in the resources within smaller deposits increase their ranking overtaking previously larger deposits and creating new gaps in the distribution.

If the top deposit locations in the Zipf's curve are filled and grow beyond their predicted sizes, it calls into question the accuracy of the size estimation of the largest deposit (Guj, et al., 2011). A situation like this would indicate that the largest deposit isn't properly delineated, or there exists a larger as-yet undiscovered deposit, or a giant that has since eroded (Guj, et al., 2011). This study pointed out hypothetically that if the Golden Mile deposit was removed from the Yilgarn distribution as if it was eroded, the residual gold endowment calculated by the Zipf's distribution would be 22% over estimated (Guj, et al., 2011). It is important then, when assessing the potential residual gold endowment of a region that this is taken into account and the implication is that if the largest deposit in a study area has not been defined, it is impossible to calculate the maturity of the region which is a function of the total delineated endowment divided by that predicted by the Zipf's distribution curve. This has potentially major impacts on the prospectivity of an area and must be carefully assessed.

### *2.2.2 Case Study 2: "Prospectivity analysis of the Plutonic Marymia Greenstone Belt, Western Australia" by Fallon, et al., (2010)*

The Plutonic Marymia camp is the sixth largest gold camp in Western Australia with an estimated total endowment of 12.2 Moz, making it analogous to the Asanko Gold Mine camp study area in terms of size and scale. In this study Zipf's Law was applied to estimate the potential size and number of gold deposits in the Plutonic Marymia camp followed by a GIS-based prospectivity analysis to indicate where the residual gold mineralisation was likely to occur.

In this study the 4 Moz Plutonic deposit (Zone 19) is the largest and occupies rank 1 (see Figure 6). When all other known deposits are plotted they occupy rank 1 through 5 on the Zipf distribution curve. Despite this the Zipf's Law curve still predicts between 5.5 and 5.9 Moz of undiscovered deposits in 25 deposits >0.1 Moz (Fallon, et al., 2010). Significantly, the Zipf's Law distribution predicts the potential for 6 undiscovered deposits ranging in size from 0.7 to 0.4 Moz representing a promising case for further exploration (Fallon, et al., 2010).

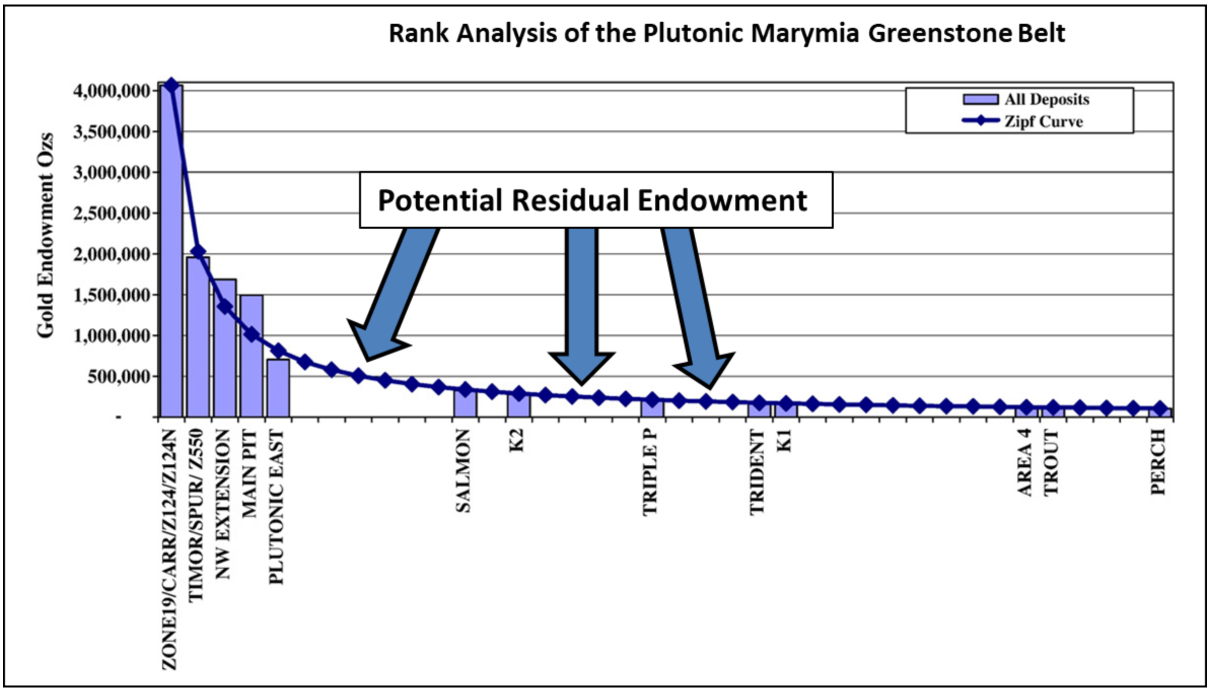


**Figure 6: Zipf's Law distribution of known deposits within the Plutonic Marymia camp. Modified from Fallon, et al., (2010)**

## 2.3 Deposit Distribution Within Kumasi Basin Gold Camps

### *2.3.1 Selected Examples of Ghana Gold Camps*

It is unknown whether a Zipf's analysis has been published publicly on Au deposits on any scale in West Africa, or Ghana. It has long been known that orogenic gold deposits tend to form in clusters or camps and the same is true for gold deposits in the Kumasi Basin study area. The deposit size distribution within camps tends to have one very large deposit which accounts for the majority of the metal endowment with multiple smaller deposits clustered around it (Guj, et al., 2011). If these camps are divided correctly into their individual components, the deposit size distribution will follow a Zipf's Law distribution. As always when applying a mineral systems approach, the issue of scale needs to be taken into account. If a craton scale distribution analysis were being conducted such as the Yilgarn example, individual gold deposits are lumped together into camps and their collective endowment used in the ranking, rather than that of the many individual deposits. At the camp scale, the Zipf's Law analysis looks at the endowment of each deposit individually so as to more accurately assess the residual endowment.

For example, at the cratonic scale the largest orogenic Paleoproterozoic gold deposit in West Africa is the giant 62 Moz Obuasi camp. At the belt or camp scale the Obuasi camp is actually made up of (8) individual ore shoots with discrete surface expressions along an 8 km strike of the Akropong fault This trend is surrounded by as many as fifteen much smaller satellite deposits (Fougerouse, et al., 2017). Figure 7 shows the location of the Obuasi deposit and the surrounding satellite deposits as well as a long section showing the individual shoots along the 8 km Obuasi trend. In a district or camp scale Zipf's analysis, even though these are connected at depth they would be treated as individual deposits. The endowment of each would be calculated separately and the individual ore deposits populate the Zipf's distribution curve.

The mineral system concept states that ore deposits are a small expression of much bigger mass flux systems that operate on scales far bigger than the individual deposits themselves. Success hinges on identifying the appropriate mappable features based on the scale of the analysis being conducted.

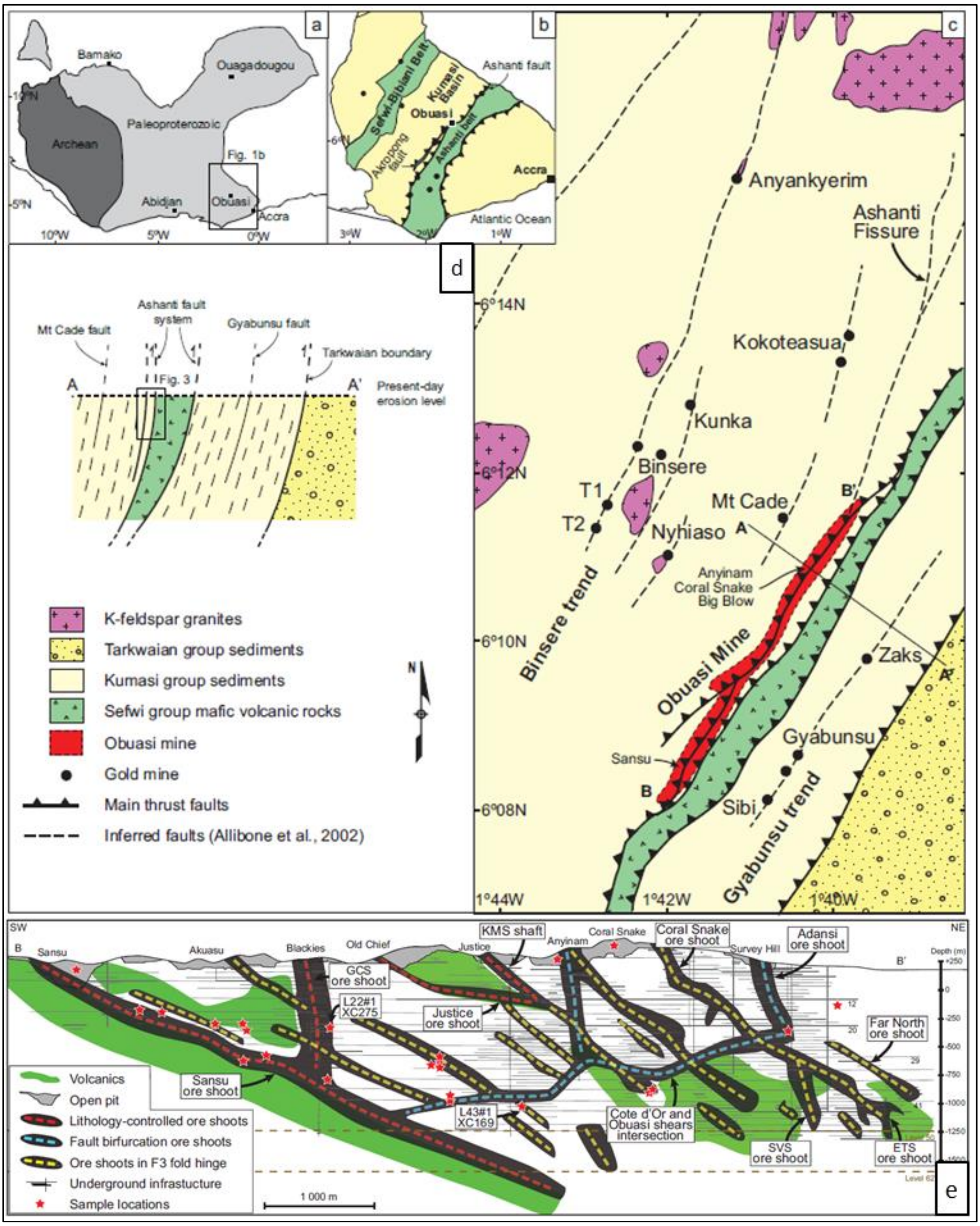


**Figure 7: Deposit distribution in the world-class Obuasi Gold Mine camp, Ghana showing (a) schematic overview of the geology Leo-Man Shield of the West African Craton, (b) simplified Birimian geology of Ghana with alternating volcanic belts and sedimentary basins, (c) Obuasi district geology showing the location of the main Obuasi trend in Red and the surrounding satellite gold deposits as black dots, (d) Cross section through the Akropong shear corridor and (e) projected long section of high-grade ore shoots showing where they discretely daylight on surface. Modified from Fougerouse, et al., (2017)**

Located along the boundary of the Ashanti volcanic belt and the Kumasi Basin sediments, the 22 Moz Prestea-Bogoso camp follows a similar trend with three large deposits surrounded by as many as 20 satellite deposits along a 20 km trend as does the 9 Moz Edikan Gold Mine camp which consists of up to fifteen deposits on and adjacent to the Akropong shear zone (see Figure 8).

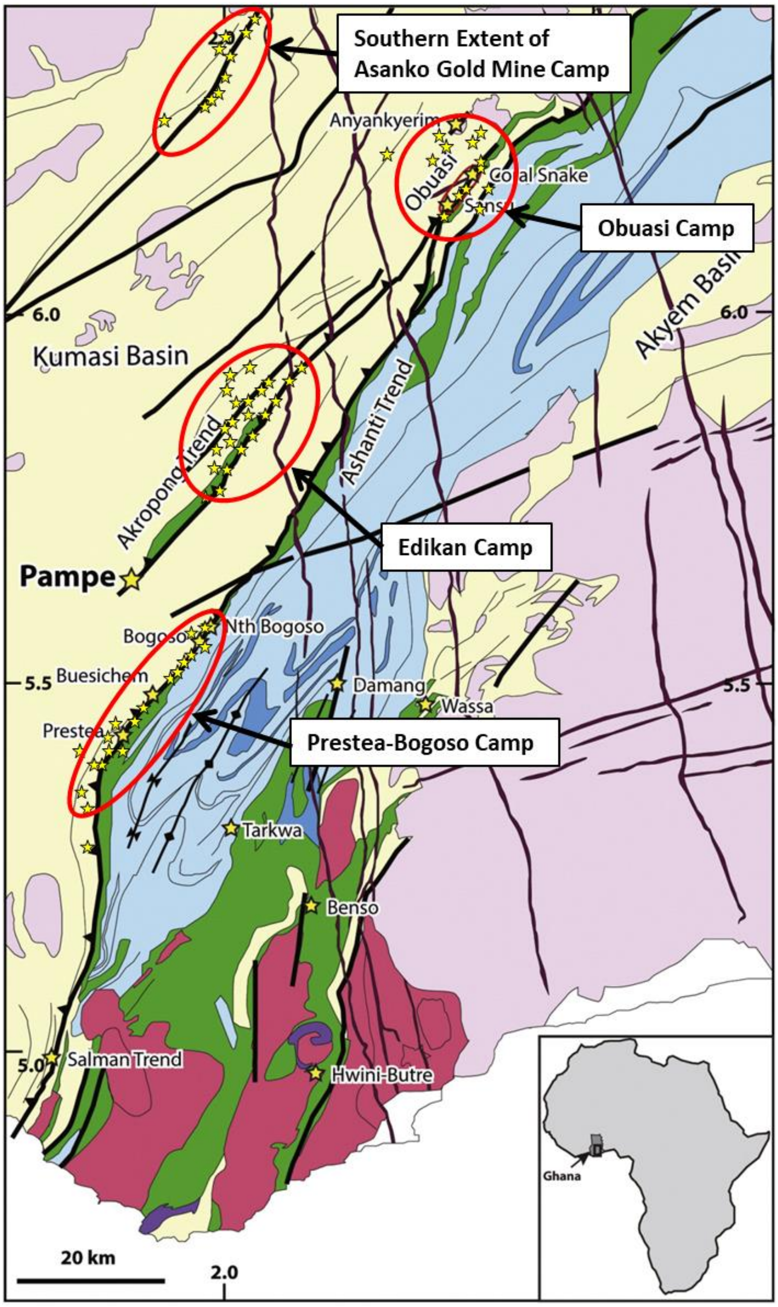


**Figure 8: Deposit location map showing the deposit distribution along the 20 km strike of the Prestea-Bogoso camp trend in relation to the Obuasi camp and Asanko Gold Mine Camp. Modified from (Salvi, et al., 2016)**

The 11 Moz Asanko Gold Mine camp in the Kumasi Basin is no different with the world class Esaase deposit surrounded by the large Nkran deposit and fifteen satellite deposits (see Figure 9).

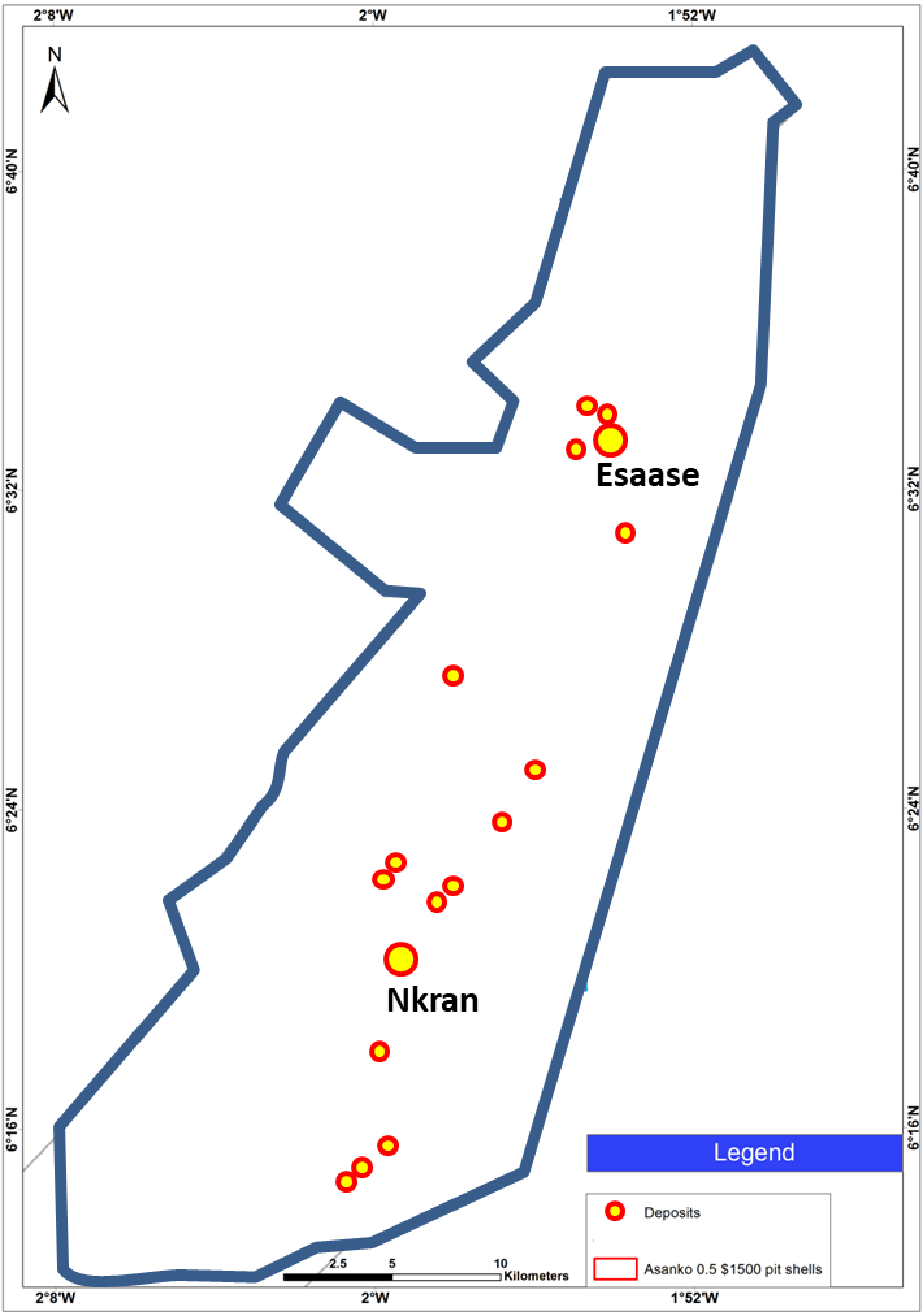


**Figure 9: Asanko Gold Mine camp study area showing deposit locations**

As we will see in this study, the Zipf's Law analysis tells us that the Asankrangwa Belt and the Asanko Gold Mine camp are still fairly immature from an exploration perspective and the chance of significant residual endowment is high. It is not known whether a Zipf's Law analysis has been conducted on these camps: it is beyond the scope of this project to focus on each of the camps individually and so the study focuses on the residual endowment of the Asankrangwa Belt and the Asanko Gold Mine camp.

## 2.4 Asankrangwa Belt Quantitative Analysis

A Zipf's analysis was carried out on the Asanko Gold Mine camp in the Asankrangwa belt. The Asanko Gold Mine camp has a current known endowment of >11 Moz Au. In creating the Zipf's analysis the following general considerations were taken into account:

(1) Populations of deposits should be genetically related as being part of the same mineral system and deposit type. Populations can then be subset into sub-populations at different scales such as cratonic, districts, or camps.

(2) Endowment for each deposit should be calculated as a total endowment by combining total residual resources plus past production.

In the case of the Asanko Gold Mine camp this is not an issue as all deposits are geographically and genetically related.

Figure 10 shows the Zipf's Law distribution of known gold deposits within the Asanko Gold Mine camp. Esaase, being the largest assumes the rank 1 position and the gaps are Zipf's Law predicted deposits not matched by known deposits and represent undiscovered gold deposits. The total sum of the undiscovered deposits is the quantum of residual endowment predicted to remain undiscovered in the belt. Despite the two largest deposits likely found, the Zipf's Law distribution predicts the potential for >19 Moz of gold in undiscovered deposits larger than 0.1 Moz in the Asankrangwa Belt. This includes 8.4 Moz from 7 deposits in the rank 3 to 9 positions ranging in size from 2.1 Moz to 0.7 Moz, and 5 deposits in the rank 11 to 15 positions ranging in size from 0.58 Moz to 0.42 Moz as well as many smaller deposits. Known endowment in the belt accounts for 39% of the predicted endowment indicating the immaturity of the Asanko Gold Mine camp.

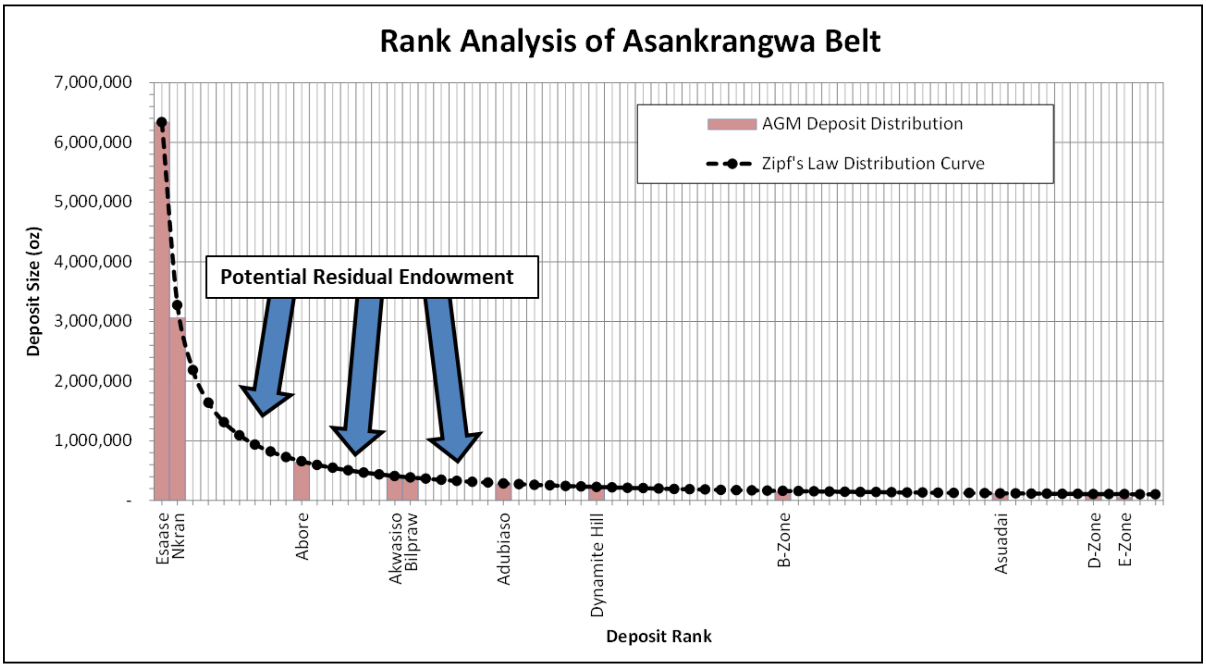


**Figure 10: Normal plot of the current Asanko Gold Mine endowment on a Zipf's Law distribution curve**

In conclusion, the residual endowment and prospectivity of the Asanko Gold Mine camp as predicted by the Zipf's analysis is very encouraging. The results of this analysis provide a robust argument for there being significant residual resources in the Asankrangwa Belt. Therefore, it would be feasible to assume that by applying robust exploration models, good science and a systematic approach the probability of making several additional major discoveries in the 2.1 Moz to 0.7 Moz range in the Asankrangwa Belt are encouraging. Two or more discoveries in this range have the ability to be game changing for any company from an economic perspective.

# 3 MINERAL SYSTEM CONCEPT

The aim of economic geology is to provide a framework for the understanding of ore deposits that is used by exploration geologists to efficiently discover and delineate major new mineral resources. Over the past few decades it is fair to say that a negative general perception has permeated through the mineral exploration industry, especially in the greenfield and grass roots exploration sectors. This is driven largely due to the fact that despite surging expenditure, the discovery rate of quality assets is in decline. Many factors can be attributed to the recent decline in discovery performance including: (1) progressive move toward exploring targets under cover, (2) increased emphasis on brownfields exploration and feasibility studies which do not deliver large discoveries at the expense of greenfield exploration, (3) a decline in drilling activity, and (4) increases in input costs during boom years (Schodde, 2017).

New discoveries are increasingly being made by applying new geophysical technologies designed to detect deeper, blind to surface deposits, or covered deposits with little, or no surface expression. New technology alone is not enough to make new discoveries and is most effective when coupled with robust exploration models and strategy which can be tested efficiently. Initial discoveries in any camp are usually found relatively easily, not requiring in depth understanding of the geological controls on mineralisation. As a camp matures however, an understanding of the geological processes responsible for the formation of the mineral deposit is essential for the discovery of blind deposits and is central to the mineral system concept (Hronsky & Groves, 2008).

This study uses a mineral system approach to holistically develop multi-scale structural targeting criteria for orogenic gold that can be used as a framework for exploration success in the Kumasi Basin and other orogenic gold belts around the world.

The mineral system concept is modified from petroleum system theory, which is the standard conceptual framework for predicting and targeting oil deposits in the petroleum exploration industry (Wyborn, et al., 1994). The fundamental concept behind the petroleum system theory is that it focuses on the elements and processes necessary for oil deposits to form and not the individual deposits themselves. These processes are: (1) the source, (2) transport, and (3) trap of oil, or gas in a reservoir (Wyborn, et al., 1994). This theory coupled with an industry committed to embrace and drive technological advances has been used for decades and has dramatically increased success rates in the petroleum industry while at the same time reducing exploration costs (Whiting & Schodde, 2006).

A good example of this is demonstrated by the exploration success rate for oil in the Gulf of Mexico from 1961-2001. Figure 11 shows how giant reserves have been discovered using a combination of a solid exploration concept and use of new technologies allowing the drilling of targets in deeper and previously inaccessible areas (Whiting & Schodde, 2006). This is analogous to using new geophysical exploration techniques in the mineral exploration industry to find deposits in prospective areas with little or no surface expression, or under cover. This is something that is very relevant to the mineral exploration industry today.

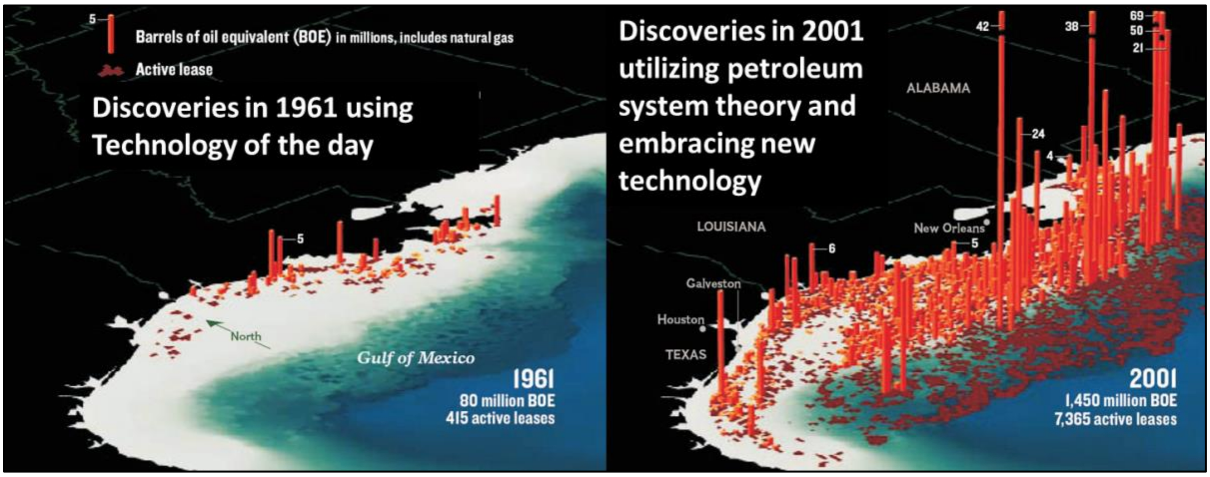


**Figure 11: The result of applying the mineral systems concept and new technology to petroleum exploration in the Gulf of Mexico. Modified from Whiting & Schodde, (2006)**

Historically mineral discoveries were made based on direct expression of surface mineralisation such as outcropping ore, gossans, geochemical anomalies and the reality is that these types of discoveries are becoming increasingly rare (Wyborn, et al., 1994). Early prospectors had little interest in the regional geological setting that they found themselves in and instead were focussed on the individual deposit scale. Exploration was traditionally driven by looking for deposit scale replicas and little thought was given to regional 4D geodynamic history, crustal scale lineaments, regional and camp ore deposit distribution trends, regional to camp scale structural architecture, regional alteration zones, or the source of the mineralising fluids related to the ore deposits that they were studying. Studies tended to be based on deposit-specific features such as oxygen fugacity, pH and salinity of the mineralising fluids locally, but not of the regional context (Wyborn, et al., 1994).

While this knowledge has significantly increased our knowledge of individual ore bodies and how to mine them, it is of limited relevance for predicting the location of new districts and assessing the endowment potential of different camps and provinces. It is now well understood that deposit scale features are known to vary significantly within a single regional mineral system that shares a common genetic origin, and thus are poor vectors for prospectivity and targeting. This is referred to as the deposit model concept and it is what was applied to mineral exploration until the 1990's (Hronsky, et al., 2012).

In the 1990's exploration expenditure rose sharply in response to commodity price increases. In response one would expect that that the number of large and giant deposits discovered would increase with it but this was not the case and led to the 1997 metal commodities crash. It would appear that the mineral exploration industry is slow to learn, as this is exactly what happened again almost two decades later during the next upswing in global metal prices, only this time more extreme as is shown in Figure 12. As discussed previously, this was exacerbated largely by a greater focus on brownfields exploration and feasibility studies that did not deliver discoveries (Schodde, 2017).

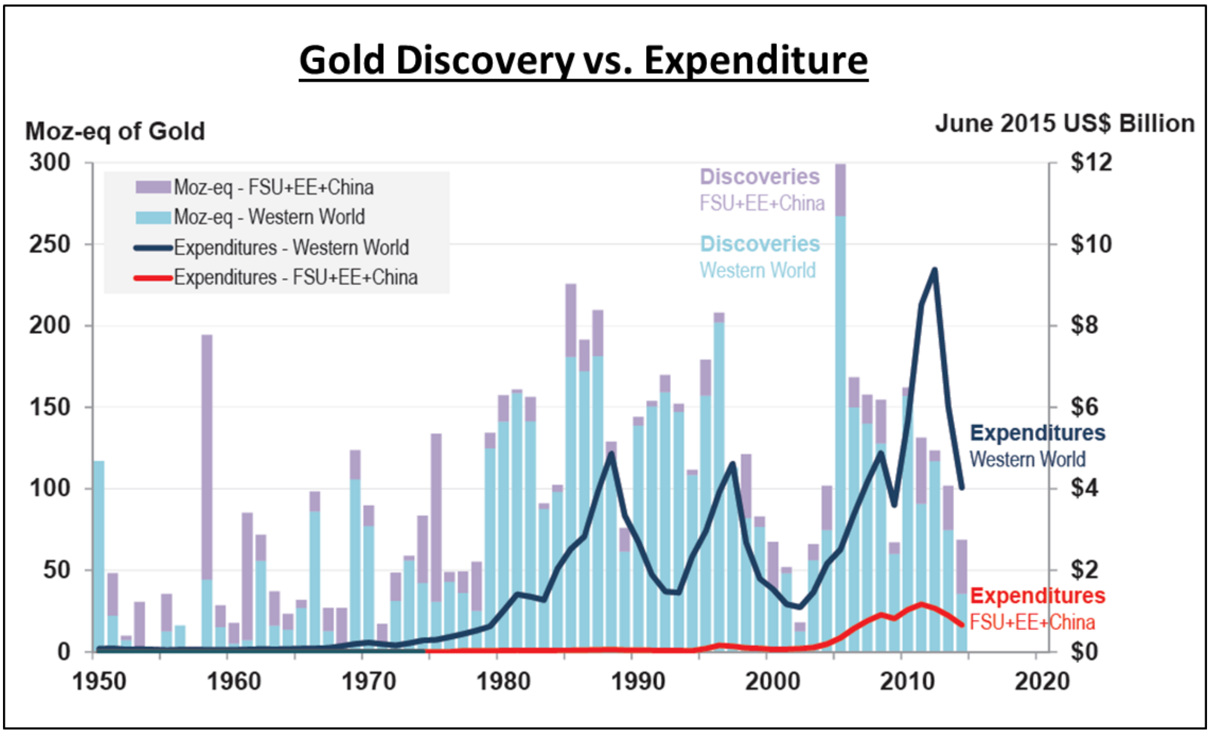


**Figure 12: Global gold discovery vs. total expenditure through time. Modified from Schodde, (2017)**

Although there were many factors responsible for the lack of discoveries, one could argue that a large part of it was due to the fact that the deposit models being employed for exploration were too rigid in approach, and not capable of effectively targeting at regional scales. In addition, by this time many easy to find deposits had been found, and the deposit model was not effective in detecting deposits with more cryptic surface expression. After studying this phenomenon extensively in the Eastern Goldfields of the Archean Yilgarn craton of Western Australia, McCuaig, Beresford, & Hronsky, (2010) offer (5) five reasons why deposit models are challenged when applied in regional exploration scenarios.

(1) Focussing too much on one geological feature such as a particular lithology can lead to a myopic targeting approach. Features which may be weighted too heavily may not be fundamental to the process of ore formation.

(2) On the other hand, focussing too much on one geological feature which may not be fundamental to the mineralisation process can introduce many false positives into a model.

(3) In some commodities there are too many defined deposit models. In this case there can be too many variations on a theme for practical application to exploration.

(4) The deposit model approach has difficulty differentiating between large, or high-quality deposits and small, or low-quality deposits because at the deposit scale they contain the same lithological, structural and alteration elements.

(5) Deposit models are focused on describing the controls on mineralisation at the deposit scale, but not on spatial prediction for the discovery of new large deposits.

All of the above point to the ineffectiveness of applying a deposit model approach to regional exploration. Much of the literature on the mineral system approach suggests that deposit models are unable to effectively identify critical elements key to mineralisation on a larger scale and this is their limitation. Features that are seen at the deposit scale are simply not mappable at this scale. Subsequently however, a lot of work has been done with respect to the development of a mineral system concept to identify what the critical elements at various scales are and how to apply them in prospectivity analyses and targeting exercises in exploration geology.

The mineral system concept was first applied to hard rock exploration geology by Wyborn, Heinrich, & Jacques, (1994) in the seminal paper titled “Australian Proterozoic mineral systems: Essential ingredients and mappable criteria”. In this paper the foundation for the mineral systems concept was developed, which states that although individual mineral deposits are relatively small and rare, resulting from exceptional coincidence of geological processes, these processes are mappable on a much larger, district to regional scale and constitute a mineral system of which the deposit is the central feature. In this paper a mineral system is defined as all of the geological factors that control the generation and preservation of mineral deposits and focus on the processes that are involved in mobilising ore components from a source, transporting and trapping them in a more concentrated form, and then preserving them throughout the subsequent geological history. Much work has been done on developing and refining the mineral systems concept since Wyborn’s paper, largely coming out of the Centre for Exploration Targeting (CET) at the University of

Western Australia. The CET, formerly led by Professor Campbell McCuaig, is an applied research enterprise in UWA's School of Earth and Environment focused on increasing both the rate and quality of mineral resource discoveries through innovative and cost effective developments in exploration and resource management (Centre for Exploration Targeting Website, 2017). Equally important work was done my the predictive mineral discovery Cooperative Research Centre (pmd*CRC) which was established to generate a fundamental shift in exploration practice and cost effectivelness by developing a vastly improved comprehension of mineralising processes and a four dimensional understanding of the evolution of the geology of mineralised terranes (Geoscience Australia, 2018).

In the mineral systems concept, ore deposits are viewed as small-scale expressions of a range of earth processes that take place at different temporal and spatial scales (McCuaig & Hronsky, 2014). On a broad regional scale, the mineral system concept proposes that all mineral systems comprise four critical elements that must combine in space and time in order for a deposit to form. These include:

(1) Lithospheric architecture.

(2) Favourable transient geodynamics.

(3) Fertility.

(4) Preservation of the primary deposition zone (McCuaig & Hronsky, 2014) and are illustrated in Figure 13.

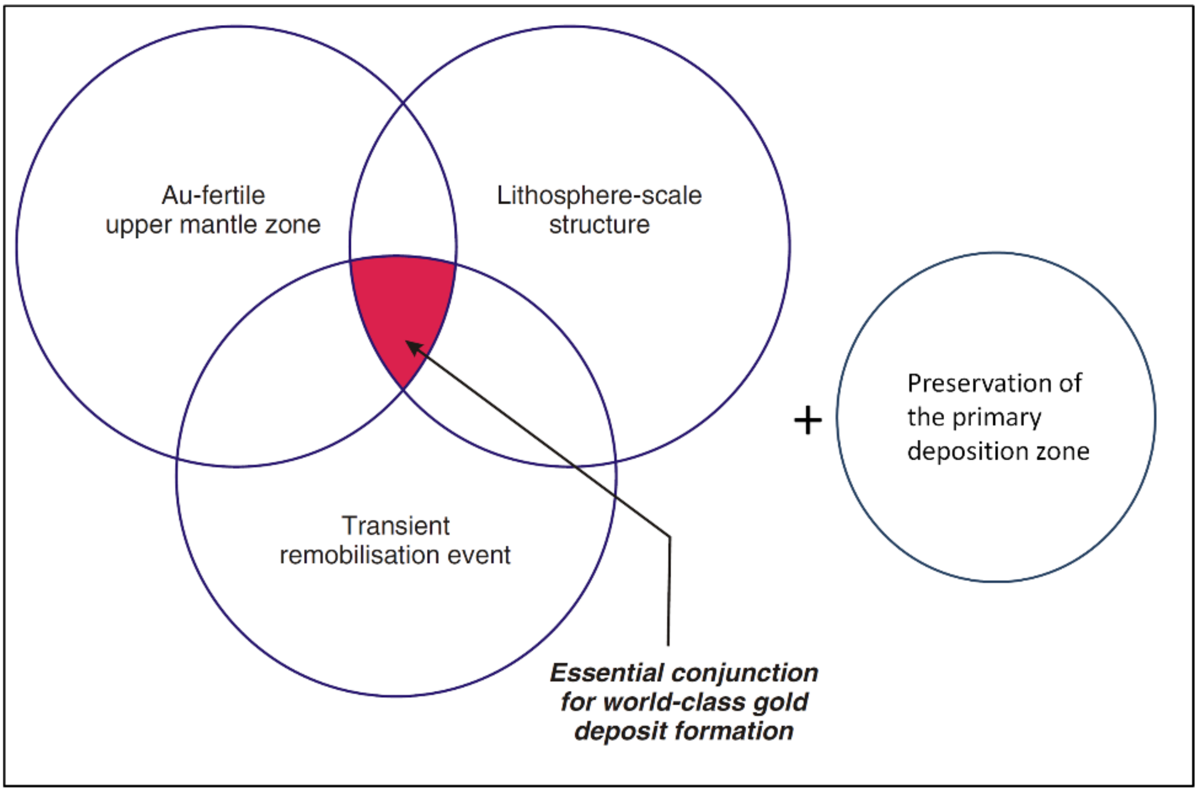


**Figure 13: Critical elements required to form world-class gold deposits. Modified from Hronsky, et al.,, (2012)**

The mineral systems concept is based on processes which are common to mineral systems. This process-driven approach allows the minerals system concept to focus commonalities across mineral systems, rather than characteristics that are specific to individual deposits and as a result allows for the identification and discovery of new styles of deposit that are formed through similar processes, rather than just analogues of deposits already discovered (McCuaig, et al., 2010). Identification of these processes can be applied across all scales making the mineral systems concept a dynamic tool for determining prospectivity of a province, or camp, as well as determining targeting criteria common to deposits in a particular system.

Giant ore deposits are zones of focussed mass and energy flux (McCuaig & Hronsky, 2014). Understanding fluid flow in the crust is key to understanding how and why ore deposits form where they do. In the mineral system approach this concept is referred to as self-organizing critical systems. The key elements of self-organising critical systems are the physical processes that come together to produce the fertilised fluids and the lithospheric architecture which acts as a delivery system, ultimately determining where deposition occurs (Hronsky, 2011). The major features of self-organized systems and how they contribute to the mineral system concept and predictive targeting of ore bodies, are that deposition events display power-law (Zipf's Law) distribution, and the spatial distribution of deposits within a camp, or province form complex patterns which are not predictable using deposit-scale observations (Hronsky, 2011). This understanding can then be translated into effective targeting criteria allowing the creation of robust exploration models which can be tested in the field which is the focus of this study. Both of these concepts are demonstrated in this study by using a Zipf's Law analysis to quantify the residual endowment of the Asanko Gold Mine camp, a Fry analysis to determine the structural trends on the spatial distribution of ore bodies, and geophysical data interpretation to map the structural architecture at the regional and belt scale within the Kumasi Basin at various scales.

The outcomes of these analyses are then corroborated with geophysical interpretations to develop a robust targeting criteria for orogenic gold deposits in the Asanko Gold Mine camp and Kumasi Basin. The power of this is that being process driven, this approach can be replicated in any gold camp, or district in the world both mature and emerging.

Using this approach, it is very important to identify what scale is being looked at as the mappable criteria for each are very different. If one was to look for district scale criteria on the global, or cratonic scale, or vice versa, the effectiveness of the concept would be greatly reduced. It is beyond the scope of this paper to cover the global and cratonic scales and will instead focus largely on the regional, district, and camp scales. Figure 14 illustrates the various scales on which the mineral system concept can be applied from a global scale down to the craton, province, district and deposit scales. This study focuses on the transport and trap of mineralising fluids at the regional, district and camp scales.

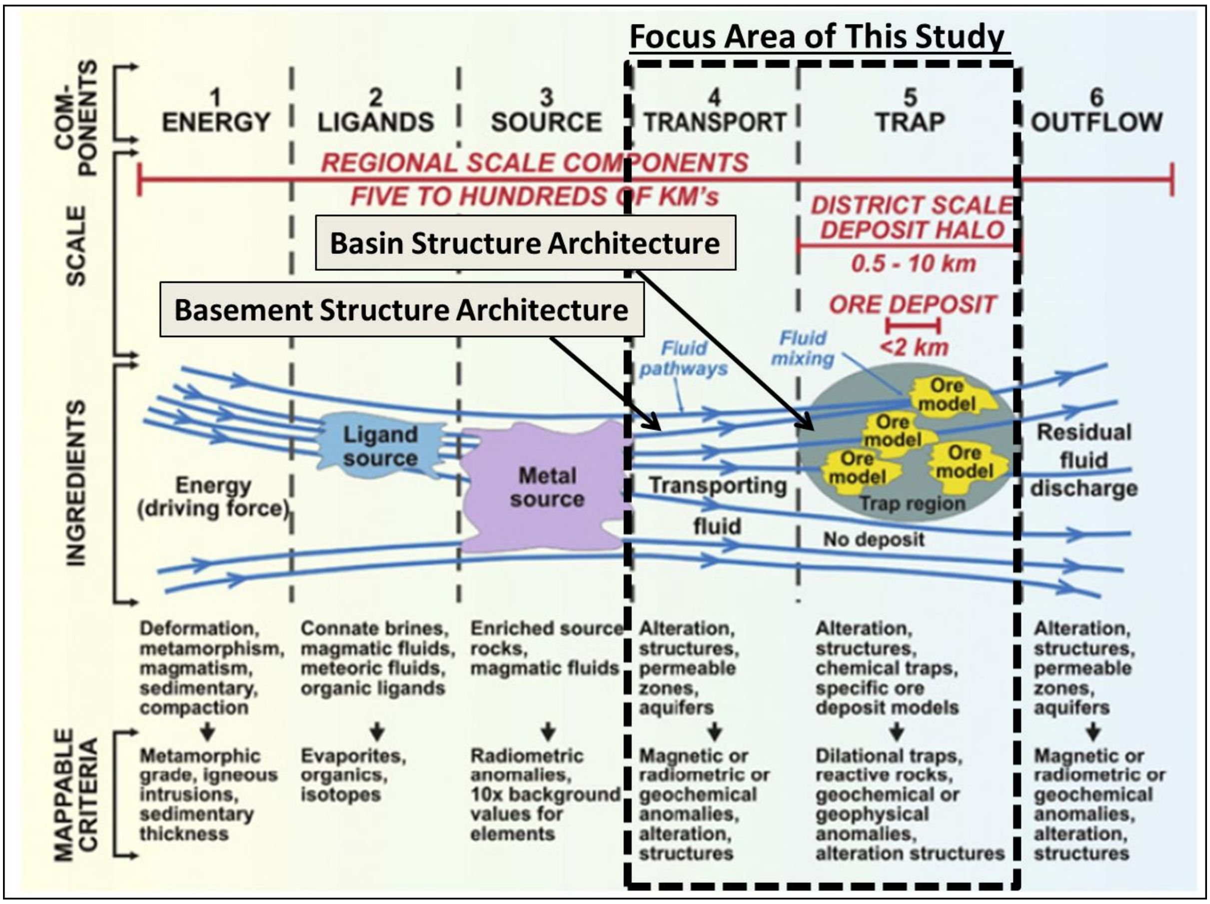


**Figure 14: The mineral system concept and associated mappable features at various scales. Modified from Hagemann, et al., (2016)**

Figure 14 shows that the components at the district and camp scale are the transport and trap elements, and the mappable criteria are geophysical and geochemical anomalies, alteration, structures, dilational traps, reactive rocks, and rheological contrasts. More precisely, this study focused on structural architecture of the Kumasi Basin and how it exerts controls over deposit location at the camp and district scales. It aims to identify critical structural elements which must be present for ore deposit formation, and which can be applied as a predictive targeting tool elsewhere in the belt.

This study focuses on stage 4 and 5 in Figure 14, and the fact that Ghana is in a zone of Au-fertile upper mantle is assumed based on the historic and current known endowment. The transient remobilisation events that allowed mineralising fluids to migrate upward through the crust are critical to this study and the geodynamic history is covered in Section 3 and Section 6 of this study. Although the lithospheric architecture is the primary focus it does not exist in isolation from the other processes and relating structural observations to the geodynamic history is critical for gauging the importance of certain structural trends. These structural trends can then be mapped and the lithospheric architecture can be used as robust targeting criteria for additional discovery.

## 3.1 Focus on Structural Controls

Traditional exploration has generally focused on the prospect level and concentrated on deposit scale features such as orientation of ore shoots and surficial structural architecture, not the underlying factors controlling deposit location. This study attempts to identify the underlying structural controls on mineralisation and to understand the basement and basin structural architecture that is controlling the location of gold camps in the Kumasi Basin at the regional scale, and orebodies at the camp scale. Understanding the structural architecture is the driver for systematic prospectivity modelling and reduction of exploration uncertainty.

The structural architecture of a mineral system controls the inter-connected permeability network and conduits for fluid flow and can be formed long before the mineralising event (Hagemann, et al., 2016). Transport of mineralised fluids require the presence of lithosphere-scale basement structures, or translithospheric faults, which are essential to allow the focused flow of hydrothermal fluids into the upper crust (Hronsky, et al., 2012). Particularly important for deposition are the intersection of orogen-parallel structures and their conjugate sets with these basement structures (Hronsky, et al., 2012). These basement structures can be difficult to recognise in surface geological mapping. Historically these structures were only identified as linear arrays of mineral deposits associated with subtle linear patterns of structural discontinuities and often referred to as lineaments (McCuaig & Hronsky, 2014).

This has changed in recent times however, largely due to the accessibility of large-scale regional geophysical data sets, as well as deep penetrating geophysical technologies that allow the imaging of these features at depth (McCuaig & Hronsky, 2014). These ore controlling translithospheric basement structures propagate to surface by what is termed “vertical accretive growth” (McCuaig & Hronsky, 2014). The theory behind this is that following burial by large volumes of basin sediments in the case of the Kumasi Basin, reactivation of the underlying structures over long periods of time during successive deformation events produces complex anastomosing fractures in the overlying rock mass which propagate through the overlying strata (McCuaig & Hronsky, 2014) This process is illustrated in Figure 15.

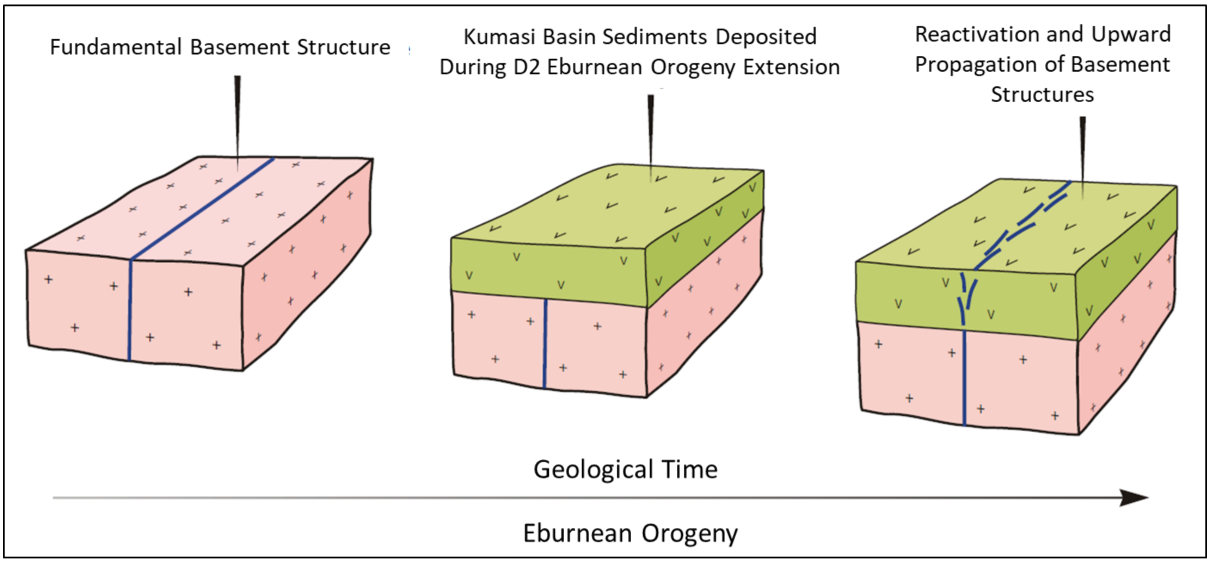


**Figure 15: The process by which translithospheric basement structures propagate upward into the overlying strata is termed "vertical accretive growth". Modified from McCuaig & Hronsky, (2014)**

Major lineaments have been identified since the 1930's (Hronsky, 2013). More recently through the use of deeper penetrating geophysics, these features have been related to large-scale lithospheric structures, now called translithospheric faults, that penetrate through the basement lithology and into the mantle (Hronsky, et al., 2012). These structures can be mapped over 100's of kilometres, are generally steeply dipping, have a low ratio of recent displacement to strike length, and juxtapose distinctly different basement domains (Hronsky, 2013). Mineral systems theory has identified that these structures can influence mineralisation on a much larger scale than individual belts or camps (Hronsky, et al., 2012). Zones of Au-fertile upper mantle can encompass multiple belts in a region and translithospheric structures are the conduits that introduce mineralising melts and fluids into the upper crust (Hronsky, et al., 2012). As such, mapping their location is critical for regional scale prospectivity. This study will show that the interaction between translithospheric structures and major upper crustal structures is critical for belt and camp formation, and understanding this interaction is fundamental for the generation of predictive models.

Identification of these basement structures is key feature of this study and understanding their orientation is fundamental to targeting in the Kumasi Basin. In the case of the NW-SE basement structures interpreted in the 3D inversion models later in this study, it is unclear if these are the actual basement structures themselves and they are more likely the complex anastomosing structures propagating upward through the overlying basin sediments. Due to the depth resolution of the source VTEM and magnetic data used in the 3D model generation for this study and the unknown depth to basement in the Kumasi Basin this is likely. These structures are largely in the general orientation of the basement structures and are referred to as upward propagating basement structures in this study. This study will show that these structures play a critical role in deposit location in the Asankrangwa Belt.

This study identifies structural controls on various scales. For the purpose of this study regional scale is defined as >50 km and includes the entire Kumasi Basin. District or belt-scale is >25km and up to 50 km, and camp scale is is <25km. Across this range of scales, the relevance of targeting criteria will change due to: (1) the scale at which different critical processes of the mineral system are operating, and (2) the availability of geoscience datasets from which mappable targeting criteria can be identified over the the entire project area (McCuaig, et al., 2010). The scale being observed determines whether the structures identified are likely to be basement structures themselves, or upward propagations of basement structures in the overlying strata. In the case of the basin scale observations, lineaments observed in the regional gravity survey are interpreted to represent the basement features themselves due to the deep penetrating nature of gravity surveys. In the case of the belt and camp scale observations, structures mapped are both upward propagating manifestations of basement structures caused through countless reactivations, as well as upper crustal orogeny parallel structures emplaced during the Eburnean Orogeny.

Irrespective of this, this study argues that the interaction between these basement structures, their upward propagations, and the overlying deep-seated orogen-parallel structures is critical for creating interconnected permeability networks allowing the upward mobility of mineralising fluids and ultimately deposit formation. In the case of the Kumasi Basin, any surface manifestation of these deep structures has been completely overprinted by the Eburnean Orogeny deformation events, and detection of them shows up as deep dislocations and lineaments in the geophysical signatures. Identification of these lineaments is fundamental as they are often in a completely different, if not orthogonal, orientation to the orogen-parallel structures controlling mineralisation on the camp scale, and this is what is observed in the Kumasi Basin.

Although being a relatively new concept in ore deposit formation, basement structure architecture exerting direct control over mineralisation has been observed in many orogenic districts, including the Granites-Tanami Orogen in Northern Australia (Joly, et al., 2010), the western goldfield in Tanzania (Lawley, et al., 2013), the Dharwar Craton, South India (Kolb, et al., 2004), the world-class St. Ives goldfield in Western Australia (Miller, et al., 2010), The Eastern Yilgarn Craton, Western Australia (Blewett, et al., 2010), and the Charters Towers goldfield , NE Australia (Kreuzer, et al., 2007)

Similar reactivation of basement structures has been identified as the main control of deposit location in other commodities as well such as giant sediment hosted uranium deposits of the Athabasca Basin, Saskatchewan, Canada (Mercadier, et al., 2013), giant porphyry districts in Peru and Chile (Love, et al., 2004), giant Carlin trend gold deposits in Nevada (Howard, 2003) and sediment hosted Pb-Zn deposits along the Caledonian Front, Sweden (Saintilan, et al., 2015). McCuaig & Hronsky, (2014) formulated (6) six salient features that these fundamental mineralisation controlling structures share that are important for targeting across commodities:

(1) Basement structures are strike and depth extensive and usually penetrate through lithospheric mantle.

(2) They are relatively difficult to trace in surficial map patters and are not obvious at, or above the level of mineralisation.

(3) They are never flat dipping thrust zones, and are usually not the continuous major shear zones that are obvious in regional maps.

(4) They have anomalously low ratio of displacement along strike.

(5) They record multiple reactivations and are long lived structures.

(6) Commonly they juxtapose distinctly different basement domains.

Identification of basement structural architecture can pose one of the biggest challenges to employing the mineral systems concept in practice. As mentioned in point (2) above, this is because pre-existing basement structure architecture generally has very subtle, or non-existent surface expression and is not easily observed in the field. Other fundamental elements to the mineral systems concept such as a fertile mantle sources are also not directly detectable on surface, but are not important at the scale of this study as it is already known that SW Ghana is in a zone of fertile mantle because of the known gold endowment. In the case of a global prospectivity analysis this would be in an important factor.

Although beyond the scope of this study, it is hypothesized that the basement structures in the Kumasi Basin correspond to transtensional structures formed during the extensional phase as the basin opened. Throughout the Eburnean Orogeny deformation event it is thought that these structures were repeatedly reactivated creating an interconnected permeability, ultimately facilitating fluid flow into the overlying host rocks. A modern-day manifestation of basin opening processes is the Bismarck Sea, north of Papua New Guinea seen in Figure 16. Here the transtensional faults are clearly visible, forming as the basin opens and is pulled apart. The process of pulling apart caused by the extension creates conduits from the basement to the mantle derived fluid source. It is at this stage that these critical fluid pathways are established. These pathways are then repeatedly reactivated during subsequent deformation events allowing the upward migration of mineralised fluids into the upper crust.

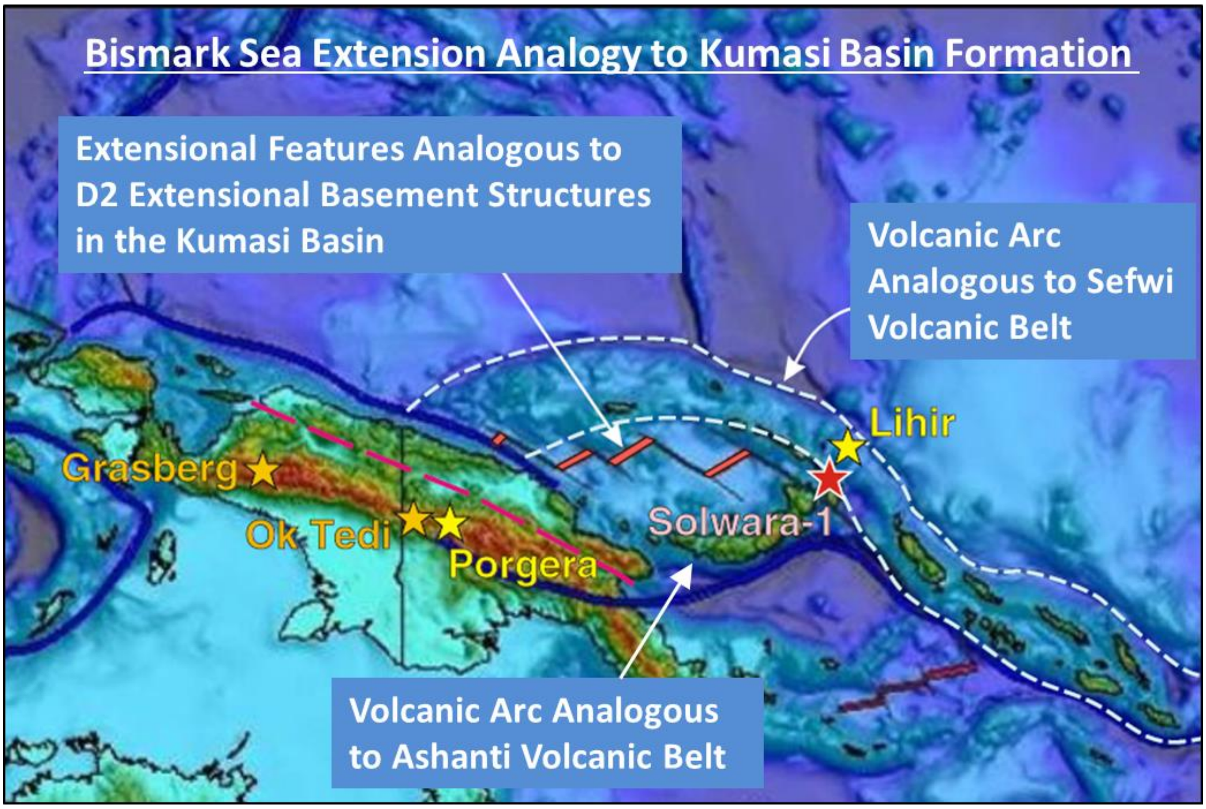


**Figure 16: Transtensional faults forming during the opening of the Bismarck Sea north of Papua New Guinea. This is an example of basement structure formation. These structures are deeply penetrating and would be reactivated during subsequent deformation events. Stars represent the location of major epithermal and porphyry deposits. Modified from Hronsky, et al., (2012)**

It is difficult to be certain of the exact nature of the Kumasi Basin basement structures as these faults are interpreted only from geophysics and are not able to be studied directly. However, their orientation was also identified by Chudasama, et al., (2016) and Jessell, et al., (2016). Both papers site the age and associated deformation event of these structures as undefined. The orientation of the basement structures emerges again in the Fry analysis of the Kumasi Basin as one of the dominant orientations of mineralisation and is touched on in more detail later in this paper.

Understanding the genesis of basement structure architecture can require complex 4D reconstruction of the tectonic evolution and history. This generally requires the integration seismic tomography, teleseismic receiver functions, and synthesis of regional gravity and magnetics data sets (Jessell, et al., 2016). Using these techniques to understanding the genesis of the basement structure architecture of the Kumasi Basin identified here is outside of the scope of this study. Instead, this study uses a Fry auto-correlation analysis to corroborate the relationship between basin wide basement lineaments observed in regional gravity data with gold camp and deposit location trends. A Fry analysis is a much simpler approach to determining trends controlling deposit location and only requires a modest amount of deposit and prospect point data to operate, and can be conducted using a decent mineral occurrence database. Where the geodynamic history of the basement structure architecture may not be known, correlating the surficial basin structures to specific deformation events is critical to understanding what structural features are important for controlling gold deposit formation. It is not critical to fully understand the exact deformation kinematics forming basement structures to identify the control they exert over deposit location, only that they exert a fundamental control over deposit location by providing conduits for ore bearing fluids from the source region into the upper crust. These structures are then repeatedly reactivated during subsequent deformation events, propagating upwards in anastomosing networks creating permeability pathways for mineralised fluids to connect with structures from subsequent deformation events.

The basement structures are almost always oblique to the orientation of the structures associated with the mineralising events and thus exert a different structural control on mineralisation at a province to district scale than at the camp and deposit scale (McCuaig & Hronsky, 2014). It is very important from a prospectivity and targeting perspective to be cognisant of scale, and understand what features are critical for ore deposition at the scale being explored. This is one of the fundamental tenants of the mineral systems concept and a fundamental element of this study and understanding this is critical for targeting at all scales.

At the scale of the Kumasi Basin, identifying the basement structure architecture is key to predicting gold camp location on the regional scale. At the scale of the Asankrangwa Belt and focus of this paper, understanding the interaction between upward propagated basement structures juxtaposed against first, second, and third order structures emplaced during the Eburnean Orogeny is fundamental for effectively predicting gold deposits locations in the Asanko Gold Mine camp.

## 3.2 Applications of Mineral System Theory for Exploration

The main focus of the mineral system concept is to translate mappable criteria into robust, testable exploration models (McCuaig & Hronsky, 2014). This project focuses on the transport and trap processes within the overall mineral system concept. The objective of this study is to identify trends of structural controls at various scales, and use geophysics to map out the basement structure architecture to develop targeting criteria that can be used as a key driver in prospectivity studies and ultimately new discovery. Identifying the mappable criteria is not always straight forward and the right combination of analyses must be used. Several papers have focused on identifying mappable criteria at the applicable scale and translating it into useful models. Hagemann, Lisitsin, & Huston, (2016) summarises five recent developments in the mineral system geoscience to help improve predictive exploration targeting at the regional to camp scale. Recognition of these critical elements to ore formation is critical to effective targeting and they are listed as follows:

(1) Cognisance of the scale of mineral systems elements and processes.

(2) Understanding the 4D tectonic history with respect to lithospheric boundaries and translithospheric fault architecture as the major factor controlling mineral system fertility.

(3) The importance of pre-existing reactivated deep penetrating basement structure architecture needed to channel these fertile mantle sources.

(4) Understanding there is risk in exploration targeting and mitigating their impact through effectively interpreting available data at the correct scale.

(5) Understanding the concept of self-organised systems and how they contribute to ore deposit formation.

Current literature stresses that the most critical factor for successfully applying mineral systems concepts to prospectivity modelling and exploration targeting is scale. This goes back to the concept that ore deposits are a tiny part of much larger systems which operate at larger scales than the deposits themselves. This is a challenging aspect of the mineral systems concept and if miscalculated can render exploration targeting ineffective. Understanding the mappable criteria that is critical at each scale from cratonic (1000's of km) to deposit (<5 km) is fundamental to exploration targeting success. In applying the mineral system concepts to exploration, Hronsky & Groves, (2008) suggest three sequential steps:

(1) Development of a business strategy.

(2) Creation and application of a targeting model.

(3) Follow-up with direct detection methodologies in defined high profile domains, quantify the residual mineralisation in the Asanko Gold Mine camp.

In the case of this project, the Zipf's Law quantitative analysis was used to establish the residual mineralisation potential in the Asankrangwa Belt and form the basis for the business model. A Fry autocorrelation analysis was used to identify structural trends from deposit location point data and associate them with critical geological processes identified from the geodynamic history. Interpretation of geophysical data sets is used to map out these features at various scales and develop robust structural targeting criteria. The final step in the exploration process is to test the model. While this is not part of this project, this would include standard boots on the ground deposit scale direct detection exploration techniques such as soil geochemistry, structure, geology and alteration mapping, trenching and drilling.

Scale is such an important factor in the mineral system concept and will be revisited many times in this study. Understanding the processes and features that operate at different scales is fundamental to the generation of effective predictive targeting models. A critical element of this is that features which may be exerting direct control over camp or deposit location may not be represented as mappable features at all scales, but understanding how they interact can be very important for predicting deposit location.

Previous work in the Kumasi Basin has been largely focussed on mappable features such as first, second and third order shear zones. This study argues that while these structures are fundamental to deposit formation, they only represent part of the complex structural criteria needed for ore deposit formation. Understanding how the basement structure architecture beneath the Kumasi Basin exerts a critical control on camp and deposit location allows multi scale targeting criteria to be developed. Ignoring one or more of these fundamental structural controls leads to the introduction of many false positives in any prospectivity and targeting analysis at all scales.

Unfortunately, much of the work that has been done to map basement structure at the district and camp-scales in the Kumasi Basin using regional gravity surveys and other deep penetrating geophysics methodologies remains proprietary at this time. The concept of self-organised systems, that mineral deposit location at the camp scale is dictated by underlying basement architecture, has been understood and is being investigated by some companies. Investigating this relationship requires a dedication to good science, as well as a significant capital commitment. Regional gravity and deep penetrating geophysical data sets come at a cost that is sometimes out of reach or unjustifiable to smaller companies. However, this paper attempts to show that with readily available data such as a regional gold deposit and gold occurrence database, the underlying controlling factors on deposit location can be understood.

### 3.3 Case Study: "Translating the mineral systems approach into an effective exploration targeting system" by McCuaig, et al., (2010)

One area in the world where the mineral systems concept has been applied with a great deal of success is the eastern Yilgarn, West Australia. The eastern Yilgarn is one of the most comprehensively studied orogenic gold and base metals provinces in the world. Not only is the Yilgarn one of the geological regions abnormally well-endowed with gold and base metal deposits, it has also benefitted from an exceptional synthesis between industry, government, and academia. This collaboration has resulted in the integration of massive, modern, regional data sets that has provided a platform for greater understanding of the geodynamic and architectural processes which have contributed to the extraordinarily rich endowment of this region (see Figure 17)

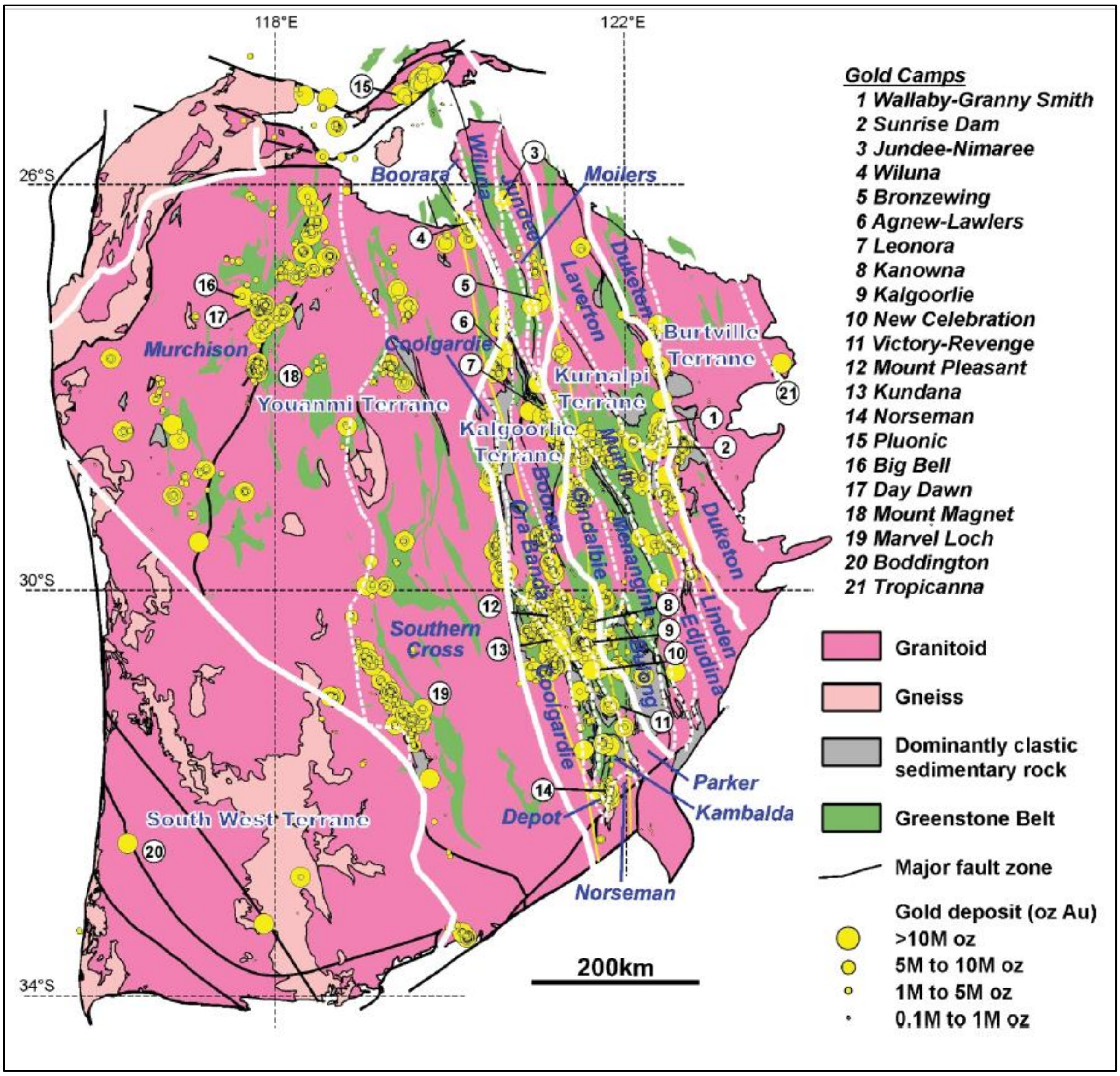


**Figure 17: Map of the Yilgarn craton showing the distribution and size of gold deposit camps. The Yilgarn is one of the most studied cratons on earth and the mineral system concept was devised and refined through testing here on the cratonic, provincial, district and camp scales. From Guj, et al., (2011)**

This has created the perfect playground to test the mineral system concept to be tested. With past and present organisations set up to study all aspects of economic geology such as the Predictive Mineral Discovery Cooperative Research Centre (pmd*CDC), Australian Mineral Industries Research Association Limited (AMIRA) and the Centre for Exploration Targeting (CET), great strides have been made in this respect. Both AMIRA and the CET have also contributed massively to understanding the controls on the mineral endowment of West Africa through the West African Exploration Initiative (WAXI), and in fact some of that research is referenced in this paper. However, where the work done on the Yilgarn excels is in the integration of high-density, potential-field, regional and camp-scale seismic reflection data, regional and mine-scale structural analysis, and geochronologically-constrained stratigraphy providing new insights into the 4D architecture and tectonic evolution of the craton (Henson, et al., 2010). In addition, new techniques in long wavelength gravity, broadband seismic tomography, and magnetotellurics also provide evidence for the signatures of the flow of fluids through the inter-connected permeability networks (Blewett, et al., 2010).

Detailed studies have been carried out on the world-class Kalgoorlie camp (Blewett, et al., 2010), St. Ives Camp (Blewett, et al., 2010), Laverton camp (Henson, et al., 2010), Tanami Province (Joly, et al., 2012), and Scotia-Kanowna camp (Korsch & Blewett, 2010), and are included in a Precambrian Research Special Edition Volume 183 published in 2010. The papers in this special edition interpret massive data sets in order to understand the lithospheric architecture on a cratonic through district scale and focus on cratonic to camp scale processes and their salient mappable features. These studies consistently show that proximity to lithospheric-scale structures is common to all of the major camps and that basement architecture is crucial to create the permeability network allowing upward transport of the mineralising fluids. Although the Yilgarn is an Archean terrane the event history is very analogous with that of West African Paleoproterozoic orogenic gold deposits.

This event history is summarised as follows:

(1) Early periods of extension that emplaces the basement structural architecture.

(2) Later contraction at a high angle to the previously established architecture creating a network of interconnected permeability pathways.

(3) A further brittle transpressive stress reactivating the permeability pathways and emplacing gold.

(4) Late stage extension. (Blewett, et al., 2010).

The key to exploration success in the Yilgarn has been in putting together the 4D structural architecture processes on a cratonic scale, translating them into mappable features at all scales. This has resulted in promoting efficient exploration, meaningful investment, and ultimately discovery.

West Africa trails a fair way behind the Yilgarn when it comes to this level of understanding. This is understandable given the logistical challenges and overall level of investment in the region, amongst other challenges. The WAXI initiative has made great strides in closing this knowledge gap however, and continues to do great work there. Although West Africa may be far off the Yilgarn with respect to this level of data collection and synthesis, it is possible to draw from the knowledge learned through the mineral system application in the Yilgarn and apply it at different scales in West Africa. This study has attempted to do that at the scale of the Kumasi Basin and Asankrangwa Belt by carefully assessing the scale of observation and determining mapping features that are important at each scale in order to develop robust predictive targeting criteria.

# 4 GEOLOGICAL SETTING

## 4.1 Regional Geology

Ghana is located within the Archean and Paleoproterozoic West African Craton (WAC), which extends across Western Africa and consists of two Archean nuclei; the Reguibat Shield in the north and the Kénéma–Man Shield in the south; adjacent to an array of Paleoproterozoic domains (Jessell, et al., 2016) (see Figure 18)

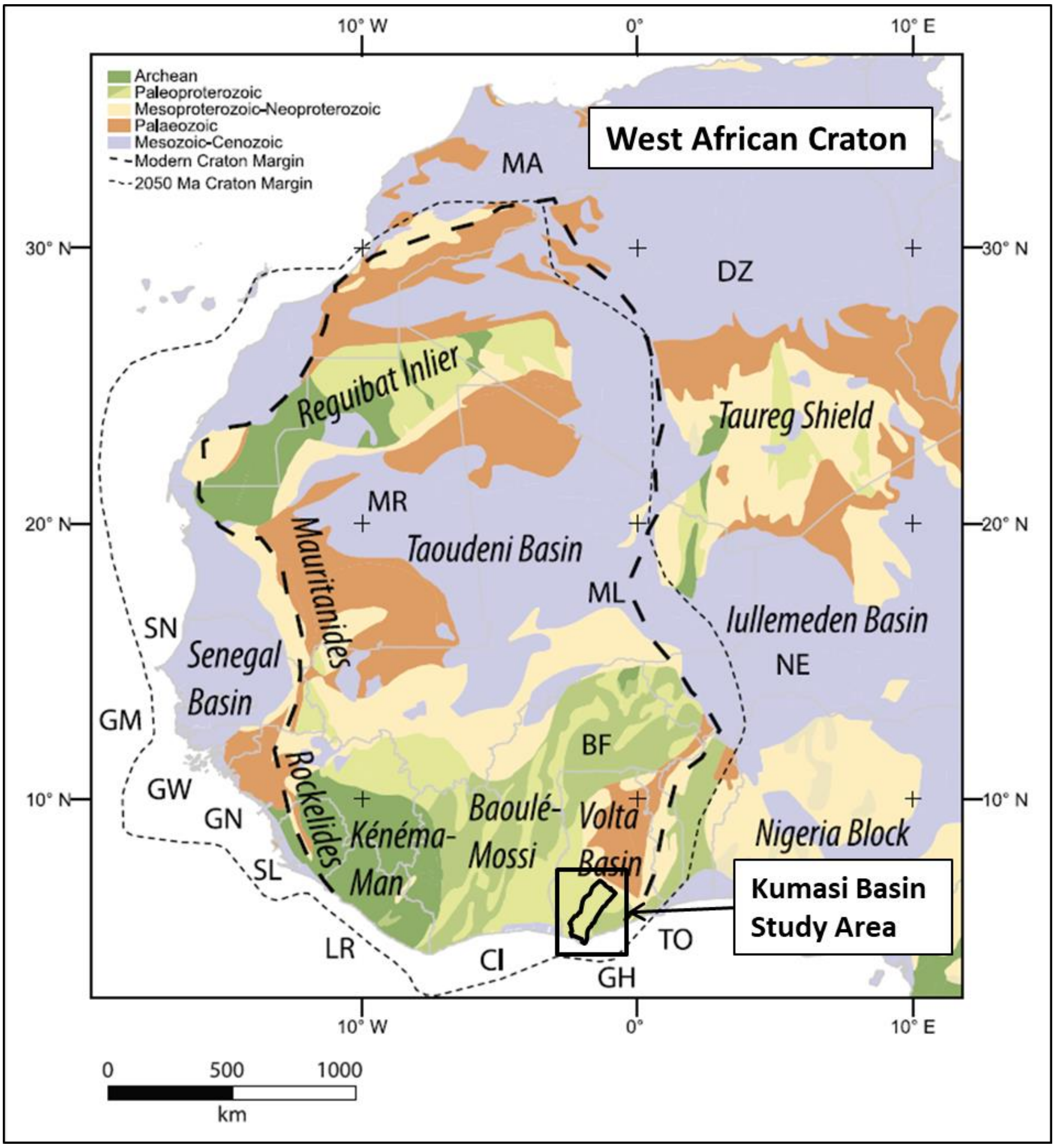


**Figure 18: Geological map of West Africa showing the major terrains and West African Craton boundary. Modified from Jessell, et al., (2016)**

The Paleoproterozoic terrains are made up of linear volcanic greenstone belts separated by sedimentary basins and intruded by extensive regions of granitoid-TTG plutons (tonalite-trondhjemite-granodiorite), which are in turn overlain by Neo-Proterozoic and younger sedimentary basins (Jessell, et al., 2016).

The Leo-Man Shield (Figure 19) forms the southern subset of the West African Craton. It is made up of an Archean core in the west, the 3.60-2.70 Ga Kénéma-Man domain, consisting primarily of alternating granite-gneiss terranes surrounded to the north and east by the Juvenile Paleoproterozoic Baoulé-Mossi domain (Block, et al., 2016). The Archean domains are separated from the adjacent Paleoproterozoic rocks to the east by major shear zones (Markwitz, et al., 2016).

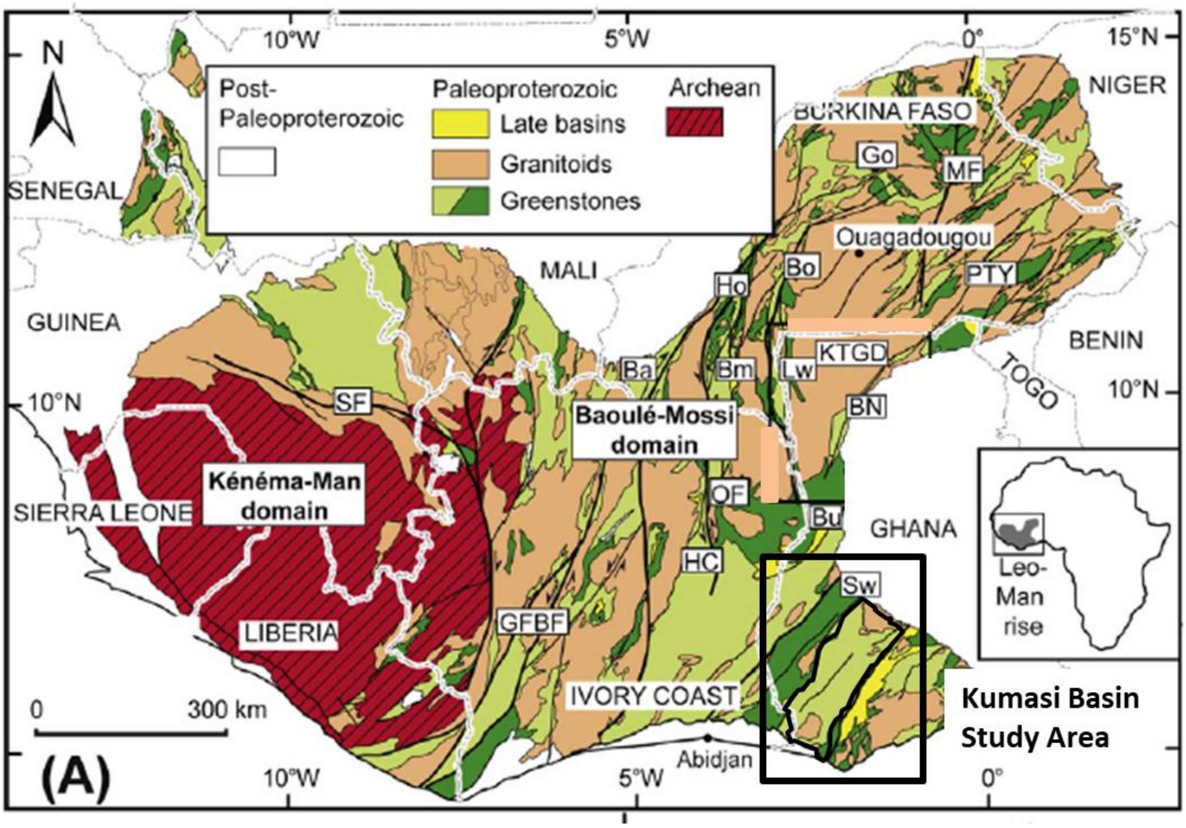


**Figure 19: Simplified map of the Leo-Man Shield showing the location of the study area. Modified from Block, et al., (2016)**

The Baoulé-Mossi domain is characterised by linear Archean-like volcanic greenstone-granitoid assemblages separated by extensive TTG and granite provinces and younger sedimentary basins whose basement is not exposed (Jessell, et al., 2016). The Kumasi Basin study area is one of these younger basins. Younger still are late Tarkwaian basins that host economically significant paleoplacer deposits. Although basement rock is not exposed in the sedimentary basins separating the volcanic belts, seismic tomography data suggest that there are Archean roots underlying the entire WAC (Begg, et al., 2009). This interpretation will be covered in more detail later and is an important concept in this thesis.

The greenstone assemblages are primarily made up of supracrustal volcanic, volcano-sedimentary, and sedimentary sequences belonging to the Birimian Supergroup which is thought to have been generated in volcanic arcs separated by oceanic basins (Jessell, et al., 2016). In several locations, late basin sediments of the Tarkwaian Group unconformably overlay the Birimian volcanic belts. These sediments consist of conglomerates, sandstones, and minor argillites metamorphosed to greenschist facies (Davis, et al., 1994). Preferential rifting of the volcanic belts formed long narrow intra-montane grabens that were subsequently infilled with Birimian supracrustal volcanic, sedimentary, and intrusive rocks that make up the volcanic belts (Davis, et al., 1994). Paleoproterozoic paleoplacer gold deposits are locally hosted in these Tarkwaian units and have been mined extensively in the south-west Ashanti belt in deposits such as Tarkwa, Iduapriem, Teberebie, and Damang. These deposits are not widespread across the region however, and although locally are a significant source of gold resources, they contain a fraction of the total gold endowment of Ghana and West Africa when compared against the orogenic gold endowment (Goldfarb, et al., 2017).

The vast majority of the gold endowment of the WAC is hosted within the Baoulé-Mossi domain, and has been the subject of much study. In particular, southwest Ghana, where the Kumasi Basin is located, has the greatest concentration of gold deposits on the WAC and is truly a world-class gold district.

## 4.2 Kumasi Basin Geological Setting

In Ghana, the Paleoproterozoic Birimian terrains consist of five linear northeast-trending volcanic belts with intervening sedimentary basins (Leube, et al., 1990). The volcanic belts have been folded by multiple deformation events and are generally 15-40 km wide and extend for several hundred kilometres laterally (Leube, et al., 1990). Gravity data has traced the volcanic belts north-east under the Neoproterozoic Volta

Basin sediments – which cover over 40% of the landmass of Ghana – and reappear in northern Togo representing strike lengths of several hundred kilometres (Leube, et al., 1990). The Kumasi Basin is 90 km wide and lies between the Ashanti Belt to the south-east and the Sefwi Belt to the north-west. The Kumasi Basin also continues under the Neoproterozoic Volta Basin to the north east, and is covered by more recent Phanerozoic sediments and the Atlantic Ocean to the south-west.

The combined Sefwi and Ashanti volcanic belts and intervening Kumasi Basin host the vast majority of the gold endowment in Ghana. A 1:1,000,000 regional geology and structural interpretation of south-west Ghana with deposit and prospect locations is shown in Figure 20.

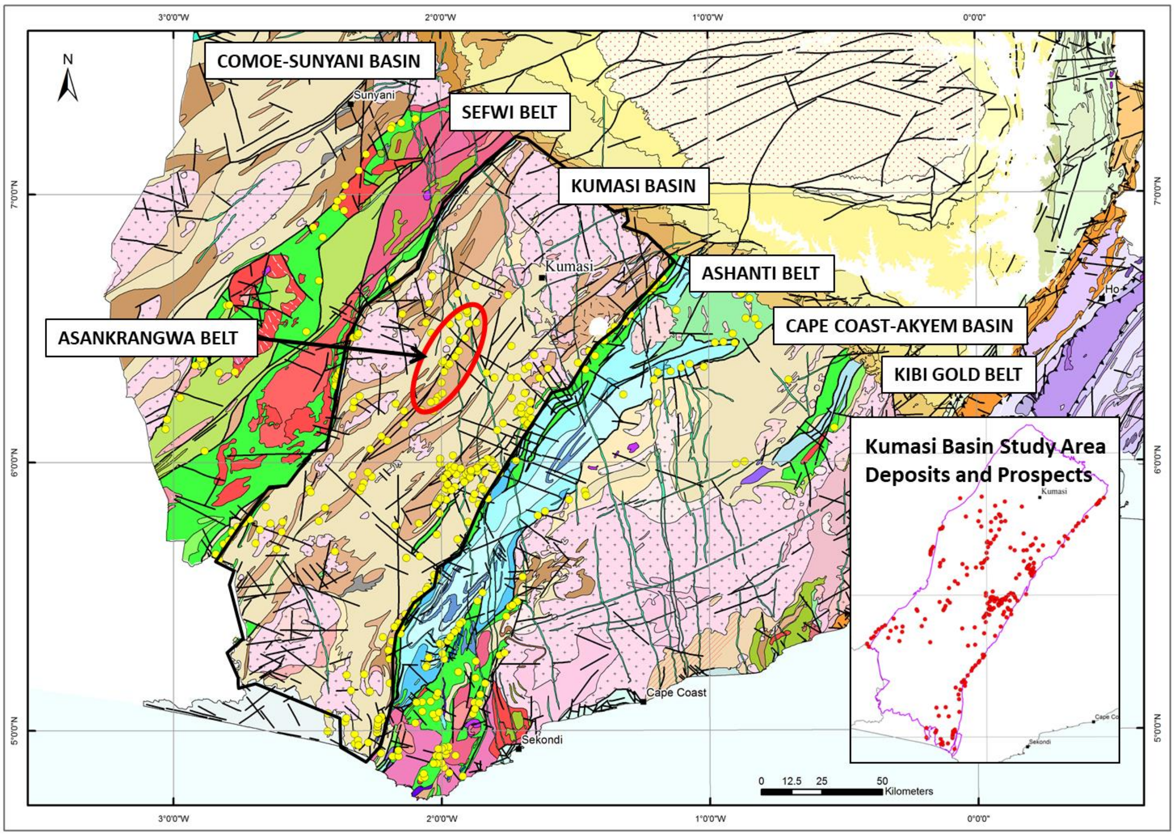


**Figure 20: Regional geology map of south-west Ghana showing location of volcanic belts and basins. Gold deposit and prospect locations are shown as yellow dots on the main map and red dots in the insert. Modified from Agyei Duodu, et al., (2009)**

In Ghana the narrow, linear, volcanic greenstone belts are widely accepted to be volcanic juvenile volcanic arcs accreted during lateral, modern-style, plate tectonics (Goldfarb, et al., 2017). The intervening basins were deposited during periods of extension within an overall compressive tectonic setting and although their ages can be comparable in places with the volcanic belts, they are generally tens of millions of years younger and the sediments are partly derived from the adjacent eroding volcanic arcs (Goldfarb, et al., 2017).

The stratigraphy of south-west Ghana (Figure 21) is divided into three groups which from oldest to youngest are: (1) the Sefwi Group, (2) the Kumasi Group, and (3) the Tarkwa Group. The Sefwi Group has been dated at >2174 ± 2 Ma, the Kumasi Group at <2154 ± 2 Ma (Perrouty, et al., 2012). The beginning of the Tarkwa Group sedimentation is less clear, but a reasonable estimation based on all concordant zircon dates and their uncertainties is <2107 Ma (Perrouty, et al., 2012).

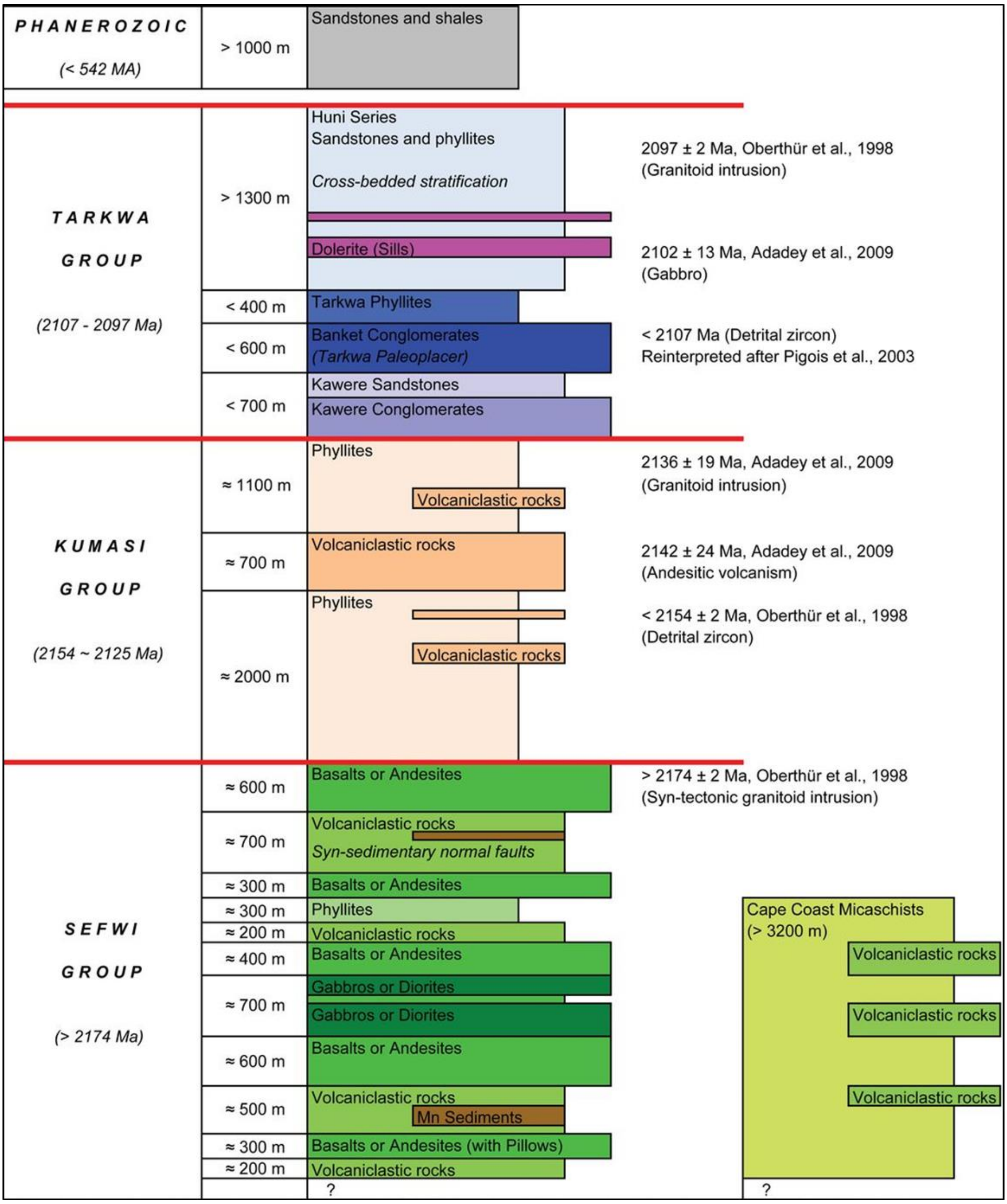


**Figure 21: General stratigraphy of south-west Ghana. From Perrouty, et al., (2012)**

<table>
<tr><th colspan="2">Regional Interpretation<br>(Perrouty et al., 2012)</th><th>In Birimian<br>Obuasi / Bogoso<br>(Allibone et al., 2002a, b)</th><th>Regional<br>(Feybesse et al., 2006)<br>(Milesi et al., 1992)</th></tr>
<tr><td rowspan="2">Eoeburnean<br>2187 - 2158 Ma</td><td>Sefwi Group volcanism and sedimentation</td><td rowspan="2">Volcanism<br>Granitoids intrusion<br>Regional metamorphism</td><td rowspan="3">Magmatic accretion<br>Plutonism<br>Birimian sedimentation</td></tr>
<tr><td>D1, N-S shortening<br>Regional scale folding in the Sefwi Group<br>Possible gold mineralization</td></tr>
<tr><td colspan="2">D2, Extension Phase (2154 - 2125 Ma)<br>Kumasi Group sedimentation</td><td>D1<br>S1 parallel to bedding<br>Flat-lying bedding parallel shearing</td></tr>
<tr><td rowspan="6">Eburnean<br>2125 - 1980 Ma</td><td rowspan="2">Tarkwa Basin Formation (2107 - 2097 Ma)<br><br>D3, NW-SE shortening<br>Km scale folds in Birimian and Tarkwaian<br>S3 subvertical crenulation cleavage NE-SE<br>Thrust faults (Ashanti, Damang, ...)<br>Peak of metamorphism (2092 Ma)</td><td>D2, NW-SE shortening<br>Isoclinal folds with axial surface parallel to the regional faults and shear zones<br>Ashanti thrust fault</td><td>D1, NW - SE shortening<br>Thrust faults<br>Tarkwaian sediments deposition (Syn D1)<br>Metamorphism (6 kbar / 550 - 650 °C)</td></tr>
<tr><td>D3<br>Low dip axial surface fold at Obuasi<br>S3 crenulation cleavage overprinting S2<br>Final stage of D2 ?</td><td rowspan="3">D2/D3, NW-SE shortening<br>Tarkwaian folds<br>Strike-slip faults and shearing<br>Gold mineralizations<br>Metamorphism (2 - 3 kbar / 200 - 300 °C)</td></tr>
<tr><td rowspan="2">D4, NNW-SSE shortening<br>Sinistral shear reactivation of D3 thrust<br>S4 crenulation cleavage ENE-WSW<br>Greenschist retrograde metamorphism<br>Remobilization and concentration of gold particle along the shear zones and at the base of Tarkwa Basin</td><td>D4, NNW-SSE shortening<br>Hm scale fold at Obuasi</td></tr>
<tr><td>D5 or syn-D4<br>Sinistral strike-slip faults and shearing<br>Gold mineralization</td></tr>
<tr><td>D5<br>Recumbant folds (< m)<br>Subhorizontal crenulation cleavage<br>Last pyrite/gold mineralization associated with quartz vein</td><td rowspan="2"></td><td rowspan="2">Late plutonism</td></tr>
<tr><td>D6, NE-SW shortening<br>Low amplitude folds + crenulation cleavage ≈ N320 / 70 (RH)<br>Reverse faults oriented NW-SE</td></tr>
</table>

**Figure 22: Comparison between the prevalent geodynamic history models for south-western Ghana reviewed in this study. Modified from Perrouty, et al., (2012)**

Initial models detailing the deformation history of south-west Ghana were derived from deposit scale studies and include the much-referenced work of Allibone, et al., (2002a) and Blenkinsop, et al., (1994) on Obuasi. The mineral systems concept was in a conceptual stage at that time, and virtually all studies were focused on the mine and deposit scale.

### *4.2.1 Geodynamic Model Case Study 1: "Structural controls on gold mineralisation at the Ashanti gold deposit, Obuasi, Ghana" by Allibone et al. (2002)*

Allibone, et al., (2002) proposed that the Birimian sediments of the Kumasi Basin formed at the end of the Eoeburnean and that the Eburnean consisted of 5 stages of deformation:

(1) D1 is a cryptic flat-lying bedding parallel shearing event leading to the development of a bedding parallel S1 fabric. This event caused crustal thickening of the Kumasi Basin sediments through unit stacking.

(2) D2-D3 was the main NW-SE basin inversion crustal shortening event resulting in the development of upright, tight, NE-trending isoclinal folds (F1) and the development of deep seated NE trending second order ductile shear zones. At Obuasi it was proposed that there was a D3 event resulting in an over printing crenulation cleavage

(3) D4-D5 is a NNW-SSE crustal shortening event leading to sinistral strike-slip re-activation of the D2 structures, brittle deformation and gold mineralisation (Allibone, et al., 2002)

There are challenges with regional models derived from deposit scale observations that have major implications for exploration targeting. It is now well understood that features controlling mineralisation at deposit-scale are often completely different to camp- or regional-scale features that control deposit location. Features observed at the deposit scale may be local phenomena and given undue importance in the district or regional setting. This can lead to a focus on features that are not fundamental to the process of ore formation and can lead to the introduction of many false positives into resulting prospectivity and targeting exercises.

#### *4.2.2 Geodynamic Model Case Study 2: "The Paleoproterozoic Ghanaian province: Geodynamic model and ore controls, including regional stress modelling" by Feybesse et al. (2006)*

The next major geodynamic history model was that of Feybesse, et al. (2006) who recognised that all previous models were, for the most part, limited in their scope to the deposits and immediate host rocks and did not consider the mineralising processes at a wider, provincial scale.

This study used a multi-criterion and multi-scale analysis of spatial and stress controls to establish the relationships between the gold-bearing hydrothermal events and the geodynamic evolution. This approach is much closer to a mineral systems concept in being based on the double premise that:

(1) An economic concentration of metal is the end result of complex processes in which several parameters play a role.

(2) That a exploration approach must go beyond the scale of the orebody and integrate the mineralizing process in its geodynamic and paleogeographic setting (Feybesse, et al., 2006).

This was achieved by considering gold deposits from multiple gold camps including Bibiani, Chirano, Obuasi, and Ahafo. The resulting model is essentially a distillation of multiple deposit-specific deformation histories into their commonalities.

The Feybesse, et al., (2006) model recognises a three phase deformation history in which the Kumasi Basin sedimentation marks the end of the Eoeburnean and beginning of the Eburnean Orogeny:

(1) D1 was a period of basin inversion and crustal shortening, resulting in foliation and fold parallel thrust faults.

(2) D2 marks the period of maximum deformation manifested by upright isoclinal folds with horizontal to slightly dipping hinges associated with NE-SW compression and the emplacement of major ductile shear zones when folding was no longer able to accommodate the shortening. Sinistral to reverse-sinistral movement is associated with these NE-SW shear structures. Gold mineralisation is associated with peak D2 deformation.

(3) D3 is defined by generally dextral brittle strike slip faults resulting from WNW-ESE shortening. Earlier NE-SW D2 structures were reactivated with dextral movement. D3 brittle faults generally have much more limited strike extension than the NE-SW D2 shear zones and post-date mineralisation, offsetting mineralisation in orebodies.

This study identified that the peak sinistral to reverse-sinistral D2 deformation facilitated the trapping of the gold-bearing hydrothermal fluids and was thus key for gold deposition across the region asserting control over the distribution of mineralisation at a range of scales:

(a) At the regional scale first order D2 faults act as the channels exercising control of deposit distribution.

(b) At the camp scale (10 km) deposits are sited in, or adjacent to, D2 second order faults associated with the regional primary faults.

(c) At the deposit scale (1 km), mineralisation is associated with folds, jogs, and structural intersections with third order faults developed locally.

This study represents considerable progress toward presenting a unified theory for gold deposition across south-west Ghana. By identifying that ore forming processes operate on scales larger than the deposits themselves and that certain processes were fundamental in order for gold deposit formation, a concise deformation history was formulated based on mappable features that all gold deposits in the study shared.

This approach marked an important shift away from the preceding deposit-based theories and a big step toward the mineral system concepts that were quickly becoming widely adopted through the industry at that time.

#### *4.2.3 Geodynamic Model Case Study 2: "Revised Eburnean geodynamic evolution of the gold-rich southern Ashanti Belt, Ghana, with new field and geophysical evidence of Pre-Tarkwaian deformations" by Perrouty, et al. (2012)*

Since the publication of the Feybesse et al. (2006) model there were major improvements in the number, extent and quality of regional data sets. The final, and most recent, geodynamic evolution model to be reviewed is that of Perrouty, et al., (2012) who integrated field mapping, reprocessed and interpreted aeromagnetic, radiometric, gravity and ALOS PALSAR geophysical data to compile their structural interpretation.

The revised deformation history recognises an Eoeburnean D1 N-S shortening event that is recorded by folding in the Ashanti and Sefwi greenstone belts and was considered the first event to introduce gold into the system (Perrouty, et al., 2012)).

D2 represents an extension event in which the Kumasi Basin opened and sedimentation occurred. During this event major structures such as the Ashanti Fault and Bibiani Fault were established as low angle detachments that controlled deposition of the Kumasi Basin sediments (Perrouty, et al., 2012).

D3 represents basin inversion and the onset of the Eburnean Orogeny NW-SE shortening event. D3 isoclinally-folded and sheared the Kumasi Basin sediments and established the NE-SW structural corridor down the axis of the Kumasi Basin, and re-activated and inverted the major belt bounding Ashanti and Bibiani Fault structures (Perrouty, et al., 2012).

D4 deformation corresponds with sinistral and reverse-sinistral reactivation of the D3 structures and is associated with the major gold deposition events. Major second-order splays of first-order belt bounding fault structures were likely to have been reactivated during the sinistral shearing and gold associated with the D1 deformation event remobilised and deposited where it is found today.

D5 and D6 post-date mineralisation and are relatively minor events associated potentially with orogenic collapse, a slight relaxation, or other far field deformation events (Perrouty, et al., 2012).. They are recorded in the Kumasi Basin sediments as crenulation cleavages on the cm scale.

This study made progress toward presenting a simple unified theory for gold deposition across SW Ghana which satisfies the critical observations common to all gold deposits in the region. By identifying that ore forming processes operate on scales larger than the deposits themselves, and that certain processes were critical for gold deposit formation, a concise deformation history was formulated based on mappable features that all gold deposits in the study had in common. Understanding the geodynamic evolution of the Kumasi Basin is fundamental to the development of predictive criteria for the discovery of additional gold deposits. The current study uses the deformation history described by Perrouty, et al., (2012) study and all deformation events referred to in subsequent sections will reference this study.

There are several aspects of the study by Perrouty, et al., (2012) that are important to this current study and should be highlighted. These deformation events will be referred to throughout the rest of this document and are as follows; (1) A fundamental deformation event included in the Perrouty, et al., (2012) study is the basin-forming D2 extension event. This event required the generation of regional extensional fault system and has major implications for the establishment of a basement structure architecture connecting the source region and the upper crust.

As this study will demonstrate, basement structures are a critical part of the permeability network to allow the gold bearing hydrothermal fluids to migrate upward from the source region through the basement rocks and into the overlying Kumasi Basin and, (2) the D3 and D4 deformation events relate to geological processes that are critical for ore deposit formation. This current study will show that structures relating to these critical events are can be mapped in the field and in geophysical data sets.

## 4.3 Kumasi Basin Gold Mineralisation

In excess of 200 deposits and prospects are documented in the Kumasi Basin and margins of the adjacent Sefwi and Ashanti belts. In fact, the Kumasi Basin hosts a significant percentage of past and present mineral reserves and resources in Ghana, including the camps of: Ashanti Gold Mine (>62 Moz), Prestea-Bogoso (>22 Moz), Edikan (>9Moz), Bibiani (>7 Moz) and Asanko Gold Mine (>11 Moz). This represents a total known resources and reserves gold endowment in excess of 107 Moz, 3033 metric tonnes hosted in deposits within the Kumasi basin and adjacent volcanic belt boundaries. This rough estimate of 3,033 metric tonnes of gold hosted within the Kumasi Basin equates to slightly less than half of the estimated 6,315 metric tonnes of past production and present gold reserves and resources estimated for the entire country of Ghana (Goldfarb, et al., 2017) (see Figure 23).

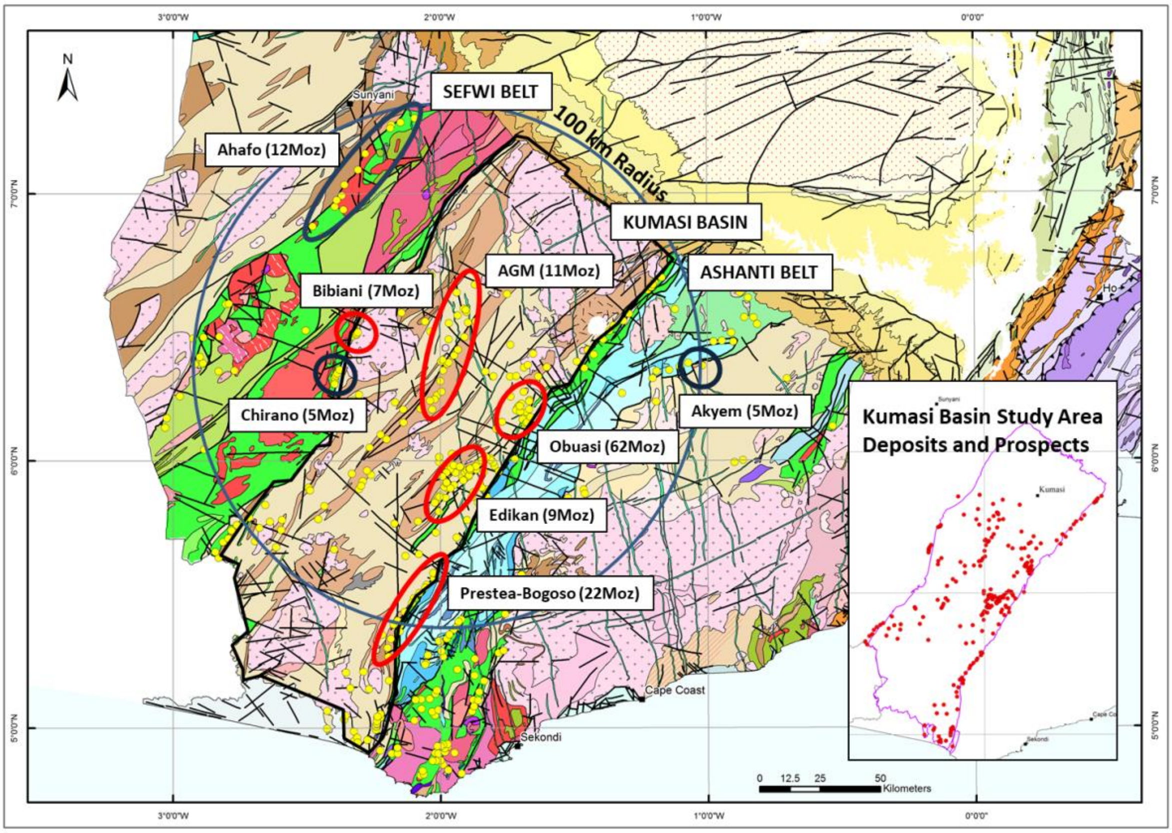


**Figure 23: Major orogenic gold camps of south-west Ghana within a 100 km radius of the Asanko Gold Mine camp. Kumasi Basin hosted camps outlined in red, volcanic belt or basin hosted camps outlined in black. Gold deposits and showing are shown as yellow circles in the main map and red circles in the inset. Modified from Agyei Duodu, et al., (2009).**

There are three principal styles of orogenic gold deposits in the Kumasi Basin study area:

(1) Quartz vein-hosted deposits which are free-milling, metasediment and granitoid hosted, and shear zone controlled.

(2) Disseminated to massive sulphide deposits with refractory gold which are metasediment hosted and shear zone controlled.

(3) Shear zone controlled disseminated and quartz vein-hosted deposits within granitoids (Carranza, et al., 2009).

Deposits in the Asanko camp are of the category (1) type: the gold is free-milling and occurs as fracture-infills and along the selvages of quartz veins and mineral grain boundaries hosted within metasediments and granitoids of the Kumasi Basin assemblage. Both metasediments and granitoids host gold mineralisation in the Asanko camp - often within the same deposit. In the Kumasi Basin there are two phases of granitoids; (1) as foliated and mineralised discrete elongate bodies and plugs hosted within D2 shear zones, and (2) as more widespread unmineralised late Eburnean K-feldspar rich granitoids hosted mainly within the Cape Coast, Kumasi and southern Sunyani basins, which post-date mineralisation and cross-cut all major regional structures (Perrouty, et al., 2012). Granitoid bodies are present in most, but not all, deposits and play a key role in providing rheological contrast causing brittle deformation critical for dilation and deposition of economic volumes of mineralisation.

Common to all orogenic gold deposits, the study area deposits generally line up along deeply-penetrating second order shear zones within the Kumasi Basin adjacent to primary major belt bounding shears which separate the basin sediments from the volcanic belt assemblages. The Asanko Gold Mine camp is located in the Asankrangwa Belt structural corridor located parallel to the axis of the Kumasi Basin. The Asankrangwa gold belt is a complex 10 km to 15 km wide, NE-SW striking structural corridor made up of five parallel shear zones which can be traced on surface for tens of kilometres. Connecting these parallel shear zone corridors is a complex network of brittle to ductile third order shear zones and faults striking ENE-WSW and are interpreted to be emplaced during the NNE-SSW D4 deformation event. This event triggered the sinistral to reverse sinistral reactivation of the second order structures. It is interpreted that compressive strain during this deformation event was partially released by the formation of these brittle to ductile faults that display relatively short and discontinuous lateral strike length. These structures are interpreted to be critical for ore deposit formation as their intersections with second order structures correspond to zones of dilation necessary for the emplacement of the gold bearing quartz veins. These third order structures are not visible at all scales of geophysical data. Due to their short strike length and lack of continuity they do not show up in regional geophysics, but in detailed magnetic data sets they are clearly visible.

All deposits in the Asanko Gold Mine camp display an interaction between the second and third order surficial structures. This surficial structural architecture forms part of the fundamental criteria for ore deposit formation. This study will attempt to show, however, that understanding the surficial structural architecture alone is not sufficient for effective targeting of gold deposits within the Asanko Gold Mine camp as it provides an incomplete picture of the interconnected fluid pathway network necessary for the upward migration of mineralised fluids. This interconnected permeability network is critical for the process for ore deposit formation. This study aims to demonstrate that there is a cryptic basement structure architecture that exerts a direct control over ore deposit location. Understanding and mapping this underlying structural architecture is fundamental for devising structural criteria for effective prospectivity and targeting exercises.

# 5 MINERAL DEPOSIT SPATIAL DISTRIBUTION ANALYSIS

Mineral deposits are small manifestations of mass flux systems which operate on much bigger scales than the deposits themselves. The underlying controls on deposit location are dictated by features that operate at much larger scales than the individual deposits (McCuaig & Hronsky, 2014). The basement and upper crust structural architecture provides the fluid permeability network which allows gold bearing fluids to migrate upward in the earth's crust to where mineralisation is deposited. Understanding this interconnected structural architecture is critical for the generation of predictive models and making new major discoveries. Although these structural relationships play an important role in mineralisation, the relationship between basement structure architecture and mineral deposits can be quite cryptic, and structural controls may vary as a function of scale within districts (Austin & Blenkinsop, 2009)

The first stage of any exploration program should involve the generation of robust, multi-scale targeting models and a good rule thumb is that exploration target models should focus on identification of structural controls one scale larger than the model explored for (Hronsky & Groves, 2008). For example, if one were looking for to target new camps at the provincial or regional scale they would be looking to identify lithospheric suture zones between cratonic blocks, translithospheric faults, and first order structures in areas with an enriched mantle fluid source and favourable 4D geodynamic history to get them into the most prospective areas of the earth. We know that Ghana is in one of the best endowed gold districts in the world so we will not focus on this scale. This project is rather focussed at the scale of the Asankrangwa Belt and camp scale and as such an understanding of the regional scale structural controls in the Kumasi Basin is necessary for successfully targeting deposits.

Basement structure architecture is notoriously difficult to accurately detect, but is fundamental for providing conduits between the source region of mineralised fluid and the upper crust. Often there are no observable features on surface that give clues to its existence and they almost always trend in a completely different orientation from observable structures recorded by overprinting deformation events.

These basement structures are repeatedly reactivated during subsequent deformation events and propagate upward creating interconnected permeability networks into the overlying strata. Deep seated structures in the overlying strata connect with this permeability network and provide the conduits to bring mineralised fluids into the upper crust where they are trapped and deposited. Understanding this relationship between the basement and upper crustal structural architectures is important because even though later deformation events are ultimately associated with the mineralisation, they do not exert total control over deposit and camp location. At both the belt and regional scale it is the interaction between the regional and belt scale structural controls which ultimately determines deposit and camp location.

Understanding that there are critical structural criteria that do not manifest as mappable features in outcrop, open pit faces, and drill core is fundamental to this study. Using only features which can be mapped , pit faces, and drill core would lead to the generation of many false positive targets in resulting targeting exercises. Exploration programs based on criteria generated in this manner are inefficient as they would chase surficial targets which do not have all of the structural elements necessary for ore deposition. Based on the mineral systems approach, deposits exist because of a critical set of processes which have occurred and if one of these processes is missing deposit formation will not occur (McCuaig & Hronsky, 2014). This is why understanding regional basement architecture is critical to effectively targeting deposits at the belt scale. This project uses several methods to identify and map basement structure orientation and location. The first method is a Fry autocorrelation analysis which is useful in identifying underlying structural controls based on spatial distribution trends in deposit location point data. These trends are then mapped and modelled as geological structures at the regional and belt scale using proprietary and publicly available geophysical datasets which will be covered in Section 7. The structural architecture models generated from the geophysical mapping are interpreted and used to develop structural targeting criteria for the predictive discovery of gold deposits in the Kumasi Basin, which has major implications for regional to camp scale exploration targeting. Using the mineral system concept as a guide, this study argues that there is an essential structural criterion that must be present for a significant deposit to form. Any prospectivity analysis that does not fully understand and identify these structural criteria will lead to the generation of many false positive targets and decrease the efficiency of exploration programs based on them.

Although largely focussed on determination of structural targeting criteria, this study also aims to draw a link between quantitative mineral resource assessment and prospectivity at the district and camp scales. The Zipf's Law analysis makes the business case for exploration expenditure in the Asankrangwa Belt and the Fry analysis and geophysical interpretation develops robust, multi-scale targeting criteria for the discovery of new deposits. Drawing the link between the quantitative assessment and prospectivity is important as one of these without the other can lead to exploration expenditure being focussed in areas with little potential for residual endowment and hence little hope for new discovery. The two combined provides a potent combination for motivating exploration expenditure in both the brownfields environment such as the Asanko Gold Mine camp, and in greenfields environments.

A Fry analysis is an alternative to variography for directional studies, and at the regional scale can assess distribution patterns of mineralisation and potential underlying controlling structures (Vearncombe & Vearncombe, 1999). A Fry analysis is a graphical form of autocorrelation analysis developed by Fry (1979) to measure rock deformation using the relative positions of geological markers in thin sections (Haddad-Martim, et al., 2017). The original study was developed to investigate strain and strain partitioning in rocks. This method has since been used in the analysis of mineral deposits in order to deduce the orientation of structural controls which may not manifest as mappable features on surface. This will be demonstrated later in this section using case studies from other gold districts around the world, and by way of this study conducted on the Kumasi Basin gold deposits. In an area that has a relatively large number of known mineral deposits such as South-west Ghana, their spatial distribution can provide valuable information on the processes controlling mineralisation and deposit location operating at different scales (Lisitsin, 2015).

This study suggests that gold deposit locations in the Kumasi Basin are directly linked to a cryptic basement structure architecture which has no observable surficial expression but is essential for deposit formation. These structures are oriented obliquely to the over printing surficial features which can be mapped. This study utilises a Fry auto-correlation analysis to reveal the relationships between basement structures and spatial distribution of mineralisation at different scales within the Kumasi Basin. Interpretation of regional gravity data, airborne EM and magnetic geophysical data, and 3D inversions of airborne EM and magnetic data are used to verify structural orientations observed in the Fry analysis. Where applicable structural trends observed and mapped are related to the geodynamic history of the study area, confirming that they are resultant from the processes known to be critical for gold mineralisation. The combination of these techniques creates a powerful methodology for identifying mappable features of critical geological processes and ultimately leading to the development of targeting criteria for gold in the Kumasi Basin. This methodology has major implications for the generation of multi-scale exploration models not only for the Kumasi Basin but for other orogenic gold belts in the world.

## 5.1 Fry Analysis Application

A Fry analysis is performed through the construction of an autocorrelation diagram called a Fry diagram, or Fry plot. Fry plots enhance subtle patterns in sets of points and allow trends between all Fry points within specific distances of each other to be identified using rose diagrams. This allows trends that operate at different scales to be identified.

Fry diagrams were originally constructed manually, but are now generated using computer programs. The Fry plots analysed in this study used a freeware program called DotProc, although other programs are also available. Using either methodology the following procedure is used to create Fry plots (as described by Haddad-Martim, et al., (2017)):

(1) One of the points in the original distribution is placed at the centre of the diagram, preserving the distances and orientation of all other points.

(2) The positions of every point of the original distribution are marked on the new diagram (these are called “Fry points”).

(3) A second point is placed at the diagram centre, and the positions of the remaining points are registered.

This procedure is repeated until every point in the original distribution is used as the centre of the diagram. As such, for every n data points there are $n^2$-n translations in the Fry diagram. The benefits of using a computer program are that much larger data sets can be analysed, which in some cases can involve millions of translations. In the case of the entire Kumasi Basin study area, the total number of gold deposits and prospects used was 240, for a total of 57,360 translations.

Fry analyses have been used by many authors to gain understanding of deep seated crustal, regional, and district-scale structural controls on gold mineralisation. In this section we will look at the first application of Fry analysis to mineral deposits by (Vearncombe & Vearncombe, 1999), Controls on gold distribution in the South-west Ashanti belt by (Carranza, et al., 2009), structur control detection in the Hodgkinson Province and West Lachlan gold belt of Eastern Australia by (Lisitsin & Pitcairn, 2016), a study on the structural controls of mineralisation in the Charters Towers goldfield in NE Australia by (Kreuzer, et al., 2007), and a study on local to regional scale structural controls on mineralisation and the influence of a major basement lineament in the Mount Isa Inlier, Australia by (Austin & Blenkinsop, 2009).

## 5.2 Case Studies

### *5.2.1 "The spatial distribution of mineralisation: Applications of Fry Analysis" by Vearncombe & Vearncombe, (1999)*

The first to apply Fry analysis to the spatial distribution of mineralisation at various scales were Vearncombe & Vearncombe, (1999). In their seminal paper titled "The spatial distribution of mineralisation: Applications of Fry analysis" they examined:

(1) Kimberlites of Guinea, West Africa at the district scale.

(2) Hydrothermal and porphyry copper deposits in Arizona at the district scale.

(3) Orogenic gold deposits at Mount Pleasant (northwest of Kalgoorlie) at the district scale.

(4) Advanced exploration drilling from the Jundee gold mine, Western Australia at the deposit scale.

(5) Grade control drilling data from the Bronzewing gold mine in Western Australia at the deposit bench scale (Vearncombe & Vearncombe, 1999).

This thesis project focuses on the orogenic gold deposits at in the Mount Pleasant district. From the deposit location data used in the Mount Pleasant study the deposits have an obvious and very strong NW trend, reflecting an initial bias (Vearncombe & Vearncombe, 1999).

This study conducted the Fry analysis using searches for translations within different radii to attempt to minimise the effect of this bias. This helps to identify structural controls at different scales. When all of the deposits in the belt were used in the analysis, the strong regional bias orientation is dominant. When a search radius of 10 km was used a secondary orientation trending 025° is observed as shown in Figure 24. This trend corresponds to linear features, which when compared with Aeromagnetic data interpretations and outcrop mapping where possible, are shown to be Late Archean faults (Vearncombe & Vearncombe, 1999). These faults are systematically well developed, mineralised, and are coincident with all of the larger deposits in the study area (Vearncombe & Vearncombe, 1999). Although in this area the Archean basement is mappable on surface, this study still has relevance to this thesis project in demonstrating that the Fry analysis is able to identify trends controlling mineralisation which are then identified and mapped which is a critical step in the development of targeting criteria.

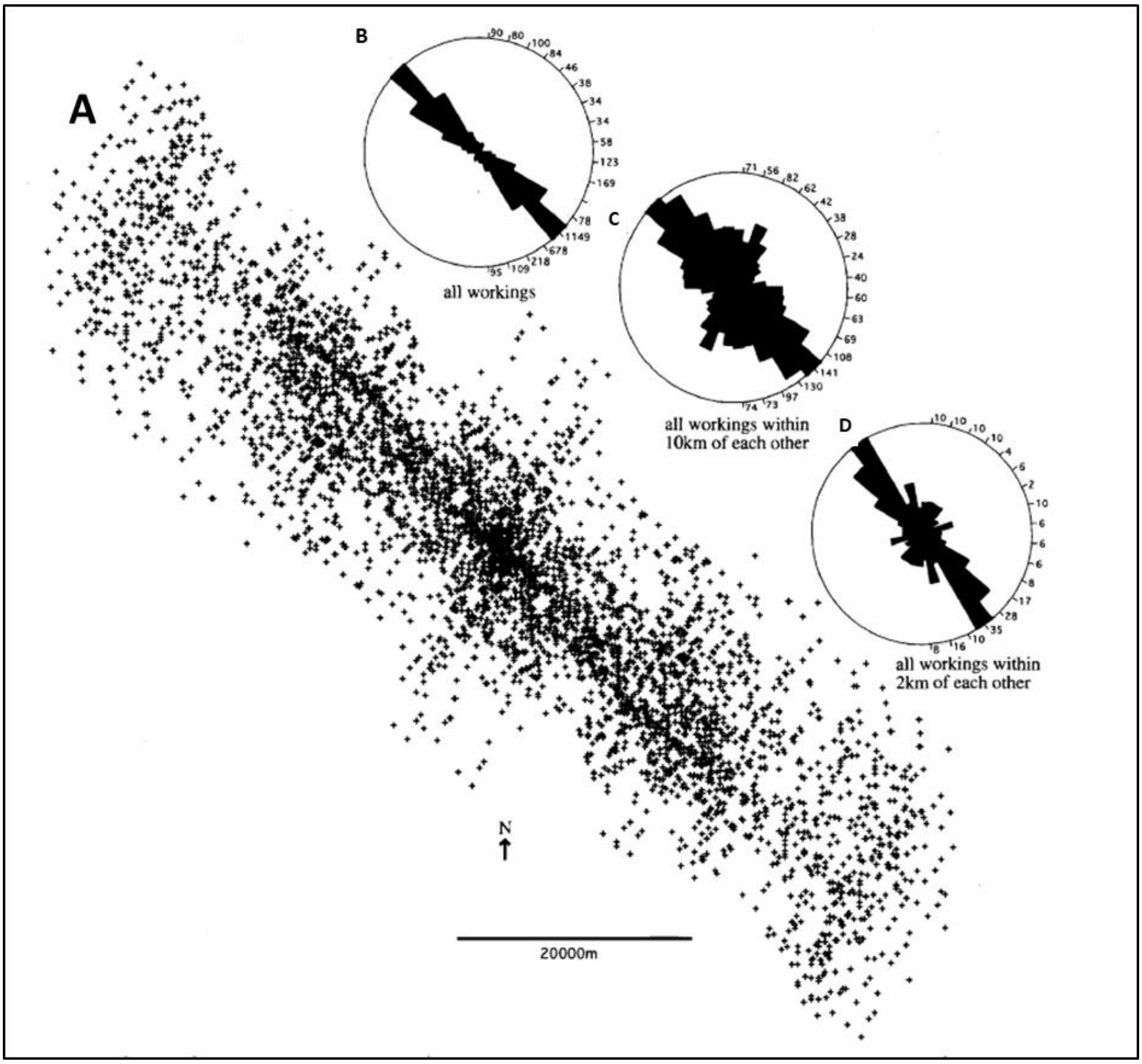


**Figure 24: District scale Fry plot of gold deposits in the Mount Pleasant camp, Western Australia showing (A) Fry plot of all translated points, (B) rose diagram trends for all translated points, (C) rose diagram trends between workings within 10 km of each other, and (D) rose diagram trends between workings within 2 km of each other. Modified from Vearncombe & Vearncombe, (1999).**

### *5.2.2 "Mapping of prospectivity and estimation of number of undiscovered prospects for lode gold, southwestern Ashanti Belt, Ghana" by Carranza, Owusu, & Hale, (2009)*

A very applicable study to this thesis was completed by Carranza, Owusu, & Hale, (2009) which mapped prospectivity and estimated the number of undiscovered lode gold prospects in the south-west Ashanti Belt. This study used a Fry analysis of 51 known mines and prospects, most of them orogenic gold, although several paleoplacer deposits were included as well, and analysed their spatial associations with faults and fault intersections in order to determine the structural controls on gold mineralisation at camp and district scales. This work has obvious analogies to this study in that it focuses on determining structural controls at different scales based on known deposit spatial distribution. Both studies combine elements of prospectivity mapping and mineral resource assessment, albeit by slightly different methodologies.

The results of the Fry analysis showed that all pairs of points for the 51 mines and prospects show mainly NNE and NW trends (see Figure 25), suggesting structural controls by not only NNE-trending faults but also by NW trending faults. This is not surprising as these are mappable structures within the study area. However, in addition to these observations the Fry analysis also shows two additional trends which are not obvious in the point data. The first is a sub-parallel NNE-trend which is interpreted to be parallel district-scale hydrothermal systems controlled by the periodicity of the NNE trending faults (Carranza, et al., 2009). The second association is visible in the Fry analysis looking at points <6.8 km apart and shows a subsidiary trend of 120-135° (or 300-315°) suggesting that NW-trending faults and intersections of NNE-NE- and NW-trending faults are plausible structural controls on gold mineralisation in the study area (Carranza, et al., 2009). Importantly, these observations are not made in isolation and are backed up by a spatial association analysis that was conducted to examine apparent spatial associations or lack thereof between deposits and faults of different orientations.

The south-west Ashanti study used a distance distribution analysis to make these associations which backed up the findings of the Fry analysis. In the case of this study, geophysical interpretations were made to corroborate structural trends observed in the Fry analysis at different scales.

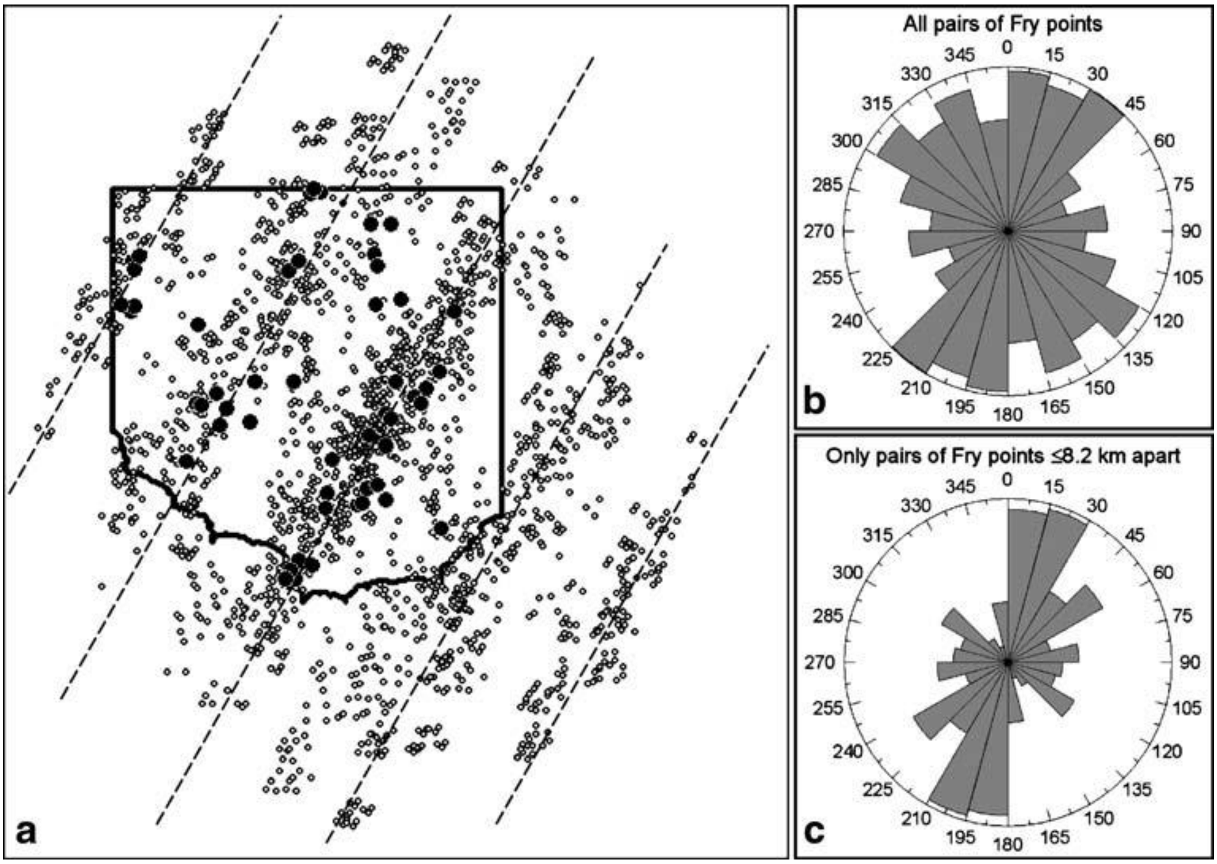


**Figure 25: Fry analysis results of the south-west Ashanti belt study area showing (a) all translated Fry points, (b) trends between all pairs of Fry points, and (c) trends between Fry points within 8.2 km, of each other. From Carranza, et al., (2009).**

### *5.2.3 "Spatial data analysis of mineral deposit point patterns: Application to exploration targeting" (Lisitsin, 2015)*

The third case study is based on Lisitsin, (2015) study and is summarised below. In this study, Lisitsin states that systematic spatial analysis of mineral deposit point patterns can reveal significant spatial properties about mineral systems with major implications for regional mineral prospectivity modelling. This study analyses the spatial distribution of orogenic gold deposits in the Hodgkinson Province in Queensland, Australia and the Western Lachlan Orogen in Victoria, Australia to indicate the presence of significant regional linear metallogenic zones and infers them to be controlled by deep crustal domain boundaries oblique and not related to any recognised surficial major faults. A key element of this study is recognising cryptic regional mineralisation controls and establishing whether deposits tend to be close or distal to each other as this has major implications for exploration targeting, especially for large deposits. If major deposits within a region are clustered along a particular lineation that is identified using a Fry analysis, one would not spend a lot of time and expense looking for large deposits outside of this zone (Lisitsin, 2015).

Alternatively, if large deposits are found to be widely spaced from each other one would not spend a lot of time and expense looking for other major deposits in their immediate vicinity (Lisitsin, 2015). This information is incredibly important for any exploration strategy and can be applied from the camp to regional scales. Ghana is a particularly good region to apply the methodology in this study because of the density of deposit and prospect data. In the study by Lisitsin, several methods of spatial analysis are used including:

(1) Fry analysis.

(2) Centrographic and directional distribution analysis.

(3) Analysis of spatial homogeneity.

(4) Analysis of point interaction.

While method 2-4 are not commonly used in mineral prospectivity modelling, they can complement the Fry analysis and be effective methods for providing insight into the spatial distribution of mineral deposits and their underlying controls. In both areas focussed on in this study the Fry analysis was used effectively to demonstrate the different results between different types of data sets. The Hodgkinson Province gold deposits showing a high degree of clustering and a very strong correlation to a linear feature as shown in Figure 26. The Lachlan Orogen gold deposits show a high degree of heterogeneity in their spatial distribution, but deposits still fall along a fairly discrete trend in the point analysis as shown in Figure 27. In addition, this study showed the effects of sub-grouping the populations based on deposit mineralisation type, in this case quartz-antimony deposits from gold-quartz vein deposits in the Hodgkinson Province.

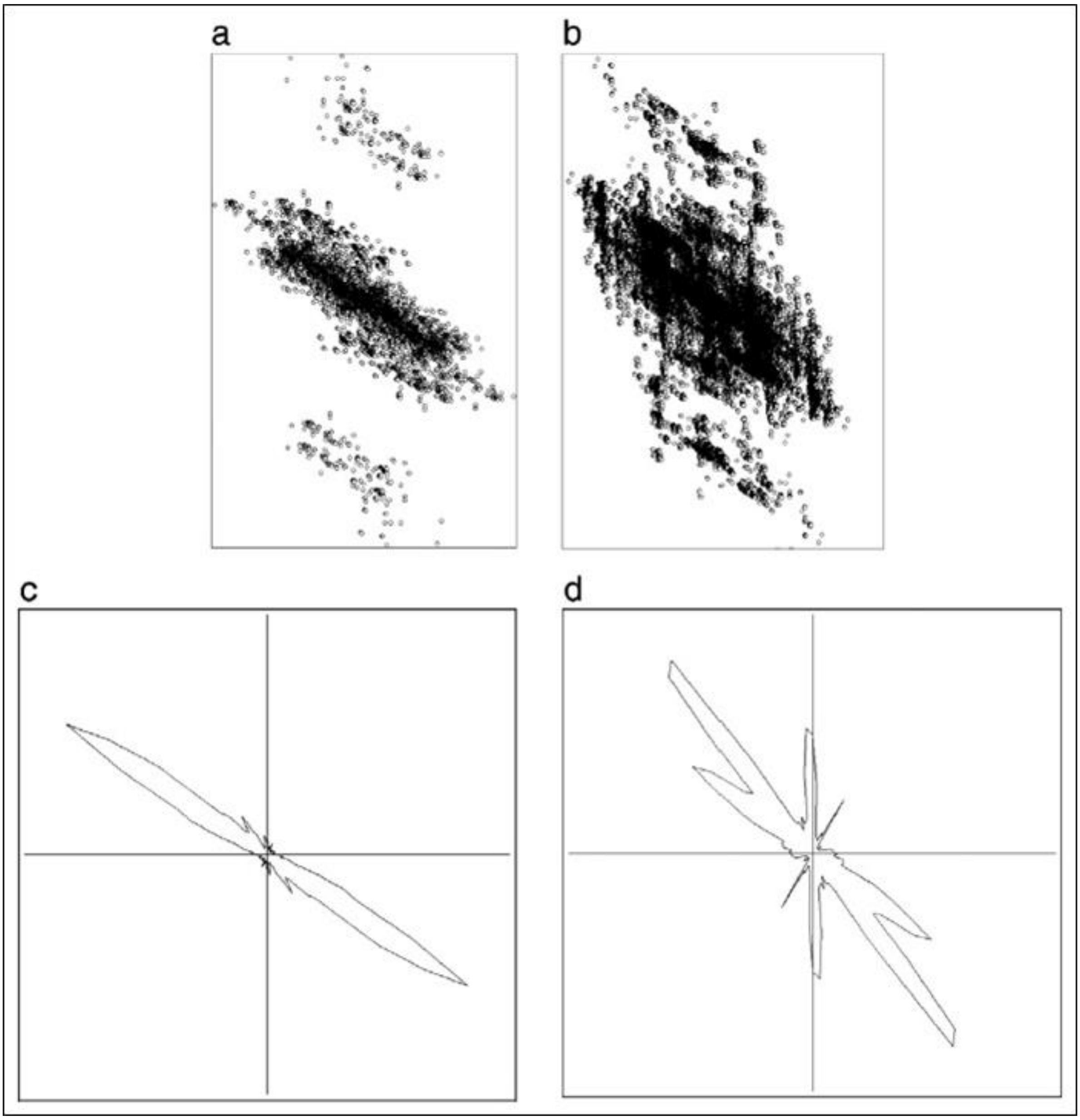


**Figure 26: Results of Fry analysis for the Hodgkinson Province gold deposits. Fry plots for: (a) gold-antimony deposits; (b) gold-quartz vein deposits; and rose diagrams for: (c) gold-antimony deposits; (d) gold-quartz vein deposits. From Lisitsin, (2015)**

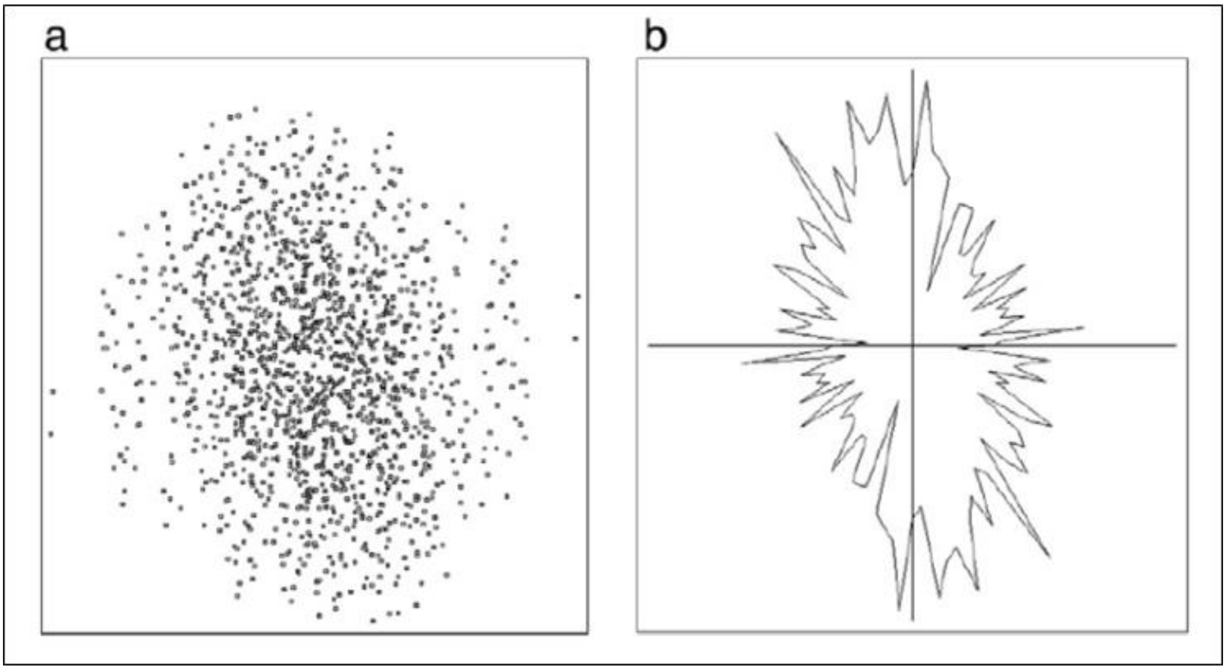


**Figure 27: Results of Fry analysis for gold-quartz vein ore fields with >0.5 t of contained gold in the Bendigo and Stawell zones: (a) Fry plot; (b) rose diagram. From Lisitsin, (2015).**

### *5.2.4 "Ore controls in the Charters Towers goldfield, NE Australia: Constraints from geological, geophysical and numerical analyses" by Kreuzer, et al., (2007)*

The fourth case study looks at the structural controls of mineralisation in the Charters Towers goldfield in NE Australia by Kreuzer, et al., (2007). A Fry analysis was conducted as part of a wide-ranging study assessing overall prospectivity and district maturity using a range of different methodologies from geology, geophysics and spatial and numerical analyses. The study found that in general, all of the different camps had a strong correlation to known geological boundaries and mapped major structural corridors. Interestingly however, was that there were structural trends identified at each of the camps which were not obvious from the mapped structural features.

In this paper these were attributed to the inherent variability of orientation of structures that controlled gold deposition in each of the camps. Alternatively, they could be related to camp-scale heterogeneities in the strain field at the time of deposition. Another option could be that these structural trends represent a basement structure architecture that is fundamental to deposit formation, although this would need to be determined through the reinterpretation of available geophysics as was done in this thesis. The results of the Fry analyses are shown in Figure 28 for individual camps and for the entire district.

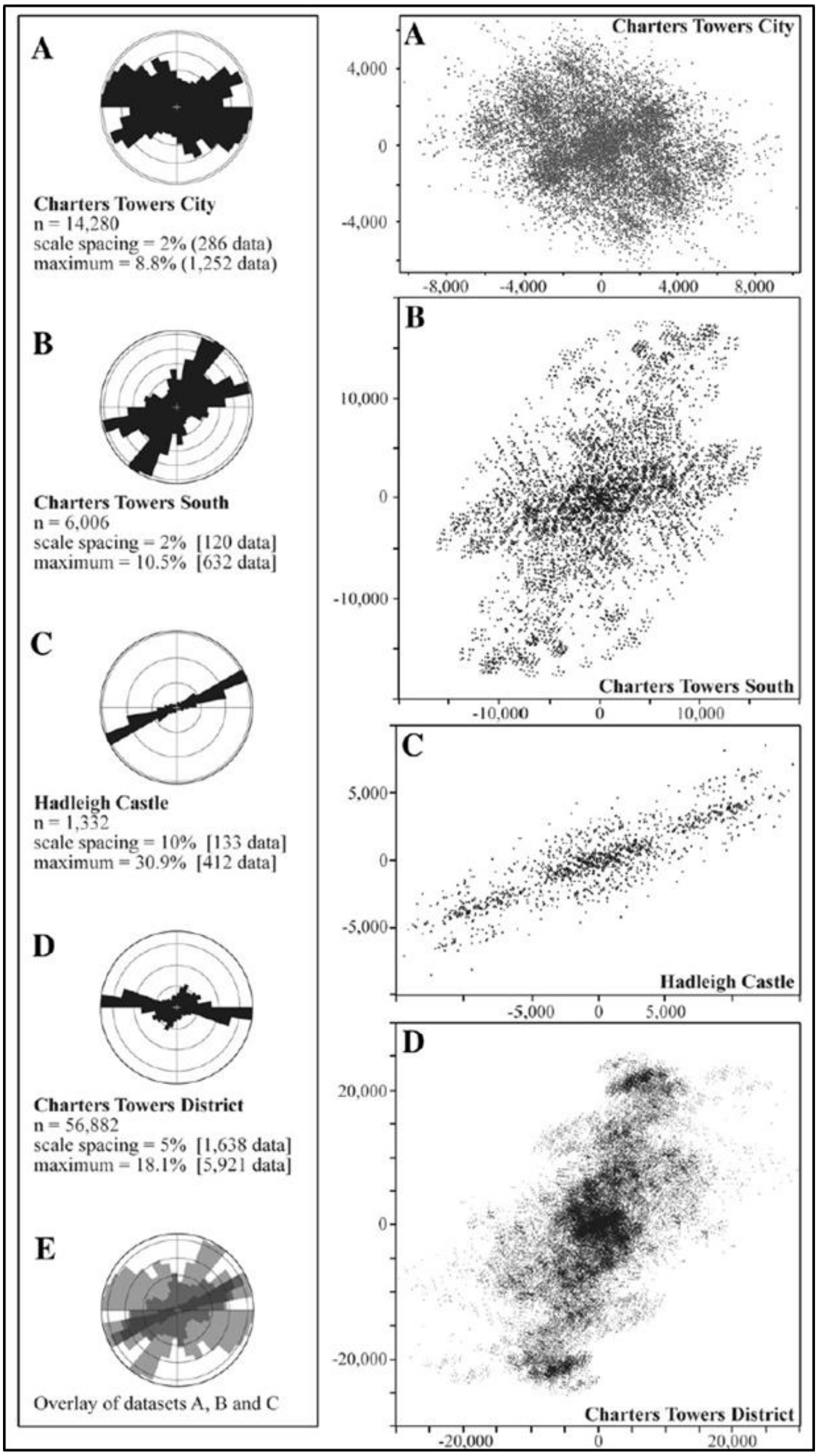


**Figure 28: Fry plots and rose diagrams of gold deposits in the Charters Towers district. (A) Charters Towers City dataset (B) Charters Towers South dataset (C) Hadleigh Castle dataset (D) Charters Towers District dataset (E) Overlay of datasets (A) to (D) From Kreuzer, et al., (2007).**

#### *5.2.5 "Local to regional scale structural controls on mineralisation and the importance of a major lineament in the eastern Mount Isa Inlier, Australia: Review and analysis with autocorrelation and weights of evidence" by Austin & Blenkinsop, (2009)*

The final case study reviewed has perhaps the most analogies to this thesis project. Austin & Blenkinsop, (2009) studied local to regional scale structural controls on mineralisation and the influence of a major lineament in the Mount Isa Inlier, Australia. The Cloncurry Lineament is a crustal-scale basement structure that has been mapped using deep penetrating magnetic geophysics and has little or no surface expression. Using a Fry analysis it is observed that the Cloncurry Lineament is a primary, regional-scale control for both Au and Cu mineralisation (Austin & Blenkinsop, 2009). As in this thesis, this study looked at the influence of this basement feature at different scales, concluding that it exerts near complete control over deposit location at the regional and district-scale and almost no control at the camp-scale where deposit location is dominated by local structural orientations. The study concludes that the extremely high correlation between Au and Au-Cu mineral occurrences with the Cloncurry Lineament suggest that it functioned as the primary regional fluid pathway and a structural trap during the introduction of Au into the system (Austin & Blenkinsop, 2009).

The structure represents a deep crustal suture zone that is a primary crustal-scale control on the location of Au and Cu mineralisation in this study area (Austin & Blenkinsop, 2009). This supports the hypothesis that major crustal features act as major regional fluid pathways and play a major role in moving mineralising fluids upwards in the crust where they are localised by surficial features (Austin & Blenkinsop, 2009). See Figure 29 for the Fry analysis results from this study showing the correlation of deposit location to structural trends at different scales. The Fry analysis results from this study show that this basement feature is fundamental for regional and district scale prospectivity mapping, but not so useful for deposit detection at the camp scale.

This type of knowledge is very important when planning exploration programs at different scales and understanding these relationships prior to executing expensive field programs is fundamental for exploration success. The Fry analysis is very important for indicating which structural orientations to focus on at different scales.

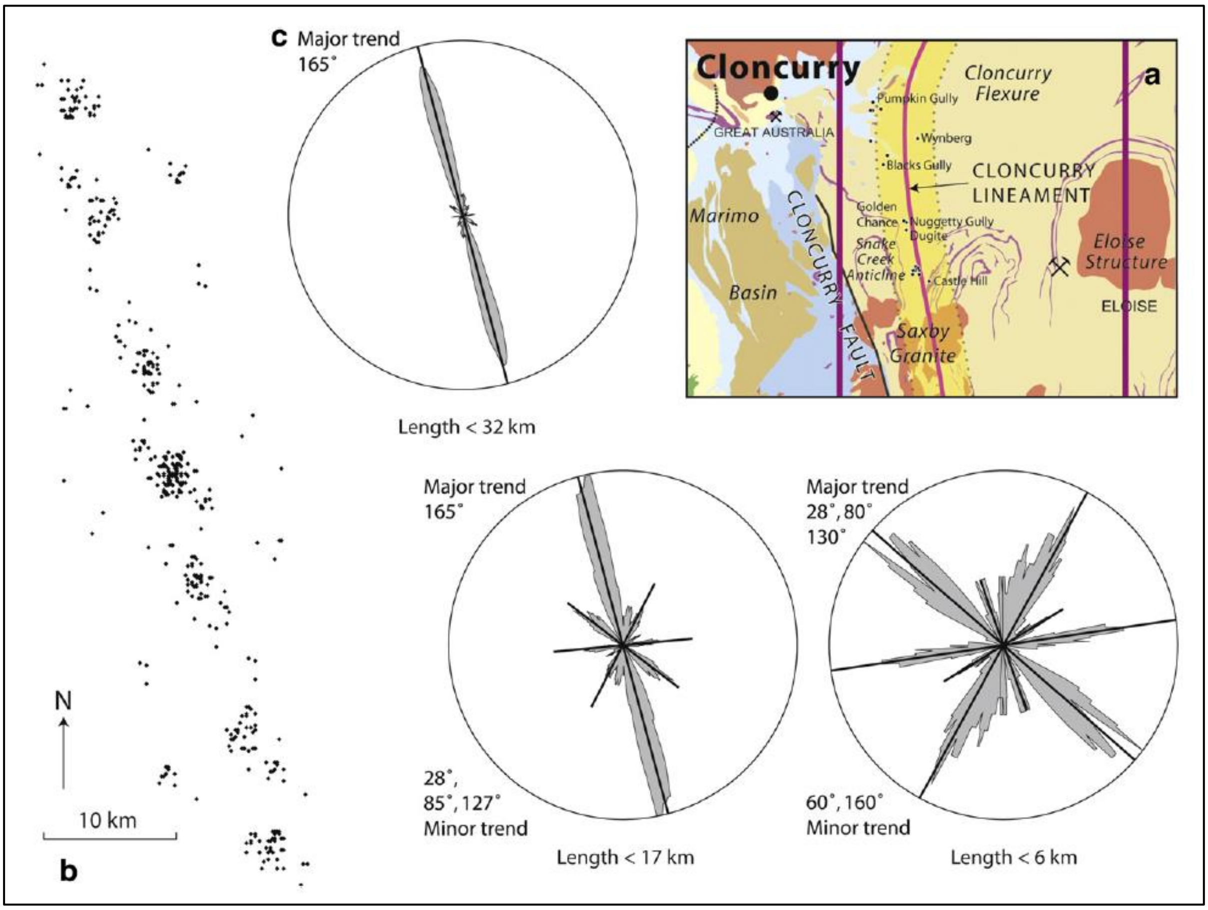


**Figure 29: Fry analysis results for Au mineral occurrences showing: (a) Mineral occurrence location and geology; (b) the Fry plot; (c) Rose diagrams at regional (up to 103 km), district (up to 75 km) and camp (up to 45 km) scales. From Austin & Blenkinsop, (2009).**

## 5.3 Kumasi Basin Study Area Fry Analysis

This study follows a similar hypothesis in that one of the fundamental controls on mineralisation is a cryptic set of basement structural features which are in a different orientation to the upper crustal mappable features. While these surficial features play a major role in the location of mineral deposits at all scales, they must interact with basement structures to create the permeability network necessary for mineralising hydrothermal fluids to migrate into the upper crust and be focussed in jogs and intersections of these second order structures. The results of the Kumasi Basin Fry analysis are discussed in the following section.

The Kumasi Basin Fry analysis in this study was conducted using mineral deposit location data provided by Asanko Gold Inc. as well as several merged regional data sets of major and minor deposit locations in the entire Kumasi Basin and adjacent Sefwi and Ashanti greenstone belt-basin boundaries. In all, 240 different gold deposits and prospects were included in the study, the location of which are shown as red dots in Figure 30. Most of these deposits are associated with seven major gold camps; Obuasi, Prestea-Bogoso, Edikan, Asanko Gold Mine camp, Bibiani, Chirano, and Nzema camps representing >120 million ounces (>3700 Tonnes) of gold endowment. Each camp consists of clusters of deposits ranging greatly in size, following the Zipf's power law distribution as described in Section 5. Gold showing data from less established camps is also included in this study. All gold deposits within the study area fall into three categories:

(1) Quartz vein free milling gold deposits hosted within metasediments, greenstones, and granitoids coincident with shear zones.

(2) Disseminated to massive sulphide deposits containing refractory gold, found in the same shear zones hosting quartz vein deposits.

(3 Gold-bearing quartz vein and disseminated sulphide deposits hosted in granitoids coincident with the same shear zones (Carranza, Owusu, & Hale, 2009).

All of the deposits are epigenetic, structurally controlled, syn-kinematic, post-metamorphic and were deposited from hydrothermal fluids during the D4 deformation event of the Eburnean Orogeny (Carranza, et al., 2009). There are over 60 active and historic producing mines in the study area and many more gold deposits and showings.

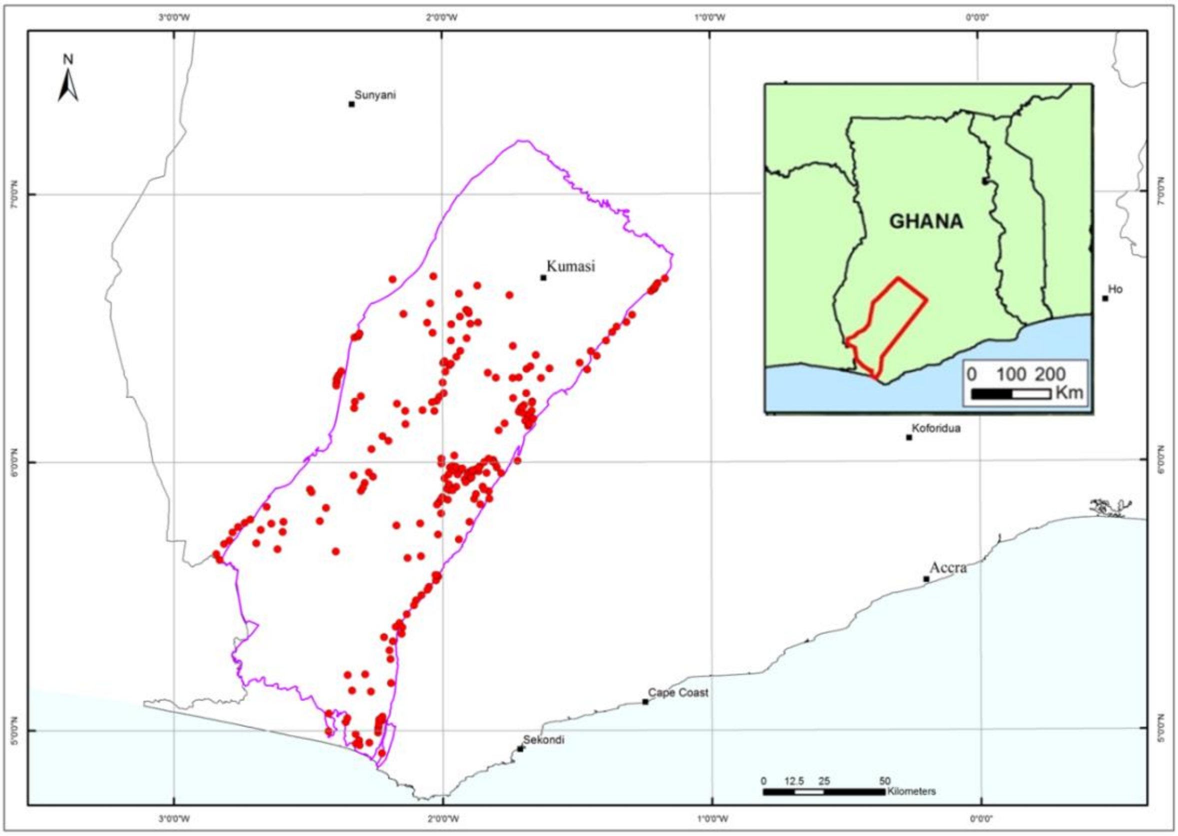


**Figure 30: Kumasi Basin study area deposit and prospect locations**

All of the deposit and prospect location data was used in this study because of the practical difficulty of accurately measuring deposit size and subdividing the dataset accordingly. Measures based on production, resources, or reserves depend on economic factors, as well as the amount of exploration activity and capital that has been spent developing them. It is well known in Ghana that deposits can pinch and swell in three dimensions and what could be a discrete surface showing can actually be a significant deposit at depth. What's more, vast areas of the Kumasi Basin have not been subjected to modern exploration techniques and what is recorded as a prospect could easily end up being a significant undiscovered deposit when properly assessed. Instead of focusing on deposit size, this study focuses on the structural architecture which influences deposit and prospect location with the aim of targeting further discovery. Should only the largest known deposits be used, it is possible that subtle, but important structural controls could be overlooked. That being said, an important follow up study would be to filter the mineral occurrence database into different sub-populations such as deposit size to potentially unlock additional information.

This study is consistent however, in that all of the deposits and showings are classified as shear zone hosted orogenic deposits and are all considered to be genetically related and share a common geodynamic history.

The Fry analysis was conducted using (3) three different sub-sets of the deposit and occurrence population to determine if structural controls on mineralisation differ at various scales. The first study area was the entire Kumasi Basin region, including the deposits located on the Sefwi and Ashanti belt-basin boundaries totalling 240 deposit locations. The second study area was on the district scale with deposits located within a 65 km radius of the centroid of the Asanko Gold Mine camp amounting to 138 deposit and prospect locations. The third camp scale study area was looked at 39 deposits and prospects within a 30 km radius of the centroid of the Asanko Gold Mine camp. These subdivisions are considered to represent regional, district and camp scale populations for the purpose of this study and the aim was to determine if different structural controls are influencing deposit location at different scales.

## 5.4 Fry Analysis Results

In this part of the study we examine spatial association between the gold deposit / prospect point data at these different scales discuss the significance of the structural trends identified. In the Kumasi Basin and belt boundaries there are 240 deposits and prospects that were used in this study.

Figure 31, Figure 32, and Figure 33 feature the most recent structural interpretation for SW Ghana released by the Ghana Geological Survey Department in 2009, which utilised regional geophysical data sets to generate this updated structural interpretation and are overlain by the Fry plots. When the trends from the Fry aanalysis are overlain on this map it is evident that some structural orientations observed in the Fry analysis are also represented in the Kumasi Basin regional structural interpretation. These have been interpreted from regional airborne datasets used in the compilation of the Ghana geology map and further validate the structural trends observed in this study using both the Fry analysis and geophysical interpretation.

### *5.4.1 Regional Scale Fry Results*

At the regional scale the study area was defined as the entire Kumasi Basin and adjacent volcanic belt boundaries. The entire deposit / prospect location dataset for this area contains 240 individual points, for a total of 57,360 autocorrelation translations (see Figure 31).

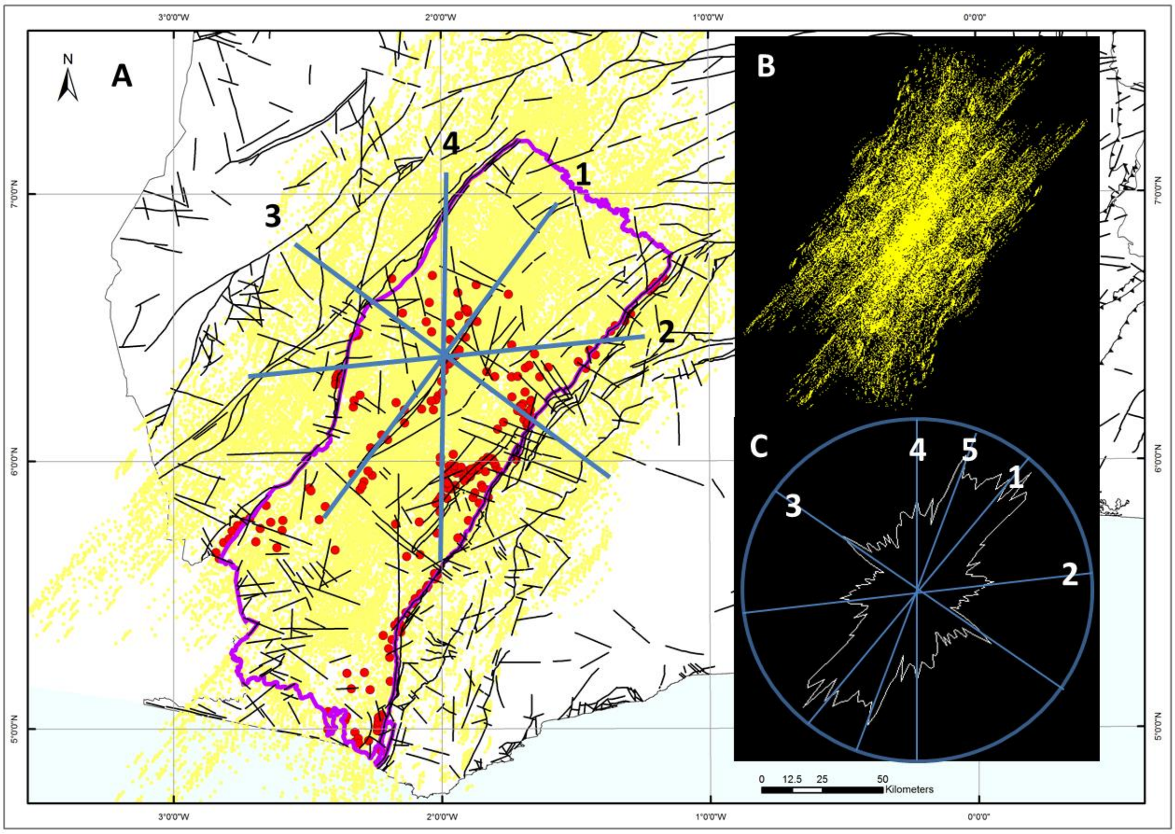


**Figure 31: Regional scale Fry analysis results showing (A) deposit locations with identified structural trends, (B) Fry distribution plot and (C) rose diagram showing the identified structural trend orientations. Modified from Agyei Duodu, et al., (2009).**

The Fry analysis plot and rose diagrams show five main trends controlling the spatial distribution of deposits and prospects; (1) NE-SW, (2) ENE-WSW, (3) NW-SE, (4) N-S, and (5) NNE-SSW. The fry analysis results show that trend (1) and (5) are dominant, and trends 2-4 all exert near equal structural control over deposit distribution.

### *5.4.2 District Scale Fry Results*

The district scale study area is defined as all deposits falling within a 65 km radius of the Asanko Gold Mine camp and located within the Kumasi Basin. This study area excludes belt boundary gold camps such as Chirano, and Konongo, but includes the Obuasi, Edikan, and Bibiani deposits which are hosted along major second order shear corridors within the basin. This was done intentionally to see if deposits located directly on belt margins exert a different set of structural control on deposit location than the basin hosted deposits. In total 138 deposits and prospects fall within this study area for a total of 18,906 translations. Deposit locations and the results of the Fry analysis are shown in Figure 32.

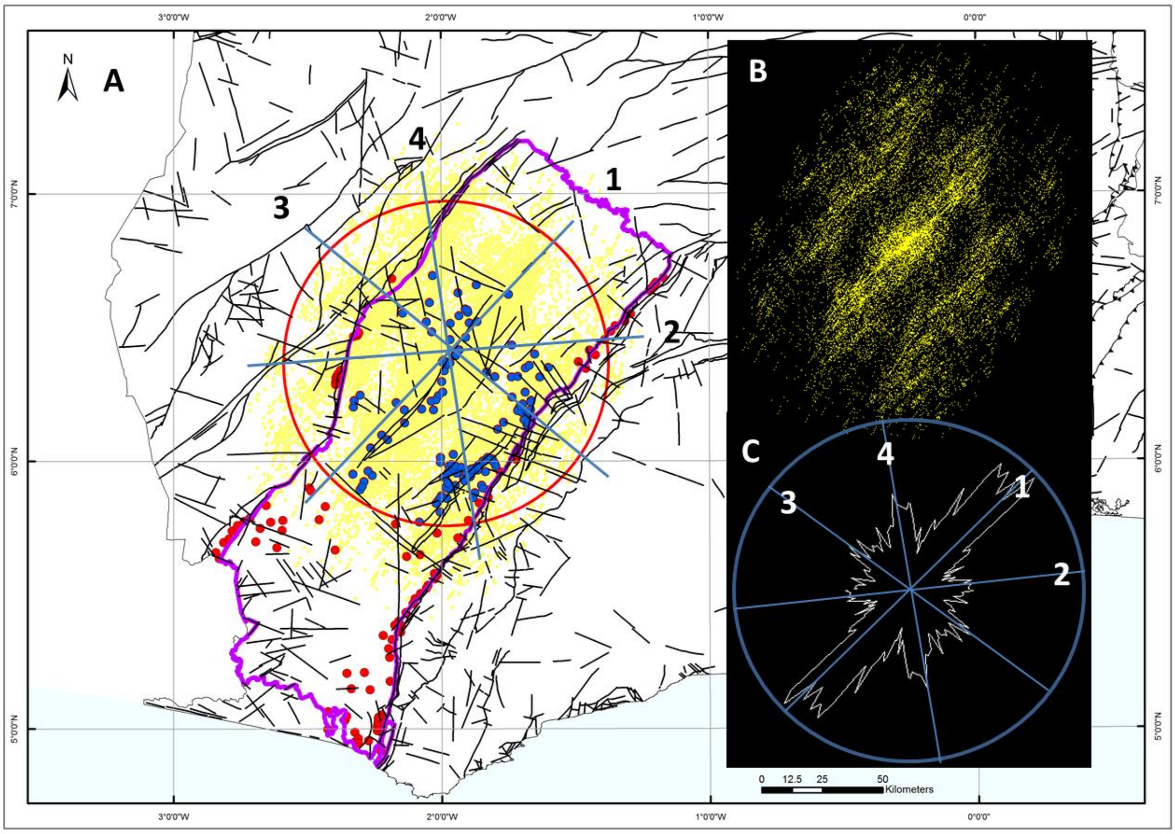


**Figure 32: District scale Fry analysis results showing (A) deposit locations with identified structural trends, (B) Fry distribution plot and (C) rose diagram showing the identified structural trend orientations. Modified from Agyei Duodu, et al., (2009).**

The district-scale Fry analysis showed very similar deposit distribution trends to the regional scale study area. Four main trends were observed: (1) NE-SW, (2) ENE-

WSW, (3) NW-SE and (4) N-S. As in the regional study area trend (1) is dominant at the district scale. Different from the regional analysis the N-S trend is more dominant in the district-scale data set. The ENE-WSW is less dominant and the NW-SE trend is consistent with the regional study. Again we see that at the district scale the trends observed in the Fry analysis are identified in the regional structural interpretation.

### *5.4.3 Camp Scale Fry Results*

The camp scale study area is defined as all deposits falling within 30 km of the AGM gold camp. This study area encompasses all of the major gold deposits of the Asankrangwa gold belt, as well as several other deposits and showings near the axis of the Kumasi Basin and is shown in Figure 33. In total 39 deposits and prospects were included in the camp scale fry analysis for 1,482 translations.

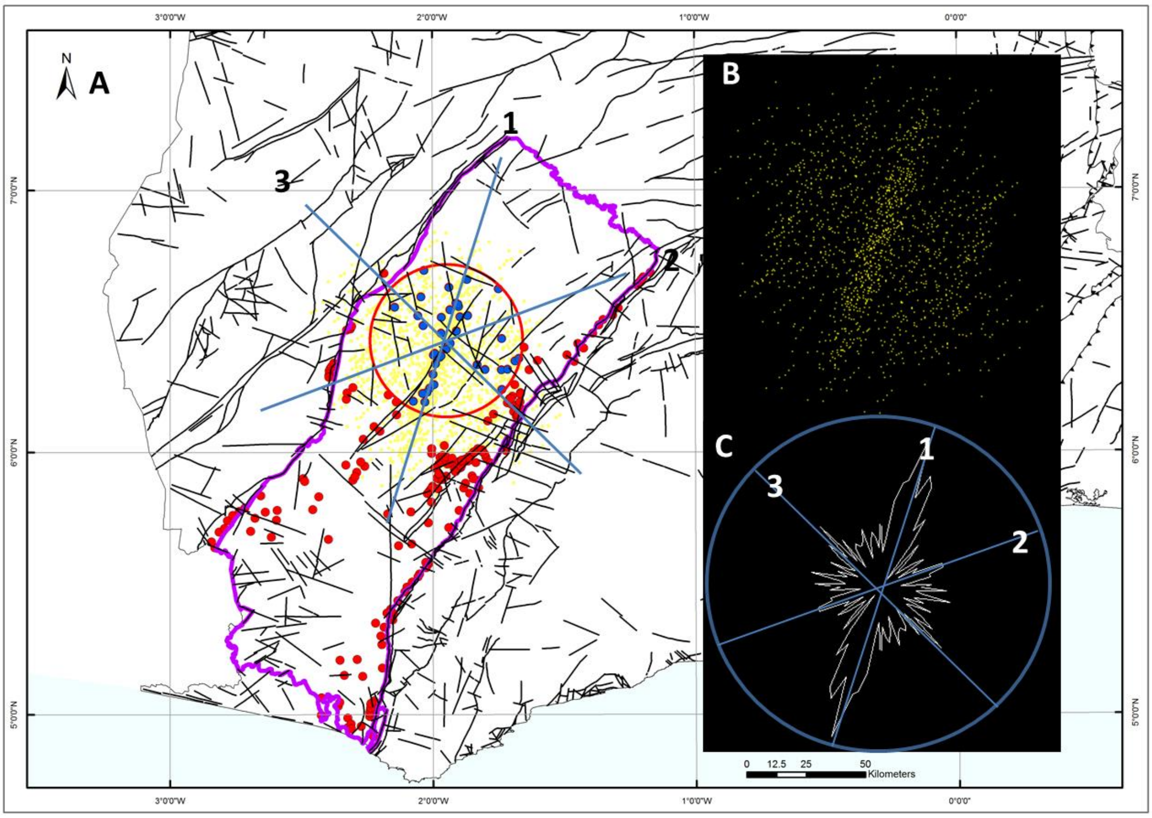


**Figure 33: Camp scale Fry analysis results showing (A) deposit locations with identified structural trends, (B) Fry distribution plot and (C) rose diagram showing the identified structural trend orientations. Modified from Agyei Duodu, et al., (2009).**

At the camp scale, the controls on mineralisation are different from the regional and district scale controls. Three main trends are observed at the camp scale: (1) NNE-SSW, (2) ENE-WSW and (3) NW-SE. Trend (1) is by far the dominant trend at the camp scale and interestingly is oriented slightly oblique to the orientation of the D3 fabric and structural architecture of the Asankrangwa Belt.

See Table 2 and Figure 34 for a summary of the Fry analysis results.

**Table 2: Kumasi Basin Fry Analysis Summary**

| Datasets | Gold deposits | Fry translations | Principal structural orientations | Structure desctription |
|---|---|---|---|---|
| **Regional** Entire Kumasi Basin and adjacent belt boundaries | 240 | 57,360 | NE-SW<br>ENE-WSW<br>NW-SE<br>N-S<br>NNE-SSW | Dominant orogen-parallel structural trend<br>Brittle cryptic faults associated with mineralisation<br>Cryptic upward propagated basement structures<br>Major basement lineament with no surface expression<br>Cryptic, possible conjugate set to NE-SW trend |
| **District** All deposits and showings within 65 km of the Asanko Gold Mine | 138 | 18,906 | NE-SW<br>ENE-WSW<br>NW-SE<br>N-S | Dominant orogen-parallel structural trend<br>Brittle cryptic faults associated with mineralisation<br>Cryptic upward propagated basement structures<br>Major basement lineament with no surface expression |
| **Camp** All deposits and showings within 35 km of the Asanko Gold Mine | 39 | 1,482 | NNE-SSW<br>ENE-WSW<br>NW-SE | Camp-scale trend of deposit distribution<br>Brittle cryptic faults associated with mineralisation<br>Cryptic upward propagated basement structures |

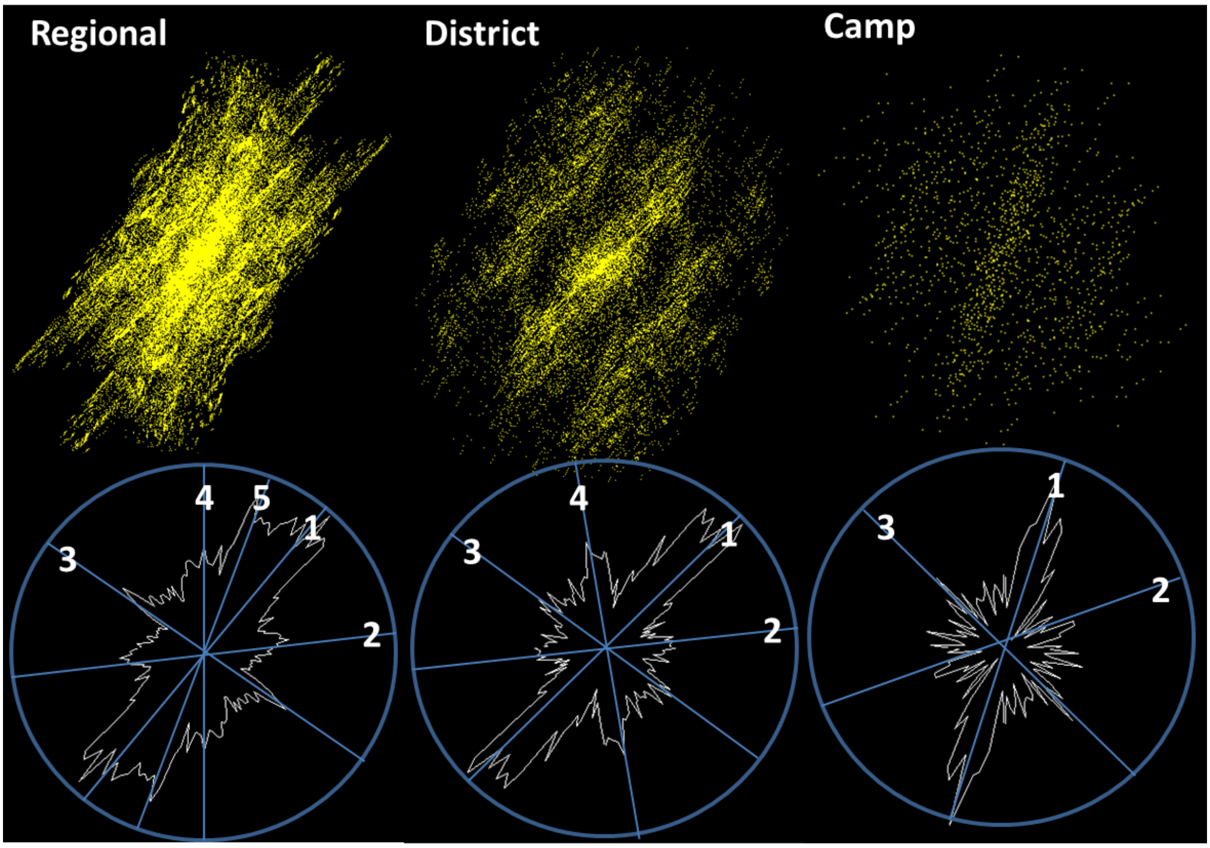


**Figure 34: Fry analysis results showing the Fry plots above and rose diagrams below. Major and minor trends identified at the regional, district, and camp scales are indicated.**

### *5.4.4 Regional and District-Scale Discussion of Fry Analysis Results*

At the regional and district scales, trend (1) corresponds with NE-SW fabric and orientation of major first and second order shear zones introduced during the D3 deformation event. This structural trend is by far the most dominant feature observed in the Kumasi Basin. Structures in this orientation were reactivated during the D4 mineralising event and are fundamental fluid pathways for ore bearing fluids. With every deposit in the Kumasi Basin and adjacent belt boundaries found either on or directly adjacent to one of these structures it is not surprising that they feature so prominently in the Fry analysis. As such, structures in this orientation are interpreted to exert a fundamental control on deposit location in the Asankrangwa Belt. This structural trend shows a much wider range than the other trends observed and this can be attributed to the camp, district and regional variations in the D3 structure orientations throughout the basin. In general, this trend dominates at the regional, district and camp scale and is essential for deposit formation.

Trend (2) is an ENE-WSW orientation and corresponds with brittle third order structures associated with the D4 deformation event in which the stress field shifted to a NNE-SSW orientation. This resulted in the sinistral and reverse-sinistral reactivation of D3 structures and introduction of brittle conjugate structures in the trend (2) orientation. The intersections between these two structural orientations are interpreted to be zones of maximum compression during the D4 event. The brittle third order structures are thought to have formed to release compressive stress in the rock mass leading to the formation of zones of dilation at the intersections. These brittle zones of dilation complete the permeability pathways between the basement structure network and the upper crust providing conduits for the upward migration of the mineralising fluids. As with trend (1), trend (2) are mappable features and are observed in the field in the Kumasi Basin. These features are also clearly identified in high resolution airborne magnetics data. Trend (2) structures are observed in the Fry analysis results at all scales, and feature in all major deposits in the Asanko Gold Mine camp.

Trends (1) and (2) are directly attributable to the Eburnean Orogeny, and are clear examples of critical processes for ore deposit formation being translated into mappable surficial features. Where trend (1) features heavily in the 2009 Ghana Geological Survey Department regional structural interpretation as one would expect, trend (2) features discretely despite being prevalent on surface at the camp scale. The reason for this is likely because trend (2) structures are quite localised and have short strike lengths. If these structures formed to release compressional stress during the D4 sinistral to reverse-sinistral re-activation of the second order structures, they may not link together to form long lineaments or through-going penetrative structures and displacement along them may be quite minor. They are however, clearly identified in the 2D and 3D geophysical interpretations and as mappable features observed in the field, and as will be shown later in this study, play a critical role in deposit formation.

Trend (3) and trend (4) are not are not represented as observable features in the Asankrangwa gold belt. Trend (3) is a NW-SE structural orientation and trend (4) an

N-S structural orientation. Trends (3) and (4) cannot be directly observed on surface, nor can they easily be explained using the existing geodynamic models. These trends are identified as major lineaments in regional gravity data. In addition, what is thought to be upward propagations of the NW-SE trend (3) are identified as cryptic features in the 3D EM inversion models and is covered in subsequent sections. This study attributes these structural trends to cryptic basement features that exert an important control on gold mineralisation by providing optimal permeability pathways through the lithosphere (Hronsky, 2013). Subsequent sections of this study will map these features and demonstrate that this basement architecture is as critical for ore deposit formation as the upper crust structural architecture that ultimately hosts the deposits.

A possible cause of the basement architecture is large-scale extensional features associated with the D2 extension event when the Kumasi Basin opened and sedimentation occurred. Depending on the orientation of the opening of the Kumasi Basin, conjugate structural orientations could possibly be explained through pull-apart basin tectonics to accommodate basin expansion. These structures were then repeatedly reactivated during the D3 and D4 crustal shortening deformation events creating an upward propagating permeability network, ultimately allowing mineralising fluids to migrate into the upper crust during the D4 mineralising event to form deposits where they are found today.

Trend (3) is a structure orientation that is picked up at all scales of the Fry analysis but has cryptic surface expression. This structural orientation is not observed in outcrop or deposits in the Kumasi Basin but features heavily in the 2009 Ghana Survey Department regional interpretations, especially in the vicinity of the Asanko Gold Mine camp. Trend (3) has also been identified at multiple scales in geophysical data and features at the craton to district scale in studies by Jessell, et al., (2016), Carranza, et al., (2009), and Chudasama, et al., (2016).

In the study by Carranza, et al., (2009), NW-SE structures were mapped in the south west Ashanti Belt. Here, the NW-SE structural orientation is fundamental to ore deposit formation and is one of the key targeting criteria identified. Given the relative timing of the emplacement of the Ashanti and Sefwi greenstone belts with respect to the basin sedimentation, it is conceivable that the basin opening event also affected these belts which were fully formed at this time. The same NW-SE extensional features affecting the Kumasi basement conceivably could have been recorded as mappable features in the adjacent greenstone belts which recorded some effects of the extensional stress fields. These features then could easily have also been reactivated during the mineralising event and hence play a fundamental role in deposit location in both the Ashanti belt and Kumasi Basin. Although outside of the scope of this study, it would be of interest to determine the kinematics along these structures recorded in the SW Ashanti belt. If they were found to be in a dextral to reverse-dextral orientation they would fit very well into the D2 extensional event as proposed in this study.

The NW-SE structural orientations are also observed in the cratonic scale study by Jessell, et.al., (2016). This paper examines existing and newly compiled geophysical representations of the West African Craton in terms of its large-scale tectonic architecture (Jessell, et al., 2016). In this study, NW-SE features in SW Ghana are clearly observed at the cratonic scale but do not fit into any of the other regional deformation events that are identified. These features are identified as potentially significant in this study and are referred to as undifferentiated structures from unknown geodynamic events and are shown in Figure 35.

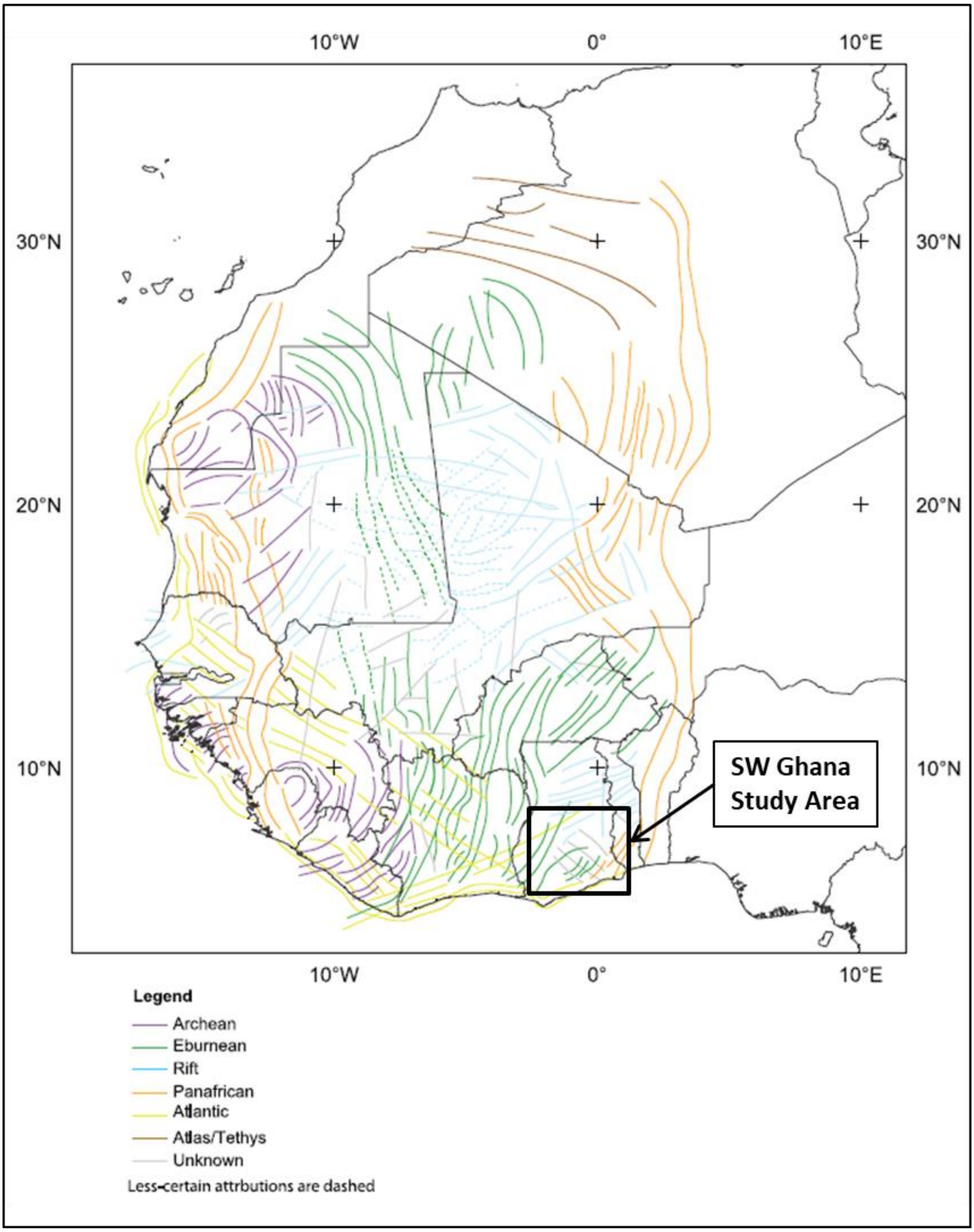


**Figure 35: West Africa cratonic to regional scale structures attributed to each major deformation event. Modified from Jessell, et al., (2016).**

In the district scale study by Chudasama, et al., (2016), the NW-SE structural orientation is also listed as undefined and shown in Figure 36. This study does not go into detail about the genesis of these structures but identifies them as cryptic lineaments from regional geophysical data sets. At the time of the Chudasama, et al., (2016) study, this structural orientation has not been identified as fundamental, nor had it been mapped using 3D inversion technology so was not included as targeting criteria in the resulting prospectivity analysis.

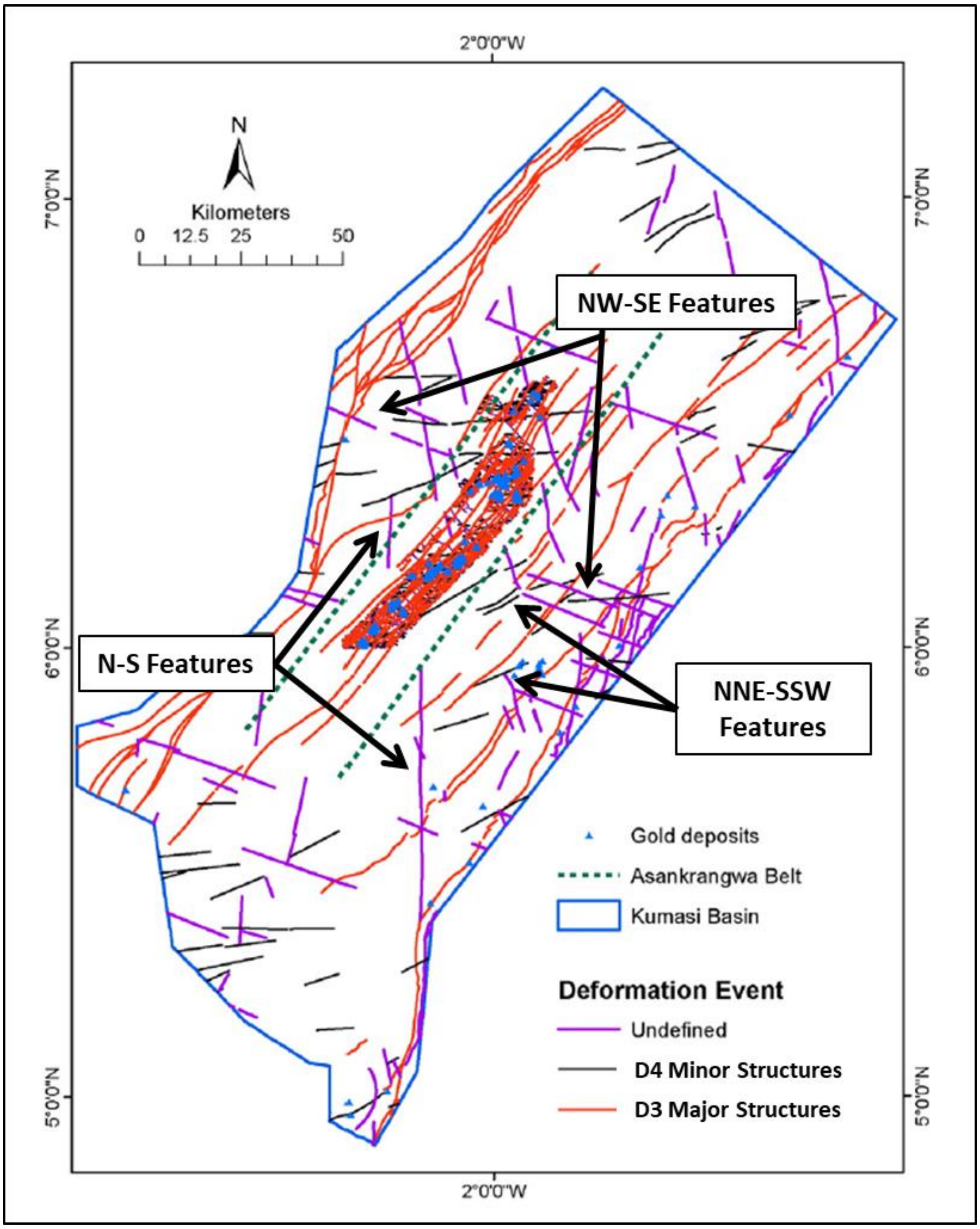


**Figure 36: Interpreted structures of the Kumasi Basin and the Asankrangwa Belt study area. Modified from Chudasama, et al., (2016).**

Trend (4) is in a N-S orientation and is perhaps the most cryptic of all structural trends observed in the Kumasi Basin Fry analysis. Trend (4) does not correspond with any mappable features and is not observed in the 2D interpretations or 3D inversion models of the VTEM and magnetics geophysical data. Trend (4) lineaments are occasionally observed in the 2009 Ghana Geological Survey Department regional interpretation near the centre of the Kumasi Basin. The difficulty in detecting N-S structures in the upper crust may be because steeply dipping N-S anomalies collected near the earth's magnetic equator are notoriously difficult to interpret, explaining why upward propagations of these features are not visible in the models used in this study (Beard, et al., 2000). Further evidence that there is an important N-S basement structural control is the presence of late N-S dolerite dykes that occur in the same orientation as the regional N-S lineament with a strike of several hundred kilometres. This mantle derived magmatism post-dates mineralisation but is evidence that there exists a fundamental structure channelling mantle derived fluids and melts into the upper crust (Hronsky, 2013).

Trend 4 is more extensively covered in Section 7 where it is observed as a N-S gravity break through the Kumasi Basin. Clearly mapped in proprietary gravity data sets, it is also discernible using publicly available regional gravity data.

### *5.4.5 Discussion of Camp-Scale Fry Analysis Results*

The camp scale Fry analysis results show three main trends of mineralisation, the results of which are shown in Figure 33 above. The NNE-SSW trend (1) is the most dominant orientation by far at the camp scale. This trend differs from trend (1) in the regional and district scale Fry analysis and appears to suggest that there are different structural controls affecting the spatial distribution of gold deposits operating at the camp scale. A fundamental tenet of the mineral systems concept is that ore deposits are small expressions of much more extensive systems and structural controls on deposit location are scale dependant. The key is to make these observations in the conceptual targeting phase and turn them into robust multi-scale targeting criteria.

At the scale of the Asankrangwa Belt, the NE-SW D3 structures also collectively form a jog to the north in the region of the camp scale study. This camp scale flexure likely has implications for dilation and permeability during D4 reactivation. It is possible that this flexure to the north is directly influenced by the interaction of a crustal basement N-S structure that is identified in regional gravity data and this will be covered in the geophysics interpretation.

The NNE-SSW trend (2) features at all scales and are directly associated with every major deposit. These structures are interpreted as brittle compressive stress relief features formed during the D4 sinistral to reverse-sinistral reactivation of the second order structures in the Kumasi Basin. Trend (2) structures do not link together to form long lineaments or through-going penetrative structures so are not as prominent in regional structural interpretations. They are however clearly identified in the 2D and 3D geophysical interpretations at the camp scale and as mappable features in the field.

NW-SE Trend (3) observed at the regional and district scale is also observed at the camp scale. Structures in the trend (3) orientation do not show up as mappable features at the camp scale. As discussed above, trend (3) represents a cryptic basement structure orientation that cannot be easily explained using current geodynamic models. This study suggests that regional trend (3) features could have formed during the basin opening D2 event, to compensate for extension in the basin. During the D3 and D4 compression events these structures would have been repeatedly reactivated.

At the camp scale deep structures in this orientation have been identified using 3D inversion modelling of VTEM and magnetic data. These features are interpreted to be caused by countless reactivations of the basement structure architectures creating a network of upward propagating basement structures within the overlying basin sedimentary rock mass. This network of structures, roughly in the same orientation as the basement structures creating them is fundamental to connect the permeability network needed to facilitate the upward mobilisation of mineralising fluids into the upper crust. 3D inversion modelling of these features has shown that they are associated with every deposit in the Asankrangwa Belt and are fundamental to mineralisation. These features will be examined in the following section and form the basis for the targeting criteria developed in this study.

## 5.5 Conclusions of Spatial Distribution Analysis

The structural controls dictating the spatial distribution of gold deposits in the Kumasi Basin are scale dependent, and vary from the regional to camp scale. This is consistent with the mineral systems concept, which states that ore deposits are small manifestations of much larger mass flux systems and that structural controls on mineral deposit location operate on much bigger scales than the deposits and camps themselves. Therefore, understanding and mapping the underlying structural controls on mineralisation at all scales is critical to the creation of predictive models for exploration and discovery. The mineral systems concept also tells us that ore deposit formation is the result of a combination of factors and if any one factor is not present, a major ore deposit will not be able to form. This study would suggest that ore deposits in the Asanko Gold Mine camp require a very specific structural architecture to form and if one element of this structural architecture is not present a major deposit will not form. The geodynamic history of the Kumasi Basin tells us which geological processes are related to ore forming events, and these are related to the structural architecture and mapped. The Fry analysis is a methodology by which the geological processes associated with ore formation can be linked to mappable features.

In the case of the Kumasi Basin study area, the Fry analysis detected four distinct structural trends at the regional to district scale and three distinct trends at the camp scale. Trend (1) and (2) at the regional/district scale clearly correspond to mappable features that are both observed in the field and in shallow airborne geophysical datasets. In the case of the Asankrangwa Belt these are second and third order structures emplaced during the Eburnean orogeny D3 and D4 deformation events. These are mappable manifestations of geological processes known to be critical for ore formation. The trend (1) orientation relates to deep seated second order D3 structures reactivated during the D4 mineralising event. These structures provide the connection to the basement structural architecture which allows the gold bearing fluids to migrate into the upper crust. The trend (1) D3 second order structures are the host of all deposits found in the Asanko Gold Mine camp and are critical for ore deposit formation.

Trend (2) D4 structures are very localised and short in strike length, typically up to a couple hundred metres. These structures are thought to be formed during the D4 deformation event and result from the release of compressive stress during the sinistral and reverse-sinistral re-activation of the second order structures, forming a lattice work of minor D4 structures in between the laterally extensive D3 Asankrangwa Belt structural corridor. This release of compressive stress causes zones of brittle deformation and dilation, and is critical for the formation of large gold deposits. Due to their relative lack of continuity along the strike of these structures, they do not feature as prominently in the regional structural interpretation as the other structural trends do, but they are observable in surface mapping and shallow geophysical datasets. These structures feature in all of the known deposits in the Asanko Gold Mine camp and are fundamental criteria for ore deposit formation.

The Fry analysis picked up two trends that do not correspond to the geodynamic history of the Kumasi Basin, suggesting that there is an underlying structural architecture to the Kumasi Basin that is controlling ore deposit location. This study suggests that during the extensional D2 event, in which the Kumasi Basin opened and sedimentation occurred, basement structure architecture formed. As the Eburnean Orogeny progressed through the D3 crustal shortening and D4 mineralising events, these basement structures were repeatedly reactivated causing an upward propagating permeability network to form in the overlying basin sedimentary package, in roughly the same orientation as the basement structures themselves. This thesis suggests that the presence of these upward propagating structures exerts a direct and fundamental control on ore deposit formation in the Asanko Gold Mine camp. Mapping the location of these upward propagating basement structures is critical for the generation of effective targeting models in order to increase accuracy and efficiency of exploration programs. Without knowledge of the basement architecture, using only mappable second and third order structures to guide exploration programs will lead to the generation of many false positive targets, and decrease the efficiency of resulting exploration programs.

Identification of these common structural trends fundamental to mineralisation allows the development of exploration criteria on which this study is based. Where the criteria might differ slightly from camp to camp within the study area, there are certain factors in each camp which must be present for exploration success in that area. Section 7 will focus on the identification of that set of criteria critical to ore formation in the Asankrangwa Belt to form using geophysical data. The structural trends identified in the Fry analysis will be mapped using regional gravity, 2D VTEM and magnetics interpretations, and 3D inversion models of VTEM and magnetics data. Interpreting the results of these surveys will allow specific features corresponding to the trends observed in the Fry analysis to be mapped, and structural targeting criteria to be devised. The ultimate aim of this is by understanding the critical structural signature necessary for ore deposit formation, many false positives can be eliminated from any prospectivity and targeting exercise.

The result of this is that exploration programs can be much more targeted which has implications on hit rate and exploration efficiency. In areas with difficult regolith this methodology is especially applicable, as it allows the targeting of blind prospects by defining a clear set of criteria necessary for exploration success.

# 6 GEOPHYSICAL DATA

Geophysical surveys are fundamental for targeting of ore deposits. The ability to peer below the subsurface allows critical geological features to be mapped in detail. The real power of geophysics however, is when it is used to complement geological knowledge to produce holistic models which can be applied to increase exploration success and prevent wasting resources in exploration programs.

This section uses proprietary Asanko Gold Inc. airborne helicopter electromagnetic and magnetic (HEM), versatile time-domain electromagnetic (VTEM) and magnetic datasets, as well as publicly available regional Bouguer gravity data sets collected by the International Gravimetric Bureau (http://bgi.omp.obs-mip.fr/) to identify and map structural controls within the Kumasi Basin at a range of scales. 2D and 3D modelling of the airborne geophysical data was conducted prior to this study for Asanko Gold Inc. by Geomagik Pty Ltd. of Perth, Australia, Fathom Geophysics Pty Ltd. of Perth, Australia, and Spectrem Air Pty Ltd. of Johannesburg, South Africa.

In exploration for all deposit types, geophysics is critical for mapping structural and geological features that control and host mineralisation. This is especially true for orogenic gold deposits in areas such as Ghana, where the deep weathering profile make surficial structure and geology detection challenging. In this section geophysical interpretation was used to map the structural architecture of the Kumasi Basin at the regional and camp-scale. Structures relating to critical geological events in the geodynamic history and Fry analysis were identified and mapped at all scales.

## 6.1 Interpretation of Regional Gravity

Large integrated data sets are required to make regional scale observations. Crustal-scale structures have been shown to exert fundamental controls on mineralisation across all scales. These cryptic structures often have little or no surface expression and can be very difficult to identify at all scales, and this is true in the case of the Kumasi Basin. These cryptic features can often be related to an underlying basement structure architecture that is critical for the transport of mineralising fluids upward in the earth’s crust from their source region. Their interaction with the overlying near surface structural architecture completes the permeability network necessary for the formation of gold deposits where we find them today (Hronsky, 2013). As such, mapping and understanding the basement structural architecture is critical for the generation of predictive exploration models on the regional or district scales.

Regional data sets are time consuming and expensive to collect. As such they are often carefully guarded as proprietary information. In some areas such as Australia and Canada, regional datasets are collected by government organisations and provided for free or for nominal fee in order to drive investment. Regional datasets can provide a significant advantage in emerging districts and provide significant information regarding regional structural architecture. This can form the basis for the creation of regional scale models and allow first mover decisions to be made, or critical decision regarding land acquisition and consolidation. Due to the enormous cost involved with their collection, junior companies rarely collect regional geophysical data themselves, but rather relay on open source data sets as was done in this study. Regional airborne data sets for the study area in Ghana were not available for this study but regional ground gravity data was.

Regional gravity data used in this study was collected by the International Gravimetric Bureau based in Figure 37 shows the isostatic and free air gravity anomalies over the entire country of Ghana.

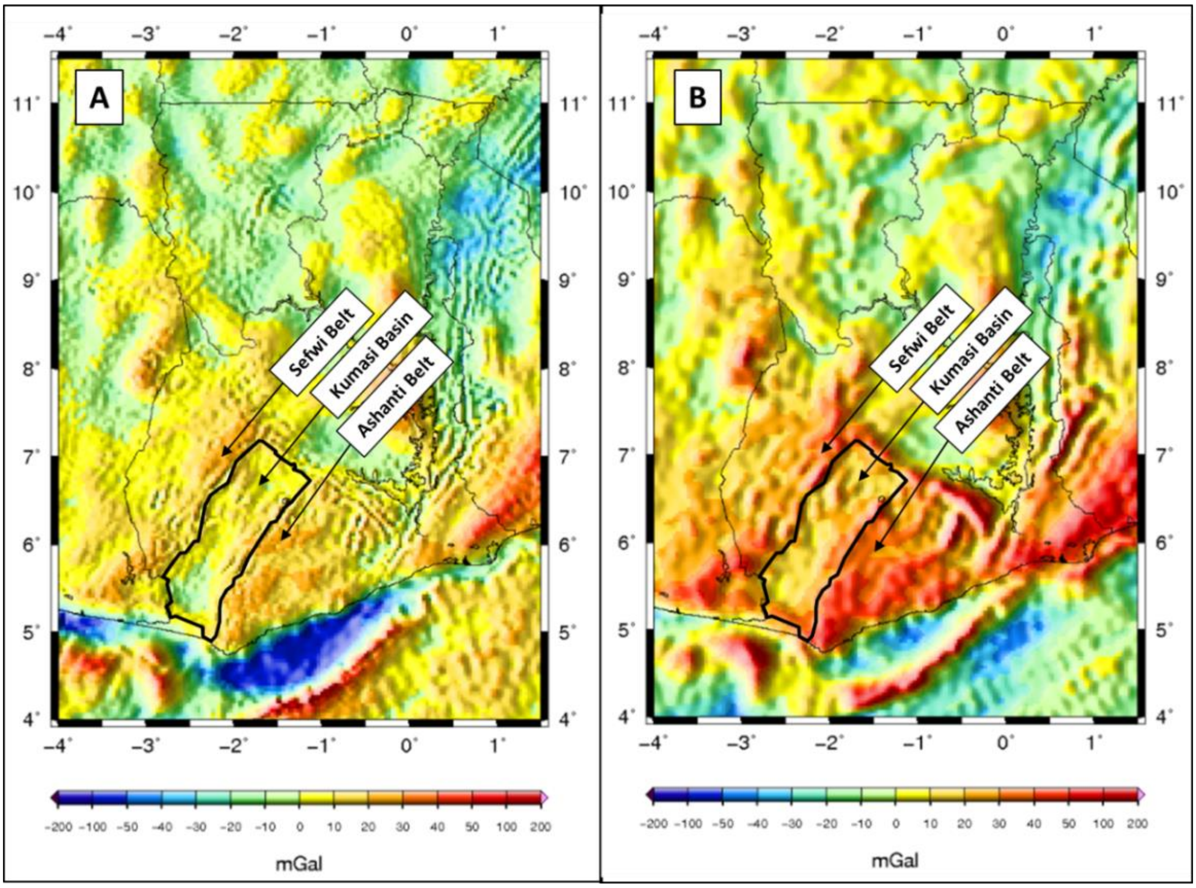


**Figure 37: Ghana regional gravimetric signatures shown as (A) isostatic gravity and (B) free air gravity. Modified from the International Gravimetric Bureau, (2017).**

Detailed regional gravity surveys have been very successfully used in Ghana. Gravity data in general can be very effective at mapping major fundamental structures because of its ability to penetrate deep into the earth's crust. In Ghana, regional gravity is very effective at mapping the first order structures along the margins of the volcanic belts which separate the volcanic belts from the adjacent sedimentary basins. This structural architecture is fundamental to gold mineralisation along the belt boundaries and so mapping these structures in detail can be an extremely effective regional targeting criterion. First order belt bounding structures are particularly prominent in the gravity data because of the density contrast between the volcanic rocks of the belts and the sedimentary rocks of the basins. Within the Kumasi Basins itself this contrast in density does not exist between sedimentary geological units that are mapped on surface. Even the contrast between the late granite intrusions and basin sediments is not readily observable in the regional data. Despite this lack of contrast between surficial geological units, lineaments are still observed within the Kumasi Basin in the low resolution regional gravity data.

Regional basement structures often manifest as linear features, or discontinuities in geophysical data. Looking at the regional scale of south-west Ghana a major break in the gravity signature is observed running N-S through the Kumasi Basin. This lineament is oblique to the dominant NE-SW volcanic belt orientation and trend of first and second order structural architecture associated with the D3 deformation event during the Eburnean Orogeny. A second lineament can also be observed at this scale running NW-SE. Both of these structural lineaments are shown in Figure 38.

Lineaments (1) and (2) in Figure 38 correspond with trends (3) and (4) observed in the Fry analysis in Figure 31 of this report. Trend (1) and trend (2) are not are not represented as mappable surficial features in the Asankrangwa gold belt. Trend (1) is a NW-SE structural orientation and trend (2) is a N-S structural orientation. Trend (1) is a NW-SE structural orientation and trend (2) is a N-S structural orientation and neither can be directly observed on surface or in shallow geophysical interpretations, nor can they easily be explained using the existing geodynamic models. This study suggests that these structural trends correspond to cryptic basement features that exert an important regional to camp scale control on gold mineralisation.

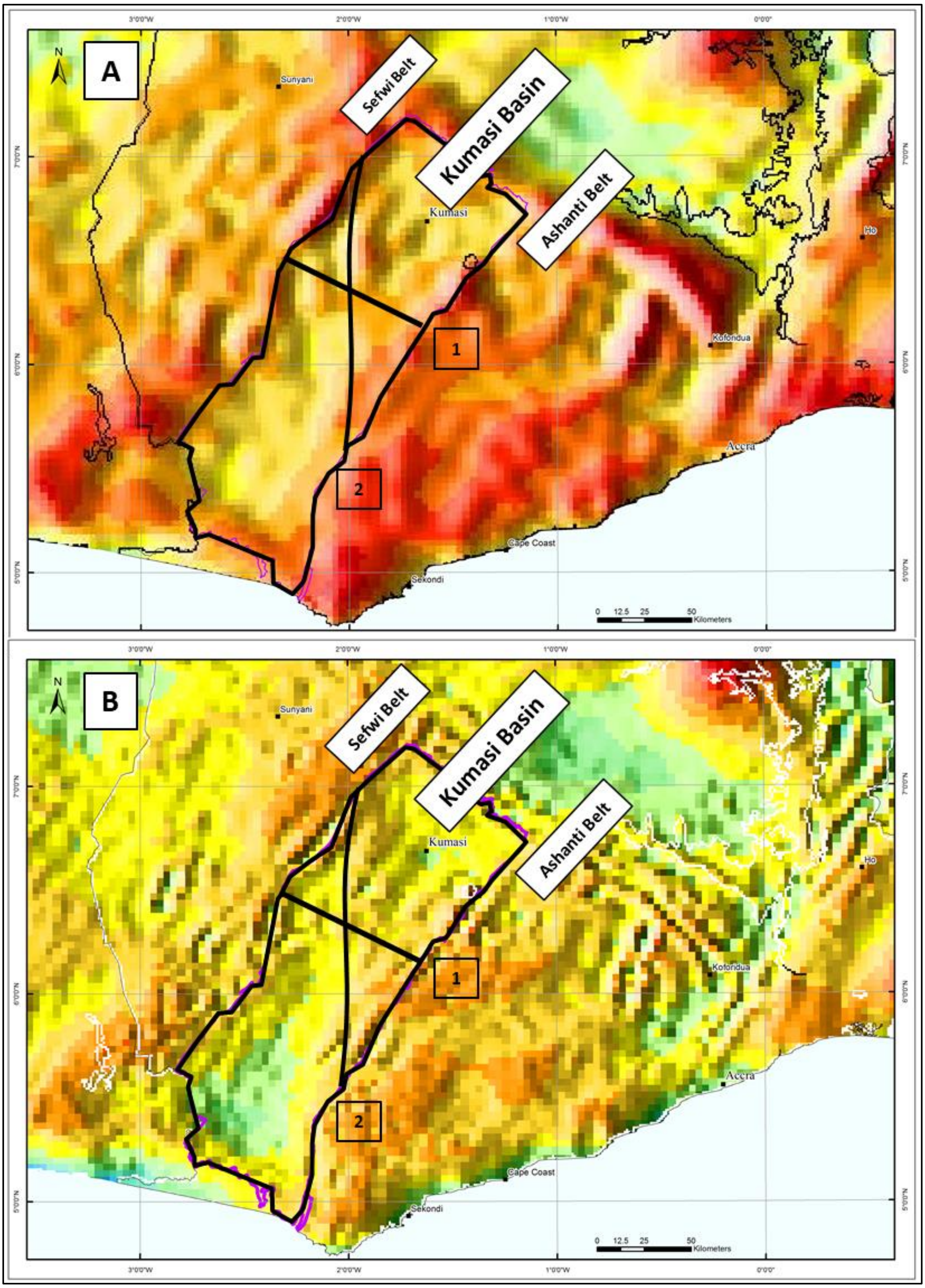


**Figure 38: Regional gravity data displayed as (A) Free air and (B) Isostatic gravity signatures. Both datasets show major structural lineaments observed in the Kumasi Basin in the (1) N-S and (2) NW-SE structural orientations. Modified from the International Gravimetric Bureau. (2017)**

A possible cause of the basement architecture is large-scale extensional features associated with the basin-forming D2 extension event when the Kumasi Basin opened and sedimentation occurred. Depending on the kinematics of the D2 extension event, conjugate structural orientations could possibly be explained through pull-apart basin tectonics to accommodate basin expansion. These structures provide a fundamental connection to the gold bearing fluid source which is critical for cold camp formation in the Kumasi Basin. During the D3 and D4 crustal shortening deformation events these structures were repeatedly reactivated creating an upward propagating permeability network allowing mineralising fluids to migrate upward in the crust during the D4 mineralising event to form deposits where they are found today.

Figure 39 shows the N-S and NW-SE gravity lineaments superimposed on the 2009 Ghana Geological Survey Department regional structure interpretation (Agyei Duodu, et al., 2009). Kumasi Basin gold deposit and prospects locations are overlain and shown as red circles with the Asanko Gold Mine camp deposits show as blue circles. Interestingly, the N-S lineament is poorly represented in the regional interpretation but the NW-SE orientation however, is represented and features strongly around the lineation identified in the regional gravity data.

The N-S lineament appears to exhibit a direct control over gold camp location within the Kumasi Basin. This lineament connects the northern portion of the Prestea-Bogoso camp on the NW boundary of the Ashanti volcanic belt, the Edikan camp, and the Asanko Gold Mine camp before continuing north until it reaches the SE boundary of the Sefwi volcanic belt. The Edikan and Asanko Gold Mine camps display very similar structural characteristics. As well as lining up along the N-S regional lineament, both camps occur at the intersection with major NE-SW second order shear corridors. In the case of the Edikan camp this is the Akropong shear corridor and in the case of the Asanko Gold Mine camp this is the Asankrangwa shear zone corridor. In both camps, the intersection between the N-S basement gravity lineament and the NE-SW shear corridors appear to be exerting a direct control over gold camp location.

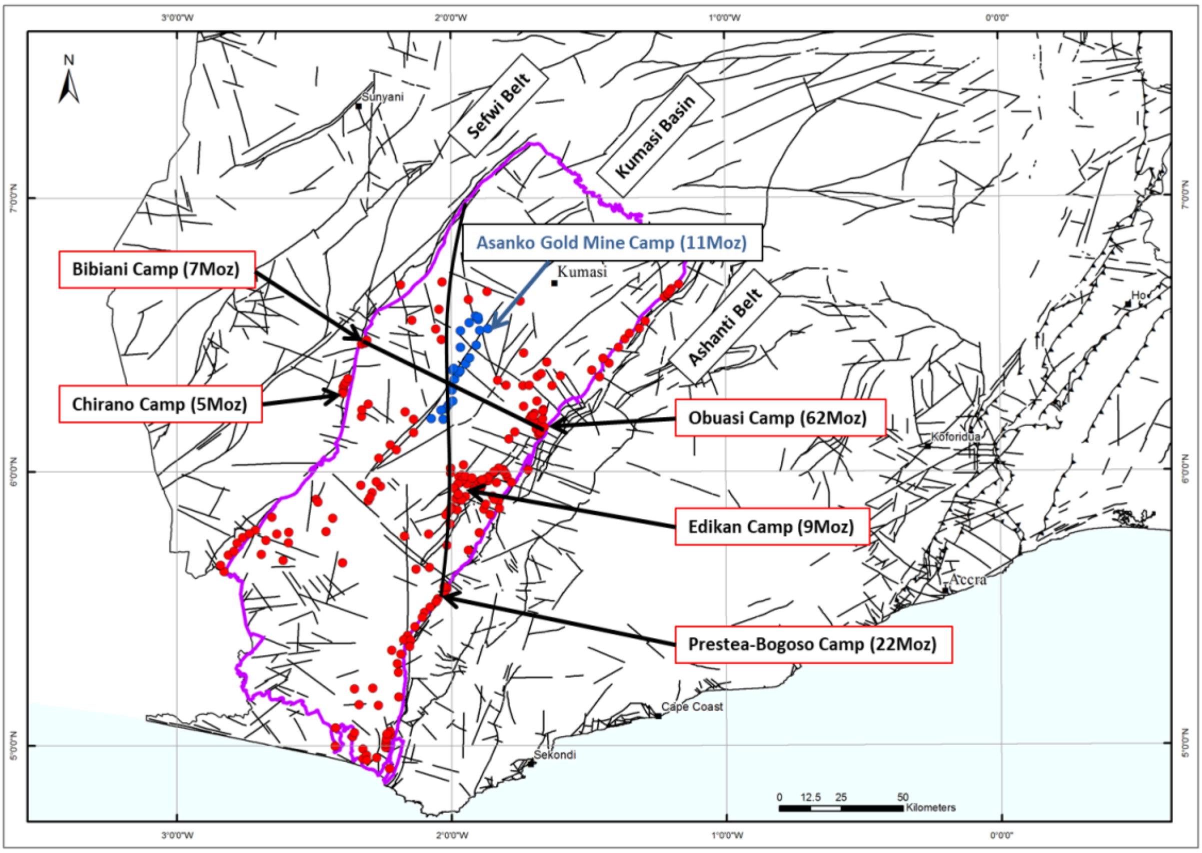


**Figure 39: Gravity lineaments with Ghana regional structure interpretation and Ghana gold deposits and prospect locations. Deposits of the Asanko Gold Mine camp are shown in blue. Modified from Agyei Duodu, et al., (2009).**

The NW-SE lineament observed in the gravity data also appears to be significant. Not only is the Asanko Gold Mine camp located directly at the intersection between these two lineaments, the Obuasi camp is located at the intersection with the Akropong shear corridor near the NW boundary of the Ashanti volcanic belt. At the other end of this lineament, where it intersects with the Bibiani-Chirano Shear Zone marking the SE boundary of the Sefwi volcanic belt is located the Bibiani camp. Not insignificantly, these two lineaments appear to be exerting a direct or indirect regional control over five (5) major gold camps in SW Ghana with endowment in excess of 110 Moz.

The targeting implications of these observations at the regional scale appears to be that in order for a gold camp to form there needs to be the combination of a basement lineament and a major first or second order shear corridor. The basement lineaments are likely to be conduits for the gold bearing fluids from the source region. Where these basement features interact with the deeply penetrating first and second order shear corridors is where the permeability networks to the upper crust are connected allowing transport into the isoclinally-folded and sheared basin sedimentary rock package which is the trap and host of the gold deposits.

## 6.2 2D Airborne Electromagnetic and Magnetic Survey Interpretation

Several airborne electromagnetic (EM) and magnetic surveys have been conducted over the Asankrangwa Belt and Asanko Gold Mine camp between 2004 and 2015 and provide continuous coverage over the Asanko Gold Mine camp. Figure 40 shows the coverage areas of the various EM and magnetic surveys through time.

In the deeply weathered and highly vegetated terrane of SW Ghana, airborne geophysical surveys are highly effective tools for mapping hidden geology and structure. In the Asankrangwa Belt outcrop is rare with the exception of late Eburnean granitoid intrusions that post-date the mineralising events. As such, airborne geophysical surveys are essential for mapping surficial geological units and structural architecture. Airborne EM and magnetic geophysical data interpretation are particularly effective in mapping geology and structure signatures in deeply weathered terranes.

### *6.2.1 2D EM and Magnetic Geophysics Interpretation Methodology*

2D airborne EM and magnetic interpretations were developed in close collaboration with the author of this study as well as the entire Asanko Gold geological team resulting in comprehensive, geologically-driven 2D geology and structure interpretations of the Asankrangwa Belt. The results presented here are a holistic synthesis of geophysical data interpretations that have been rigorously ground-checked by the Asanko exploration geology team. This interpretation is continually interrogated and adjusted based on observations made during ground-based exploration field activities.

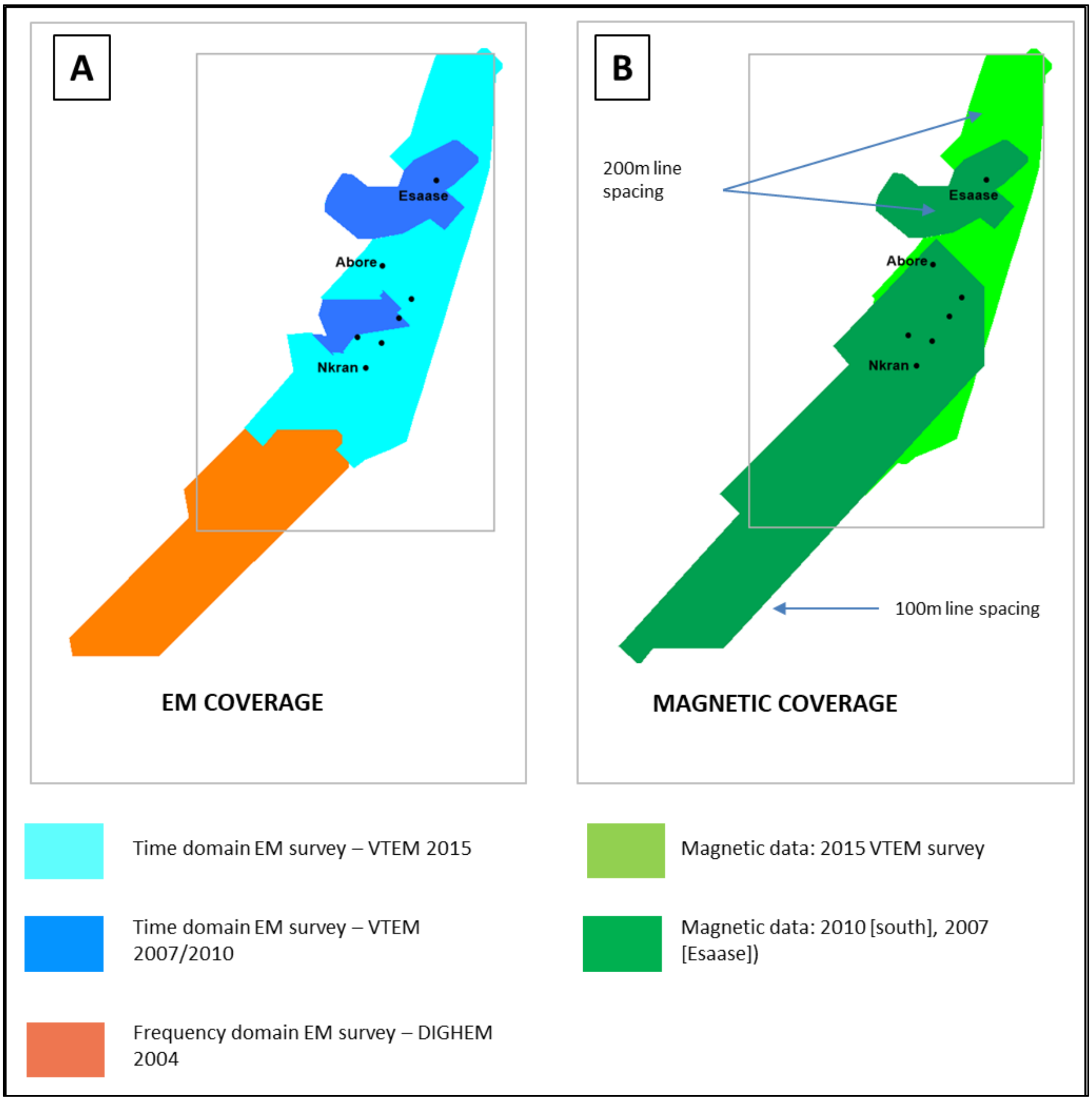


**Figure 40: Asankrangwa Belt airborne geophysics coverage maps showing (A) Electromagnetic survey coverage and (B) Magnetic survey coverage areas**

Until relatively recently, airborne magnetic surveying was not favoured as a tool for determining intra-sedimentary structures. Developments in instrumentation, navigation and processing now enable resolution of the very low level magnetic contrasts occurring within the sedimentary sequences.

In the Kumasi Basin, the Eburnean D3 crustal shortening deformation event has resulted in crustal thickening through stacking of the sedimentary units, isoclinal folding, and shearing of the of the basin sediments during basin inversion. Except for small wedges of volcanic rock along the Akropong shear corridor, host to the Edikan and Obuasi camps, all shear zones within the Kumasi Basin juxtapose sedimentary rocks against each other making magnetic signatures very subtle. Although these structural corridors are intruded by dykes and plugs of granitoids, these bodies are generally too discrete to identify from the airborne geophysical data. Magnetic signatures are important for identifying major second order shear zones, minor third order shear zones, and the late stage cross cutting dolerite dykes. EM signatures are very effective at distinguishing between geological units, as well as identifying major structures which typically separate geological units.

Faults and geological contacts manifest in geophysical data either as linear offsets of anomalies, or in the majority of instances by virtue of the fact that they generate their own linear anomalies. In theory, the anomaly pattern from a fault is characteristic of the sense of displacement, with a distinct aeromagnetic ridge formed on the up-thrown side of the fault and a trough on the downthrown side. Structural architecture and geological units are mapped in this manner and then proven through field observations.

Geological contacts, such as shear zones, unconformities and conformable bedding surfaces generate linear anomalies where they mark the boundary between rock units of different susceptibilities. In the sedimentary sequences of the Asankrangwa Belt, different geological units are distinguished by the magnetic character of the juxtaposing rock units. This is the primary way that units are mapped with geophysics in the Asankrangwa gold belt. Field check observations have shown that in general the more conductive units are typically comprised of greater amounts of siltstone, shale and phyllite and generally display an increased amount of strain and deformation. Locally within shear zones there are slightly increases in graphite content as well. More resistive units generally are more dominated by massive wacke and sandstone sequences and are much less deformed, often displaying graded bedding.

### *6.2.2 Interpretation of 2D EM and Magnetic Geophysical Models*

Major D3 second order structures are generally located along geological contacts between geological units, likely where competency contrast has led to deformation and shearing along the margins of more competent units during compression. Third order structures are interpreted to be brittle failures due to the D4 NNE-SSW mineralising deformation event. This event reactivated the D3 major second order structures in a sinistral to reverse-sinistral orientation. It is interpreted the third order structural architecture formed as a conjugate set to the major second order shears as a way to alleviate compressive stress in the rock mass. The intersections of second and third order structures are interpreted to be critical for ore deposit formation as they represent zones of maximum compression, and upon failure zones of maximum dilation creating traps for mineralisation.

Figure 41 shows the 2D Asankrangwa gold belt surficial structural interpretation overlain on top of the EM and mag images from which they are derived. The structural interpretations integrate signatures from the EM data shown in yellow, and magnetics data shown in green. Third order structures are mapped primarily using the higher resolution 2010 DIGHEM data in the southern and central portions of the study area (see Figure 40 for 2010 DIGHEM coverage area). This data was flown at 100 m line spacing as opposed to 200 m line spacing in the other surveys. Third order structures are generally in an ENE-WSW orientation and are shown in pink.

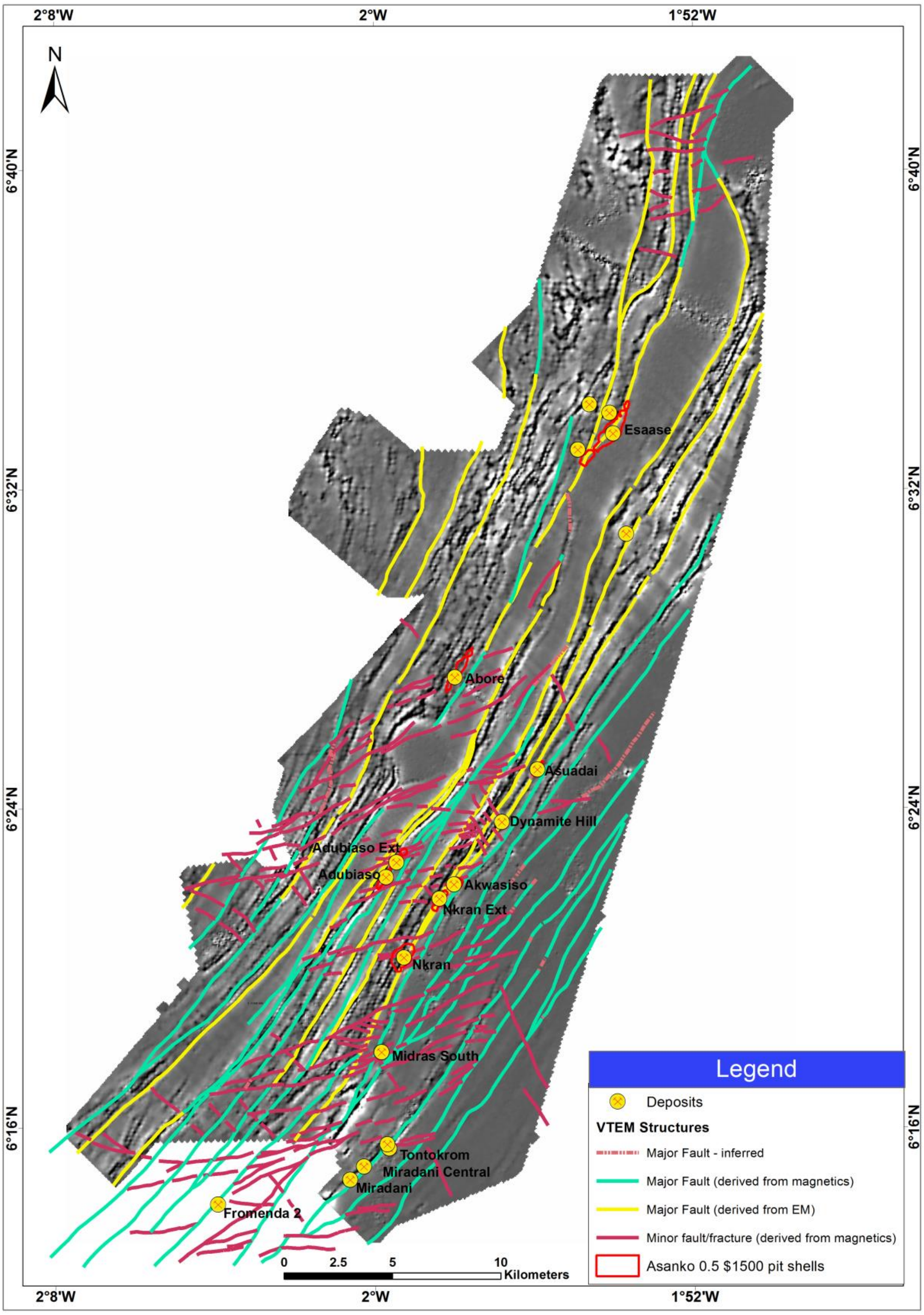


**Figure 41: 2D structural interpretation of the Asankrangwa shear corridor. Major second order D3 structures derived from EM and Mag data are shown in yellow and green. Minor third order structures derived from detailed Mag data are shown in pink. Background image is a mid-time first derivative of the EM data. Asanko Gold Mine Camp deposits are shown as yellow dots**

All of the features shown in this geophysical interpretation are mappable on surface and are fully field checked using mapping, trenching, and drilling field observations.

From this interpretation, second order D3 major shear corridors of the Asankrangwa Belt appear to exert a direct control over deposit location. All deposits of economic size found to date are located along one of five (5) parallel major NE-SW shear structures which make up the Asankrangwa Belt. Where the high resolution DIGHEM data has allowed the mapping of the third order D4 structures, it is also observed that there is a strong association between intersections of second and third order structures with deposit location. In the northern portion of the study area, around the Esaase cluster of deposits, there is no DIGIHEM coverage and the third order structural architecture has not been mapped. The second and third order structural orientations mapped in the 2D geophysical interpretation are directly relatable to critical geological processes identified in the geodynamic history of the study area and correspond to trends observed in the Fry analysis. Understanding the relationship between deposit location and the D3 and D4 structural architecture is critical to exploration success, but experience has shown that it does not tell us the full story when it comes to targeting gold deposits in the Asankrangwa Belt. There are other features exerting control over deposit location that do not manifest as mappable features on surface. These trends are observed in the Fry analysis and attributed to the regional basement structure architecture identified in the regional gravity data. At the camp scale, 3D inversion models of the airborne EM data were created to further explain the structural controls on mineralisation.

## 6.3 3D Inversions of Electromagnetic Data

This study has identified that there is another structural trend exerting control over deposit location at the camp scale. This is a NW-SE trend that is identified in the Fry analysis at all scales. This trend is not identified in the 2D structural interpretation and is not observed in the field, but it has been identified as a regional scale lineament in the regional gravity interpretation.

In 2017 Asanko commissioned Spectrem Air Pty Ltd. of Johannesburg, South Africa to conduct 3D inversion interpretations on the airborne EM geophysical data. As well as corroborating the results of the 2D structure modelling, the 3D modelling of the airborne EM data identified a structural trend that had not been identified in the 2D modelling of the same data or in field observations. This structural trend is in a NW-SE orientation and corresponds with trend (3) from the Fry analysis at all scales as well as trend (1) in the regional gravity data. This study draws a link between the NW-SE trend in the regional gravity interpretation and the same trend that is observed in the camp scale 3D inversion modelling. It is presented here that the NW-SE trend identified using the 3D inversion modelling represents an upward propagating basement structure fabric. Through modelling the upward propagating basement structures, there appears to be a link between these structures and deposit location in the belt. Identification and mapping this trend was critical for the development of the targeting criteria in this study because without it many false positives would be introduced into any resulting prospectivity and targeting study.

### *6.3.1 3D EM Inversion Modelling Methodology*

Using 3D inversion models of EM data to model and target massive sulphide deposits has been used extensively and with great success. Because of the huge variation between conductivity signatures of massive sulphide deposits and their host rocks, 3D inversion models successfully identify deposits with little or no surface expression. However, 3D inversions of EM data have not been extensively applied to structure modelling in orogenic gold belts, and there are few available publications or case studies (Khoza, 2017).

It should be reiterated that the generation of the 3D inversion models was not completed as part of this study and does not form any part of the content of this study. The aim of this section is to map structures which relate to to geological processes that are critical for ore deposit formation.

The motivation behind doing 3D inversion modelling is illustrated in Figure 42. The true model, shown in the first panel, is the model that the inversion process aims to recover. A 1D conductivity model is shown in the middle panel and a 3D inversion model is shown in the right panel. This clearly illustrates the advantage of 3D inversion model in areas of complex geology.

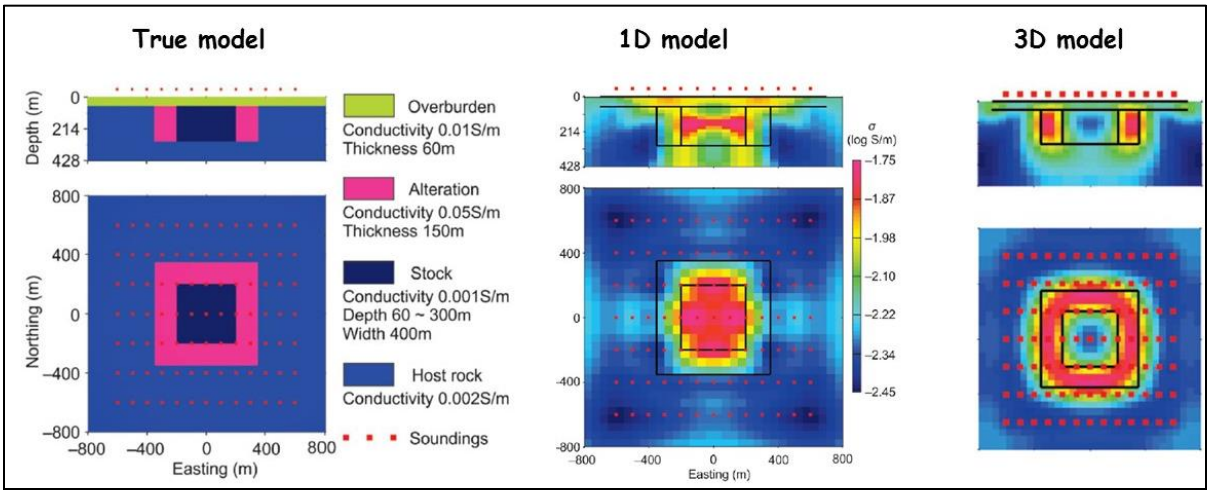


**Figure 42: The motivation behind doing 3D inversion modelling. The true model, shown in the first panel, is the model that the inversion process aims to recover. A 1D conductivity model is shown in the middle panel and a 3D inversion model is shown in the right panel, illustrating the advantage of 3D inversion model in areas of complex geology. From Khoza, (2017)**

The best representation of 3D inversion results is in the form a 3D voxel, (or cube) as shown in Figure 43. From the 3D perspective views, one immediately gets a sense of conductivity distribution and variation along strike and at depth. This is particularly informative when geological trends and structure are sought from the data. It is also possible to extract sections across any angle of the voxel to investigate geological variations.

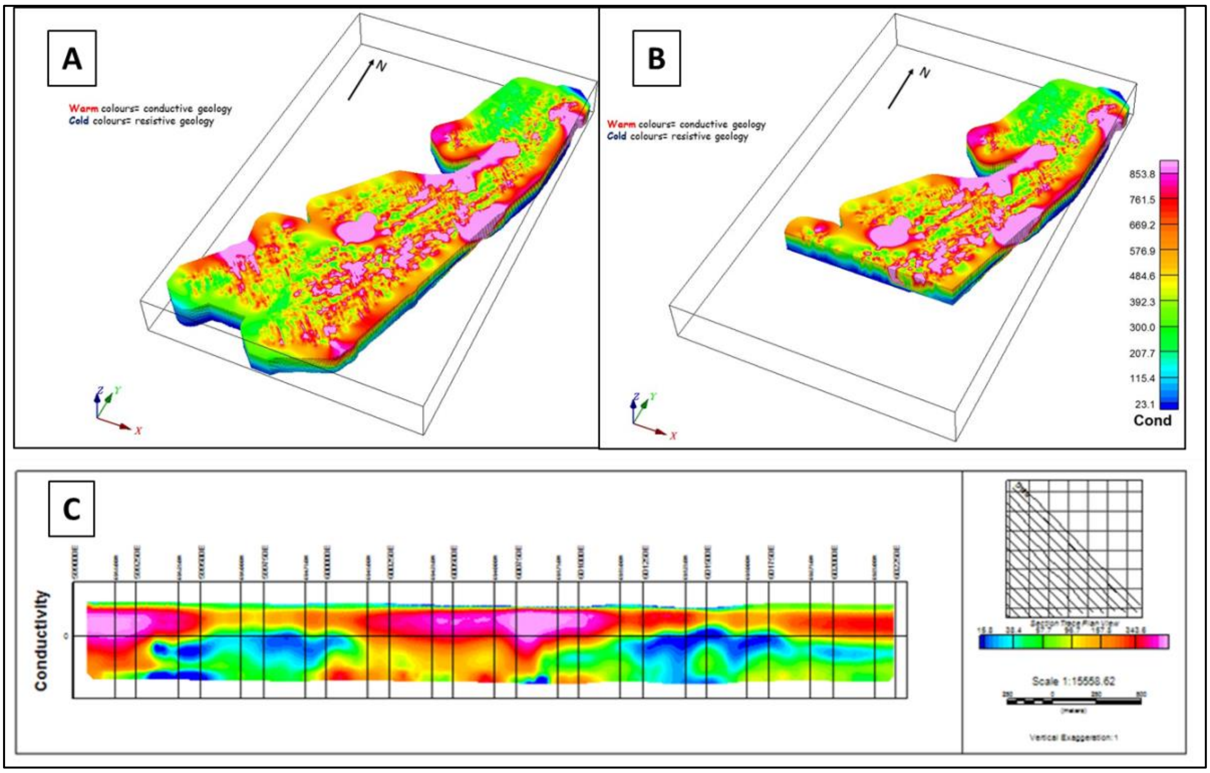


**Figure 43: 3D inversion modelling results showing (A) 3D inversion model derived from VTEM data, (B) A clipped section across the 3D inversion model, and (C) Conductivity depth section extracted from the 3D inversion section. Modified from Khoza, (2017)**

Structural interpretation using 3D inversion models involves tracing breaks in the geology, much the same as in the 2D structure interpretation in plan view. In the Asankrangwa gold belt these breaks correspond to major and minor faults and shear zones that have significant implications for gold mineralization. It is therefore critical to understand the nature of these faults at depth and their geometry. In deriving structural interpretation maps it is important to distinguish between shear zones and faults at different scales and directions. Given the important influence that structure plays on gold mineralization, a systematic approach in for mapping and interpretation was adopted to model these features. See Figure 44.

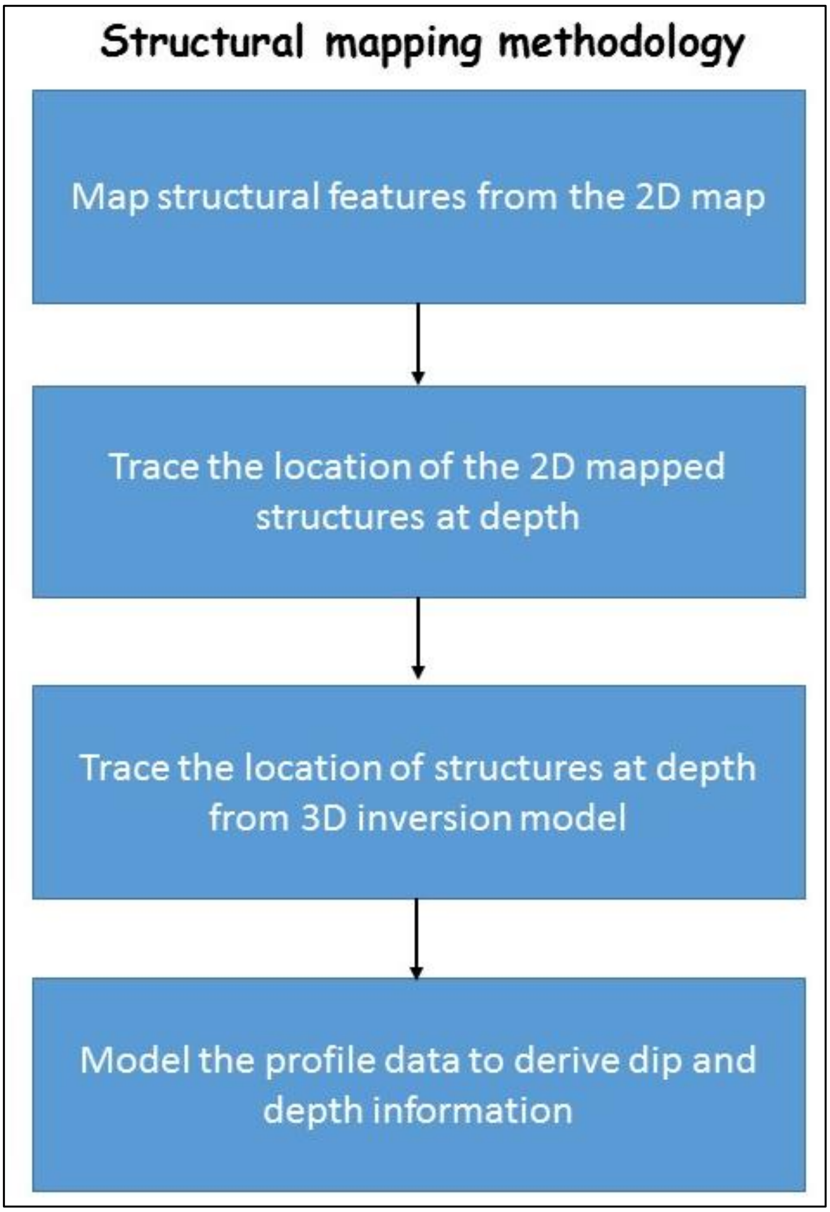


**Figure 44: Summary of methodology adopted in mapping structures from airborne EM data**

### *6.3.2 Interpretation of 3D Inversion Models*

The 3D inversion interpretation confirmed the structural trends corresponding to D3 major second and D4 minor third order features that were mapped in the 2D EM and mag interpretation. The interpretation also showed that there were subtle trends in the data that did not correspond to the features mapped in the 2D interpretation. These trends generally have a NW-SE orientation, oblique to the D3 trends observed in the field and identified in the 2D interpretation. These cryptic features differ from other structures mapped in terms of size, lateral extent, and how they affect the geological units.

Figure 45 shows examples of these interpreted basement structures that are manifested as traceable discontinuities cutting through the basement units. These structures do not affect the cover responses, and hence do not have mappable surface expressions. In the 2D depth slices the major second order structures can clearly be seen to penetrate through to the surface and generally mark geological boundaries. The third order structures and NW-SE upward propagating basement structures are more subtle and cross cut geology.

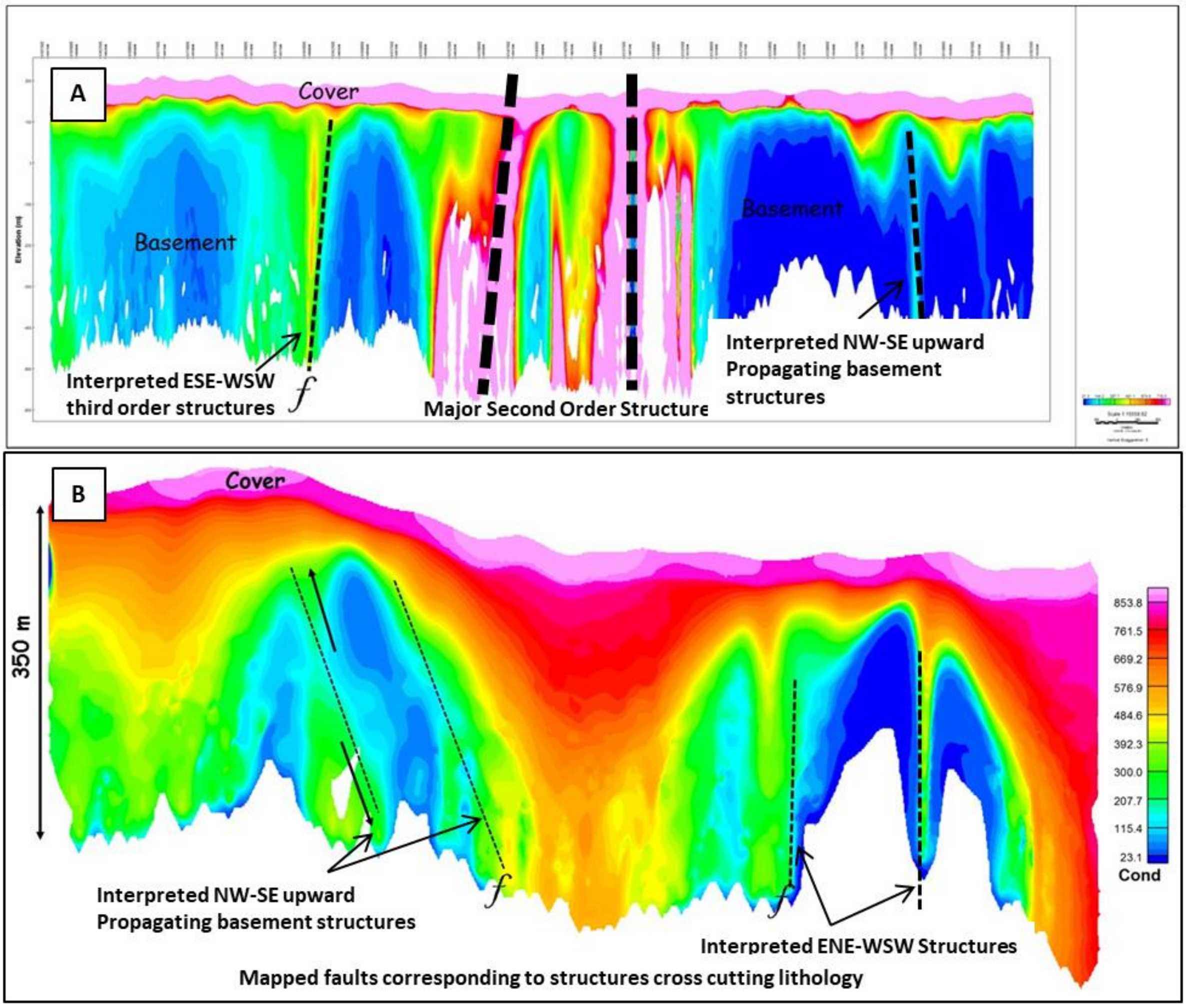


**Figure 45: 2D depth slices of the 3D inversion model showing major NE-SW second order structures and minor ENE-WSW third order structures and NW-SE upward propagating basement structures. Modified from Khoza, (2017)**

These features closely resemble each other in 2D depth sections and need to be carefully traced from section to section in order to map them in 3D. In doing so it becomes clear that there are several structural trends observable in the data.

The cryptic NW-SE structures correspond to structural trend three (3) identified in the Fry analysis and lineament one (1) identified in regional gravity interpretation. This study proposes that the NW-SE structures could be upward propagating basement structures caused by repeated reactivations of a basement structural architecture during the D3 and D4 deformation events of the Eburnean Orogeny. These structures have a unique orientation, cross cut lithology, and not propagating right through to the surface as do the third order D4 structures. The NE-SW D3 major second order structures primarily form along the boundaries of geological units and map out geological contacts where the NW-SE structures cut across all lithology. In addition D3 structures and D4 structures clearly penetrate through to the surface, where the NW-SE structures do not. Although both are quite subtle, the major differentiation between the NW-SE structures and the D4 third order ENE-WSW structures when mapped in 3D are their orientation.

The 3D inversion modelling resulted in three distinct structure types being identified; (1) cryptic NW-SE structures, (2) NE-SW D3 major second order structures and (3) ENE-WSW D4 minor third order structures. A 2D map of the NW-SE structural architecture of the Asankrangwa Belt interpreted from the 3D inversion models is shown in Figure 46. Once the NW-SE architecture is mapped through the Asankrangwa Belt a clear correlation between deposit location and NW-SW structure architecture is observed. Every deposit of economic size found in the Asankrangwa Belt are located either on, or directly adjacent to NW-SE upward propagating basement structure. This observation would suggest that the basement structures are exerting a direct control over gold deposit location.

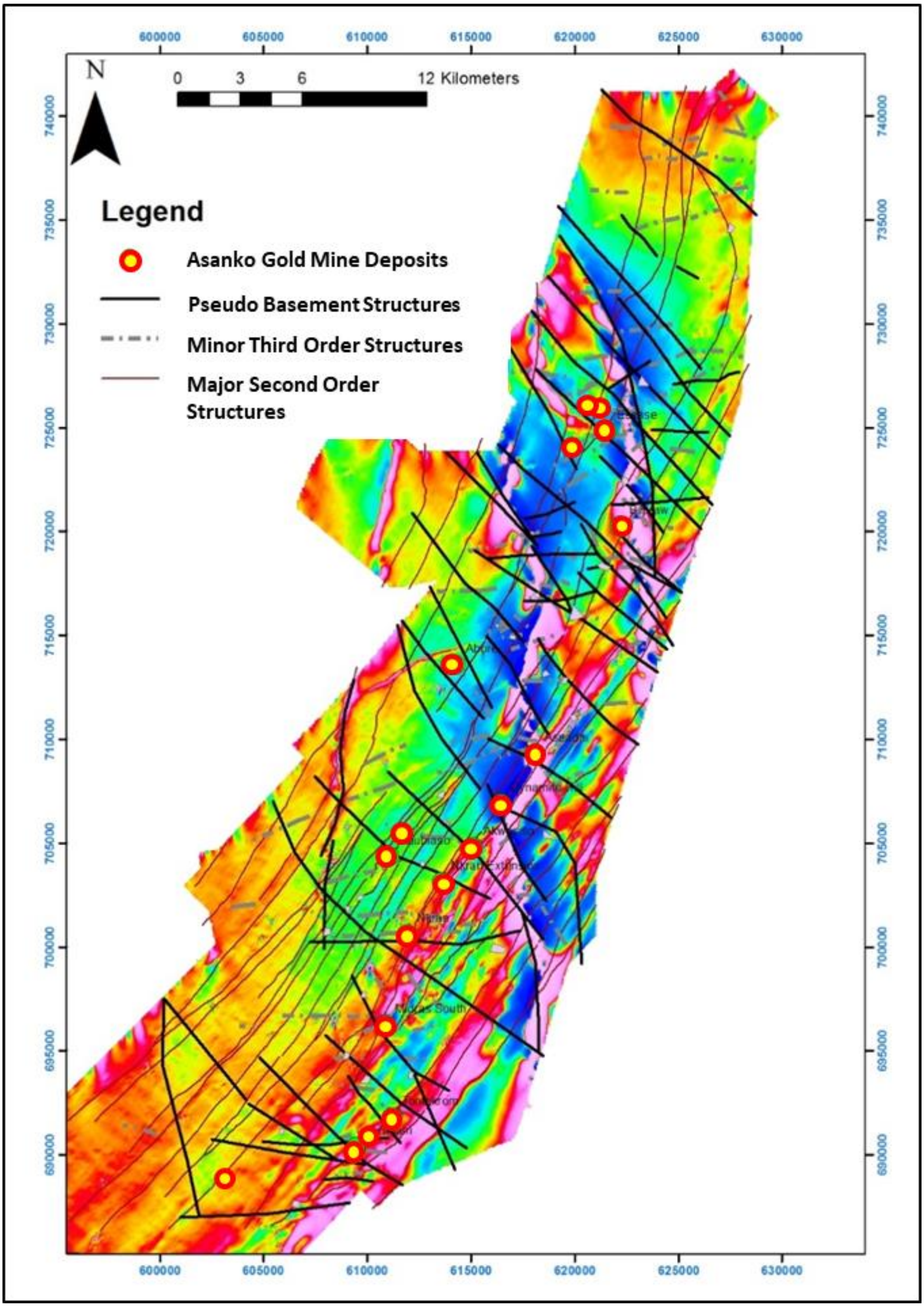


**Figure 46: Reduced to pole of total magnetic intensity (RTP_TMI) map showing the location of the interpreted upward propagating basement structures, major second order and minor third order structures. Asanko Gold Mine camp deposits are shown red outlined yellow dots**

# 7 SYNTHESIS AND CONCLUSIONS

The aim of economic geology is to provide a framework for the understanding of ore deposits that can be utilised by exploration geologists to more efficiently discover and delineate major new mineral resources. The following section synthesises the work done in this study into robust multi-scale structural targeting criteria for the Kumasi Basin and Asanko Gold Mine camp which can be used in the definition of favourable areas for future exploration work.

Using the mineral system concept as a guide, a direct link has been made between geological processes and their physical manifestations, and the location of gold deposits at multiple scales within the Kumasi Basin. This study adopted a three stage approach which included; (1) a Zipf's Law quantitative analysis to determine the residual endowment potential of the study area, (2) a Fry autocorrelation analysis to identify cryptic spatial distribution trends within deposit location point data and relate them to the critical events from the geodynamic history, and (3) interpretation of geophysical data sets to map the structural architecture at different scales to develop structural targeting criteria for the Asankrangwa gold belt. The combination of these analyses has resulted in a systematic and methodological approach to understanding the ultimate controls on mineral deposit genesis.

## 7.1 Synthesis of Regional to District Scale Results

The regional structural interpretation shows that basement gravity features exert a direct control over gold camp location within the Kumasi Basin. At the regional scale all major gold camps are found at the intersection between a D3 major first or second order shear zone corridor and N-S or NW-SE basement features. Major gold camps are shown as red outlines in Figure 47B. The Asanko Gold Mine camp is found at the intersection between a D3 major second order basin hosted shear corridor and both the N-S and NW-SE basement features identified in this study. These structural relationships have major implications for targeting gold deposits and camps within the Kumasi Basin.

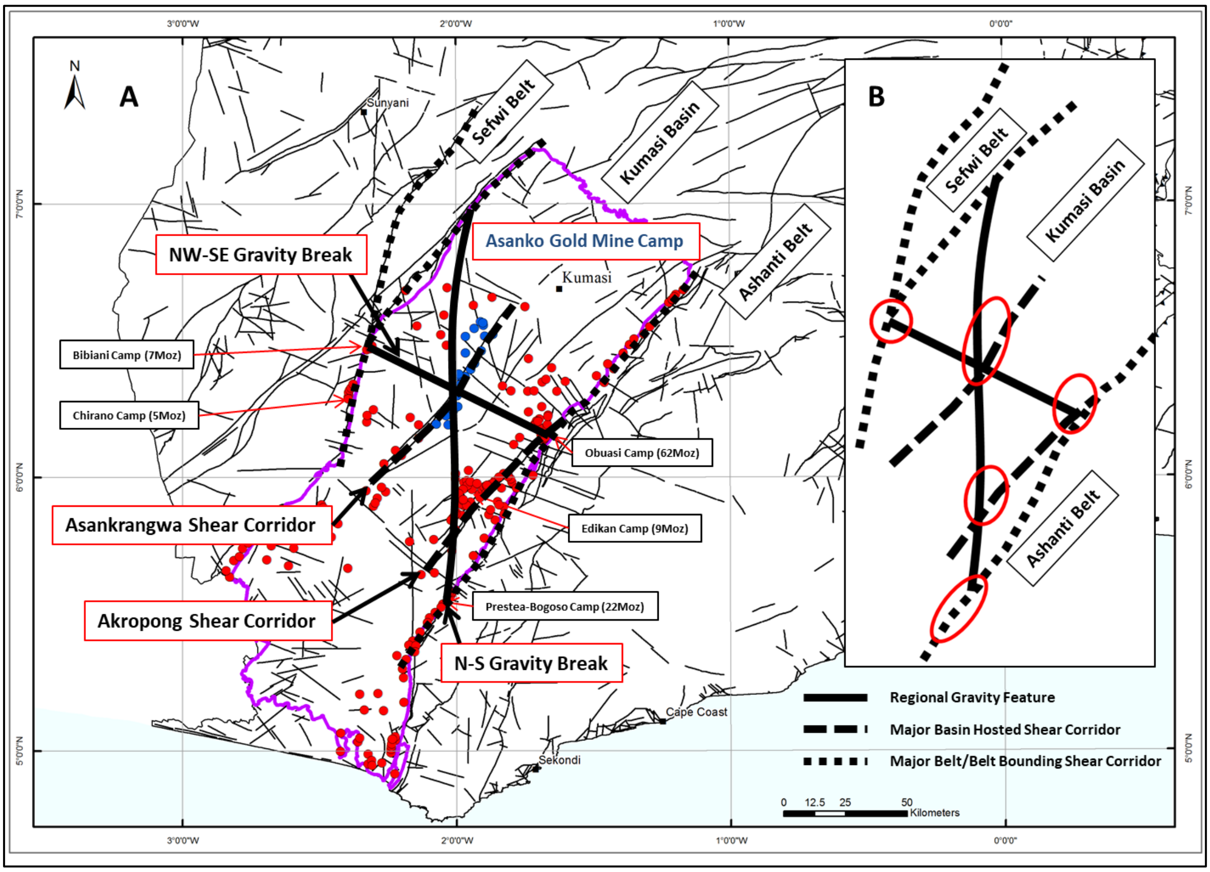


**Figure 47: Regional structure interpretation of the Kumasi Basin showing (A) regional structure interpretation with Kumasi Basin deposits and prospect locations and (B) regional structure interpretation with major gold camp locations outlined in red. Modified from Agyei Duodu, et al., (2009)**

Results shown here suggest the following structural targeting criteria at the regional-scale in the Kumasi Basin:

(a) The regional and district Fry analysis results indicate that the most dominant structural control on gold deposit location in the Kumasi Basin is in a NE-SW orientation. At the regional and district scale major gold camps, deposits and prospects are all found along NE-SW oriented D3 first and second order structural corridors that define the boundaries of the volcanic belts with the Kumasi Basin sediments (see Figure 47). Within the Kumasi Basin, major gold camps are hosted by two distinct structural corridors; the Akropong Shear corridor and the Asankrangwa Shear corridor. These D3 Eburnean structural corridors dominate the surficial structural architecture in the Kumasi Basin and play a fundamental role in gold camp formation. The NE-SW regional trend is clearly observed in geological field mapping and interpretation of regional geophysical data sets. D3 structural corridors are interpreted to penetrate deep into the basin sediments, connecting the upper crust to the basement structure network. By connecting with the basement structural architecture they act as conduits allowing the upward migration of mineralised fluids from the source region, through the basement structure network and into the upper crust. This interconnected permeability network is fundamental for fluid transport and without it ore bearing fluids cannot be transported into the upper crust and gold deposit formation is precluded. Analysis of geophysical interpretations within the Asankrangwa Belt and Asanko Gold Mine camp shows that every single gold deposit discovered to date falls along a second order shear zone structure, further proving that they play a critical role in deposit formation.

(b) A cryptic N-S trend observed is observed in the regional and district scale Fry analysis. This trend does not have a mappable surface expression. From the regional gravity data, a prominent N-S gravity break is observed running through the Kumasi Basin. This feature connects the northern extent of the Prestea-Bogoso camp to the Edikan and Asanko Gold Mine camps and appears to exert a fundamental control on gold camp location within the basin. Critically, few deposits of major economic value have been discovered west of the N-S gravity feature within the basin. The exception to this is perhaps the 0.5 Moz Pampe deposit on the SW extension of the Akropong shear corridor. Both the Asanko and Edikan camps display similar properties in that deposits are all located along parallel shears in a NNE direction from the intersection between their respective shear corridors and the N-S gravity break.

(c) A cryptic NW-SE trend observed is observed in the regional and district scale Fry analysis. This trend also does not have a mappable surficial expression. Similarly, an NW-SE gravity trend is observed in the regional gravity data that connects the Obuasi, Asanko, and Bibiani camps. Interestingly, the Asanko Gold Mine camp falls directly at the intersection between these two gravity features and the Asankrangwa shear corridor. These two features are interpreted to be fundamental basement structures that are exerting control over gold deposit camp location at the regional and district scales in the Kumasi Basin. Figure 47 shows the interpreted regional structural architecture of the Kumasi Basin.

These structural targeting criteria can then be used as primary inputs into prospectivity and targeting exercises exploring for orogenic gold deposits at the regional-scale in the Kumasi Basin.

## 7.2 Synthesis of Camp Scale Results

The final camp-scale geophysical structure model integrates the 2D airborne EM and magnetics interpretation with the 3D EM inversion models into a comprehensive structural architecture map. See Figure 49.

Results shown here suggest the following structural targeting criteria in the Asankrangwa Belt at the Asanko Gold Mine camp-scale:

(a) At the regional and district scales lineaments in regional gravity data indicate that gold camp locations are controlled by a basement structure architecture in the Kumasi Basin. All major gold camps lie at the intersection of a major N-S or NW-SE gravity lineament with a D3 major first or second order shear corridors. The intersection of these crustal structures is fundamental for gold camp formation and from a regional targeting perspective mapping these regional structures and their intersections is critical. Proximity to an intersection of a gravity lineament and first and second order shear corridors is a critical regional and district scale structural targeting criteria. See Figure 47 above for detail.

(b) At the camp scale a 2D interpretation of airborne EM and magnetic data mapped in detail the D3 second order structures of the Asankrangwa Belt. These structures form a 4-5 km wide belt of parallel to anastomosing shear zones in a general NE-SW orientation along the axis of the Kumasi Basin. These structures have been mapped as major and minor shear zones and generally map out the boundaries between geological units where deep seated shear structures are likely to form as a result of rheological contrast. These shear zones can be easily identified in the field and they show up as narrow to broad zones of intense shearing and silicification. Because of this they typically form interrupted ridges and remain proud of the surrounding terrain, especially when associated with intense hydrothermal alteration and quartz veining. In the Asanko Gold Mine camp, every deposit discovered to date is located along one of five parallel D3 major second order shear zones. As such, these structures form critical targeting criteria and are fundamental to ore deposit formation. Figure 50 shows the D3 structure interpretation from the modelling of the airborne EM and magnetic data.

(c) At the camp scale a 2D interpretation of airborne EM and magnetic data mapped in detail the D4 third order structures of the Asankrangwa Belt. The D4 deformation event is interpreted to be the gold deposition event and as such, structures associated with this event are considered critical for ore deposit formation. These structures form a less regular lattice-like network of structures in generally an ENE-WSW orientation. Although not identified in regional and district scale data sets used in this study, these structural orientation is represented in the Fry analysis at all scales. These structures generally have a much shorter strike length than other structures mapped in the belt, and are visible in 2D in high resolution DIGHEM airborne magnetic data as a discontinuous lattice work of structures covering the southern half of the Asanko Gold Mine camp study area. In the areas of the study area with lower definition data, these structures are much harder to detect. These structures are notoriously difficult to map in the field and drill core, as well as model in geophysical data (see Figure 51).

ENE-WSW structures are interpreted to be brittle failures in the crust to relieve compressive stress in response to the D4 NNW-SSE deformation event. Intersections between D4 third order and D3 second order structures are interpreted to be zones of maximum compression, and hence zones of maximum dilation upon failure. These dilation zones are critical for deposition of economic quantities of gold, and identifying their location is essential for exploration success (see Figure 51). Where these structures have been mapped there is a direct association with all known deposits in the Asanko Gold Mine camp and as such, direct or proximal association to D4 third order structures is a critical targeting criteria in the Asankrangwa Belt.

An alternative explanation is that the ENE-WSW structures formed as conjugate sets to the D3 second order structures to release compressive stress during the D3 compression event. During compression, conjugal fault structures form into interlinked networks providing important conduits for large volumes of hydrothermal fluids (Sibson, 1996). Figure 48 shows a simplified strain ellipse that has undergone compression and formation of conjugate fault sets. Geological factors such as foliation orientation or heterogeneity can contribute to one or the other of these conjugate orientations to be more prone to dilation than the other (Robert & Poulson, 2001). These pre-developed structures would have been reactivated during the D4 deformation and gold mineralising event. Whether formed during the D3 compression event and reactivated during the D4 mineralisting evet, or formed as a result of the D4 event only, in either scenario these structures are interpreted to be critical for ore deposit formation.

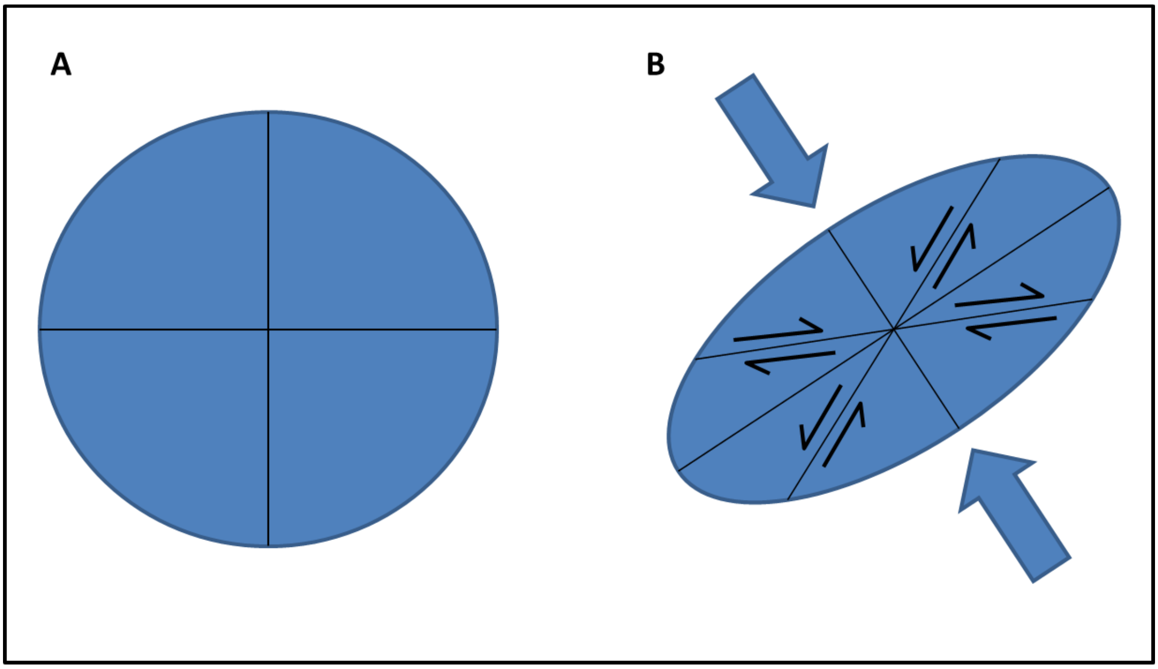


**Figure 48: 2D strain ellipse showing (A) an undeformed ellipse and (B) a deformed elli[se showing the expected areas of compression and extension during horizontal shortening and vertical elongation. Modified from Robert & Poulson, (2001)**

(d) At the camp scale, 3D inversion modelling of airborne EM and magnetic geophysical data identified a pervasive and repetitious structural fabric in a NW-SE orientation. This structural orientation is not observed in the field and was not identified in 2D airborne EM and magnetics data, but was identified both in the regional gravity data and observed as a secondary trend in the Fry analysis at all scales. In the 3D inversion modelling, these structures appear similar to the D4 third order structures in that they crosscut geological units. They differ from the D4 structures in that they do not appear to express themselves through to the surface and they are almost orthogonal to them in orientation. Figure 52 shows the 2D interpretation of the mapped NW-SE structures. The interpretation of these structures is that they are upward propagations of a fundamental basement structure observed in the regional gravity data and referred to as upward propagating basement structures. The upward propagation is caused through countless reactivations of the fundamental basement lineaments creating an interconnected porosity network that connects the upper crust structural architecture to the source region of the mineralising fluids.

This connection is key for the upward migration of mineralising fluids and critical for gold deposit formation. Observation of the relationship between these structures and gold deposit location in the Asanko Gold Mine camp shows that every deposit discovered to date has a direct association of one or more of these basement structures. As such, a direct association with one or more basement structure is considered fundamental to ore deposit formation in the Asanko Gold Mine camp.

(e) The camp scale Fry analysis shows a very dominant NNE-SSW alignment of deposit location. This trend is in between the pervasive NE-SW D3 Eburnean Orogeny structural trend observed through the entire Kumasi Basin, and the N-S gravity break lineament which controls gold camp location on a regional scale (See Figure 53). This trend forms the final targeting criterion derived in this study is perhaps less of structural criteria and more of a targeting vector. Regardless, at the camp scale this trend cannot be ignored and any camp scale targeting exercise must take this trend into account.

Given the results of this study, these structural criteria may be used as primary inputs into prospectivity and targeting exercises exploring for orogenic gold deposits in the Asankrangwa Belt.

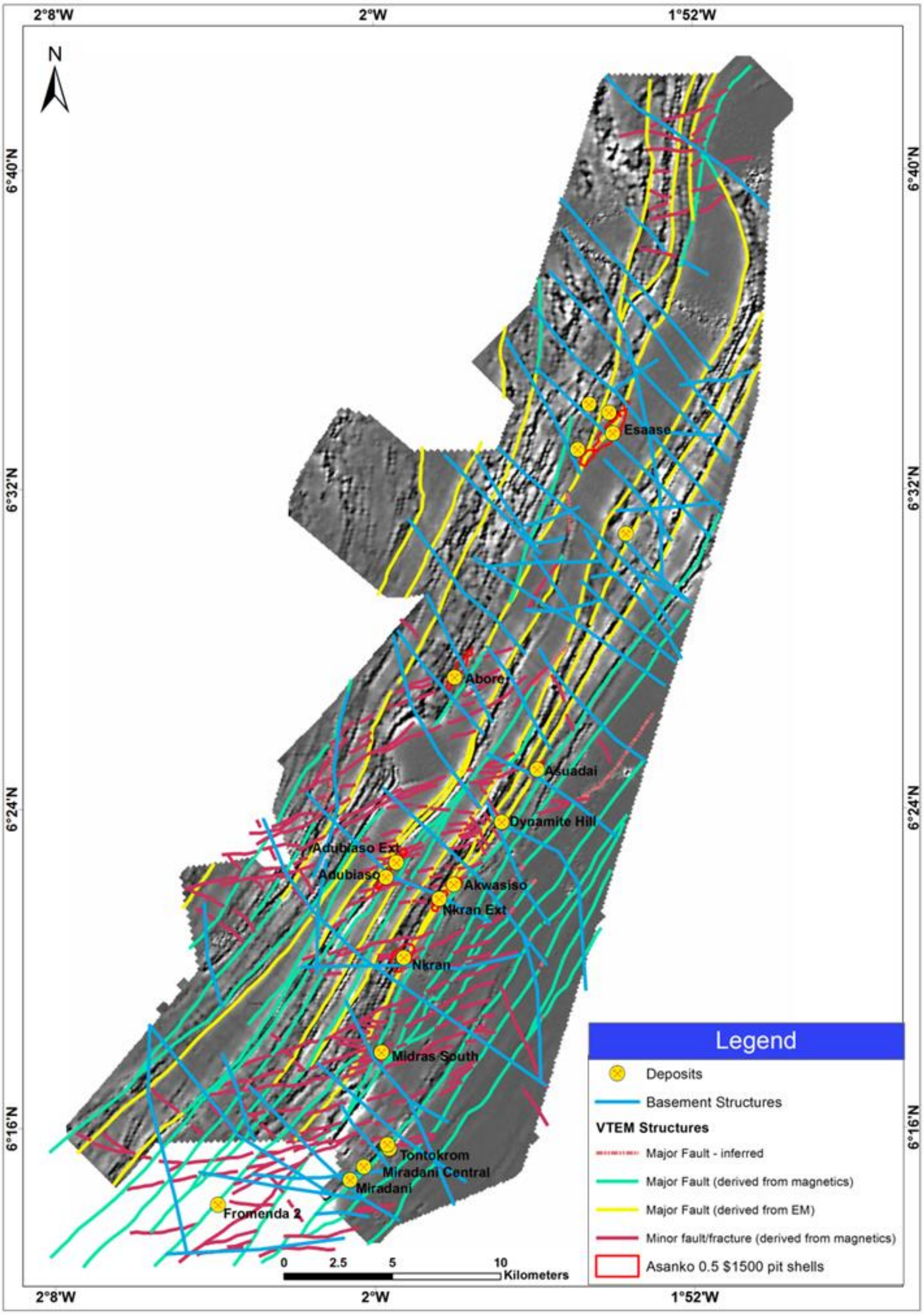


**Figure 49: 2D structural architecture interpretation of the Asanko Gold Mine camp overlain on airborne EM data. D3 major second order structures are shown in green and yellow, D4 third order brittle faults are shown in purple, and cryptic NW-SE upward propagating basement structures are shown in blue. Asanko Gold Mine deposit locations are shown as yellow circles**

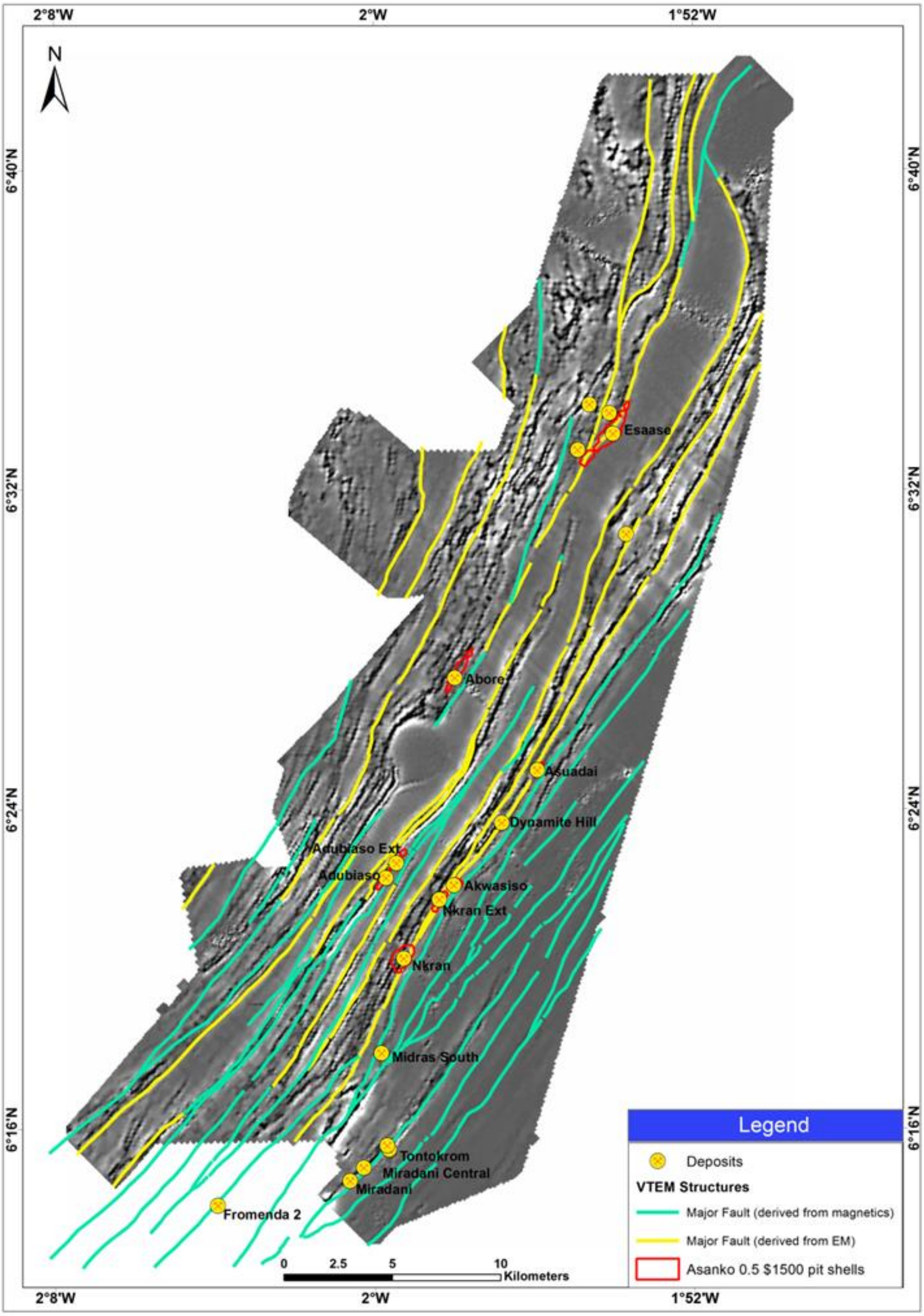


**Figure 50: Geophysical interpretation of the D3 major second order shear zones of the Asankrangwa shear corridor. Structures derived from airborne EM data are mapped in yellow, and structures derived from airborne magnetic data are mapped in green. Asanko Gold Mine deposits are shown as yellow dots**


**Figure 51: Geophysical interpretation of minor D4 third order structural architecture showing EM geophysical interpretation as the background. Asanko Gold Mine camp deposits are shown as yellow dots.**

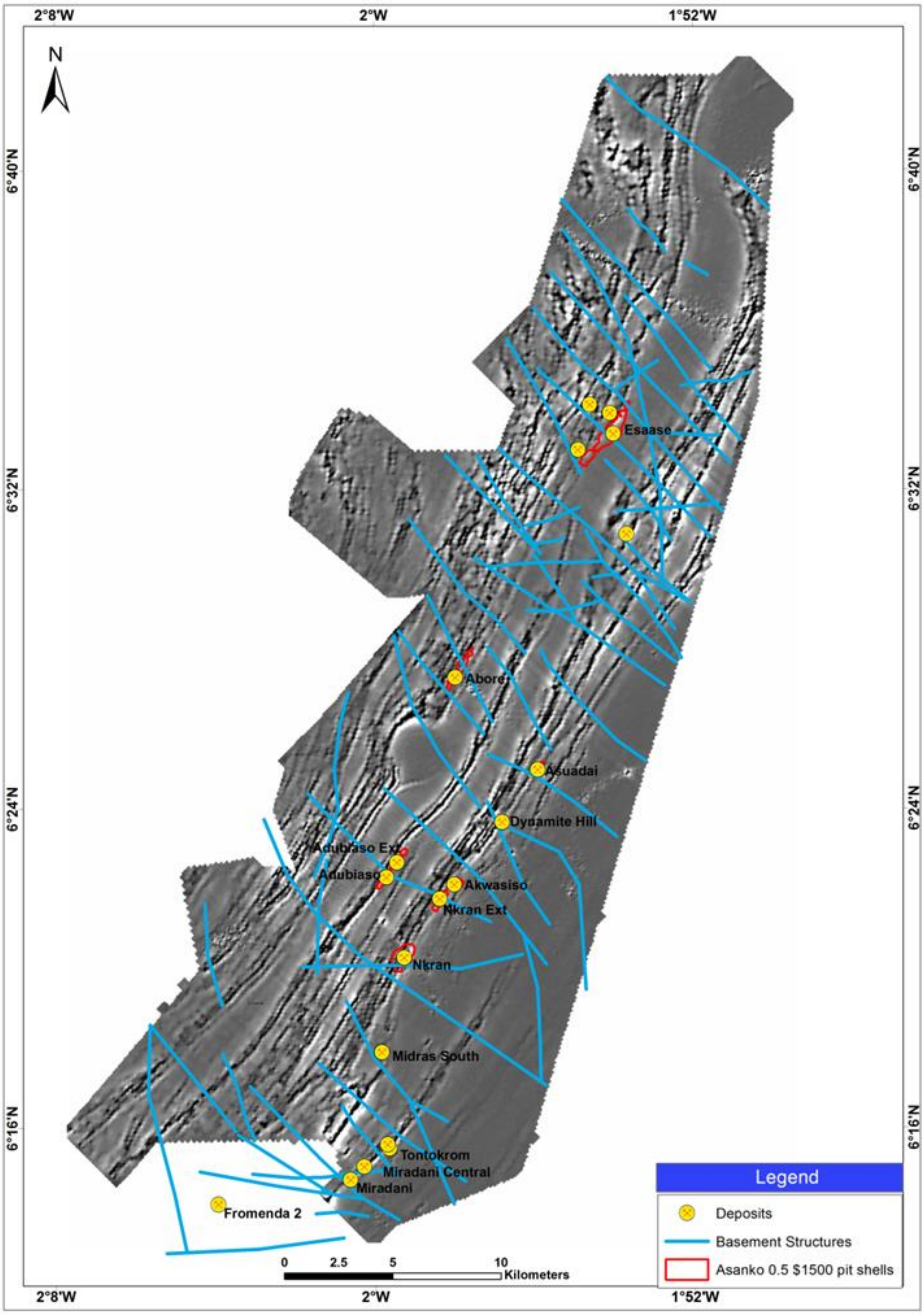


**Figure 52: Geophysical interpretation of minor cryptic upward propagating basement NW-SE structural architecture showing the EM geophysical interpretation as the background of the study area. Asanko Gold Mine camp deposits are shown as yellow dots**

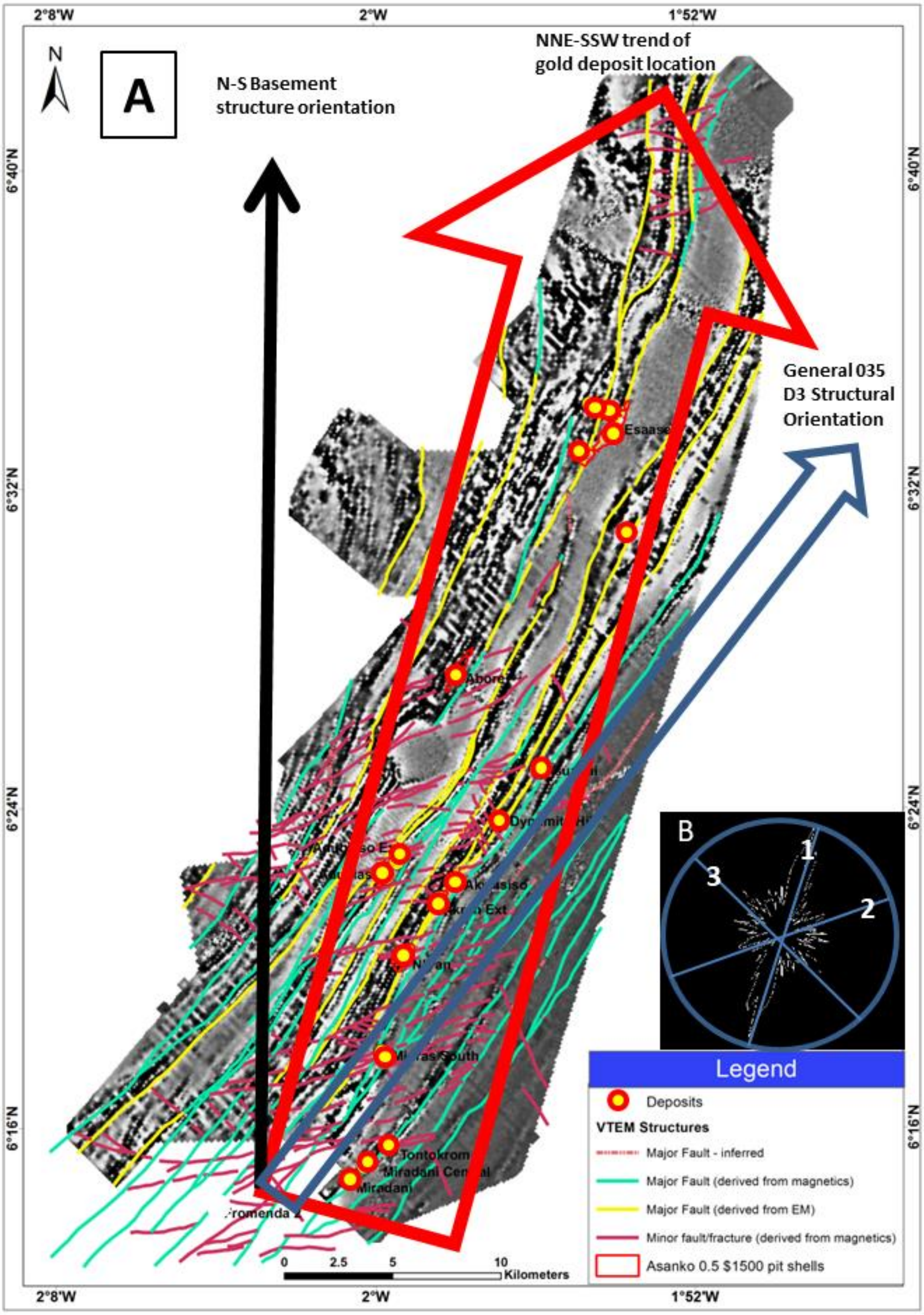


**Figure 53: Structural interpretation map of the Asanko Gold Mine camp showing (A) the trend of gold deposits in the camp in the red arrow with respect to the trends of the other major structural controls in the belt. Inset (B) shows the rose diagram from the camp scale Fry analysis showing the dominant trend in the Asanko Gold Mine camp. Deposits are shown as yellow dots with red outlines**

The camp scale Fry analysis shows that there is a dominant NNE-SSW trend in the deposit spatial distribution with the Asanko Gold Mine camp. This trend does not seem to directly correspond to any critical geological processes or structures identified so far in this study. Interestingly, this orientation lies between the dominant NE-SW structural trend of the Asankrangwa Belt and the N-S gravity break lineament observed to be controlling gold camp location at the regional scale and is shown in Figure 54.

One possible explanation for this trend at the camp scale is that the spatial distribution of the deposits is broadly tracing a zone of interaction between the regional N-S gravity break control lineament with the NE-SW D3 second order Asankrangwa shear corridor trend. An illustration of this is shown Figure 54(C). The interaction between the N-S and NE-SW structural trends form a zone of fertility in which economic deposits are likely to form. Within this zone, the basement N-S structure is connected to the upper crust by a network of upward propagating NW-SE structures and the deeply penetrating NE-SW structures of the Asankrangwa Belt shear corridor. This may explain why the deposit locations step up across parallel shear zones in an NNE-SSW orientation within the Asanko Gold Mine camp, and do not continue to follow the NE-SW trend of the Asankrangwa Belt structural corridor. How far economic deposits can be found in the NNE-SSW oriented fertility zone depends on the width of influence of the N-S gravity break, and the width of the NE-SW shear corridor. Deposit fertility drops off rapidly in both the NE and SW directions along the Asankrangwa shear corridor, as well as in the N-S trend of the basement structure.

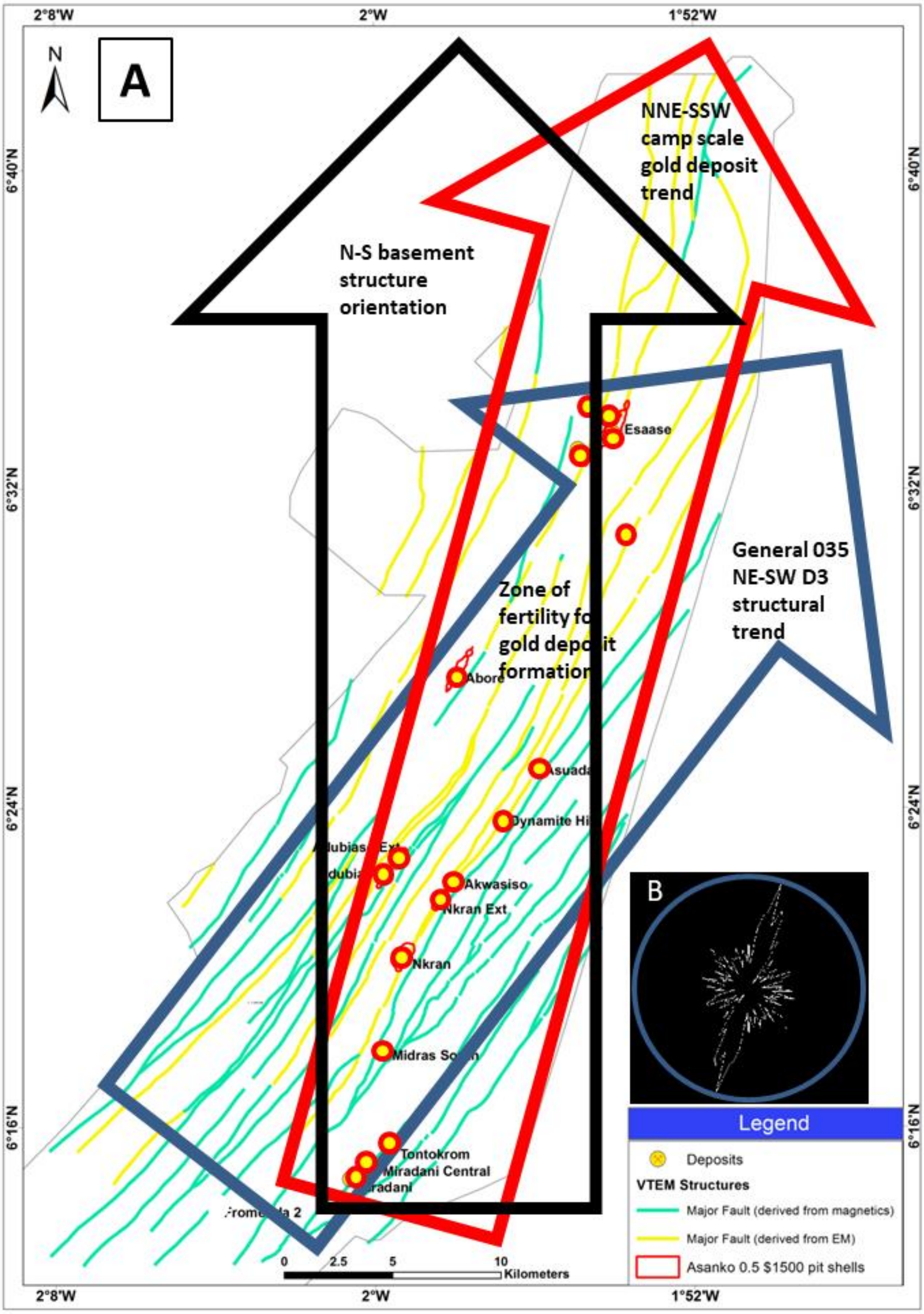


**Figure 54: Camp scale structural interpretation of the Asanko Gold Mine camp showing (A) D3 geophysical structural interpretation and deposit locations with arrows indicating structural trends, (B) camp scale rose diagram of the Fry analysis results showing the dominant trend for gold deposit spatial distribution in the camp**

Another explanation for this camp-scale trend in deposit location could be that the Asanko Gold Mine is located in a flexure to the north of the Asankrangwa Belt. From the airborne EM structural interpretation, it appears that the Asanko Gold Mine camp is located at a belt scale jog to the north. Interestingly, this jog to the north is recorded in the airborne EM data interpretation only, with the airborne magnetic data showing the main trend of the structural corridor continuing in the NE-SW direction. This can be seen in Figure 54 with some of the yellow EM interpreted structures turning northward in the direction of the red arrow and the magnetic interpreted structures generally continuing in the NE-SE orientation. Regionally, the Asankrangwa Belt does show a small jog to the north where it intersects the N-S gravity break, but not as significantly as seen in the belt scale airborne geophysical data. The significance of this should not be downplayed as we know that jogs and flexures are very important for orogenic gold deposit formation, especially when they coincide with crustal scale lineaments such as the N-S gravity feature. Whichever the case, the effect is that at the camp scale the dominant trend on deposit location is clearly NNE-SSW and understanding this has major implications on targeting additional discoveries within the camp.

Although outside of the scope of this study, this camp scale trend also appears to be displayed at the Edikan camp, located 45 km south along the same N-S gravity break at the intersection of the Akropong shear corridor. Deposit location data, shown in Figure 55, appears to demonstrate the same NNE-SSW trend originating from the structural intersection. Upon further study similar trends may be displayed in other gold camps. An interesting follow up to this study could involve detailed fry analysis in all major gold camps the Kumasi Basin to identify similarities and differences in the controls on mineralisation at the camp scale.

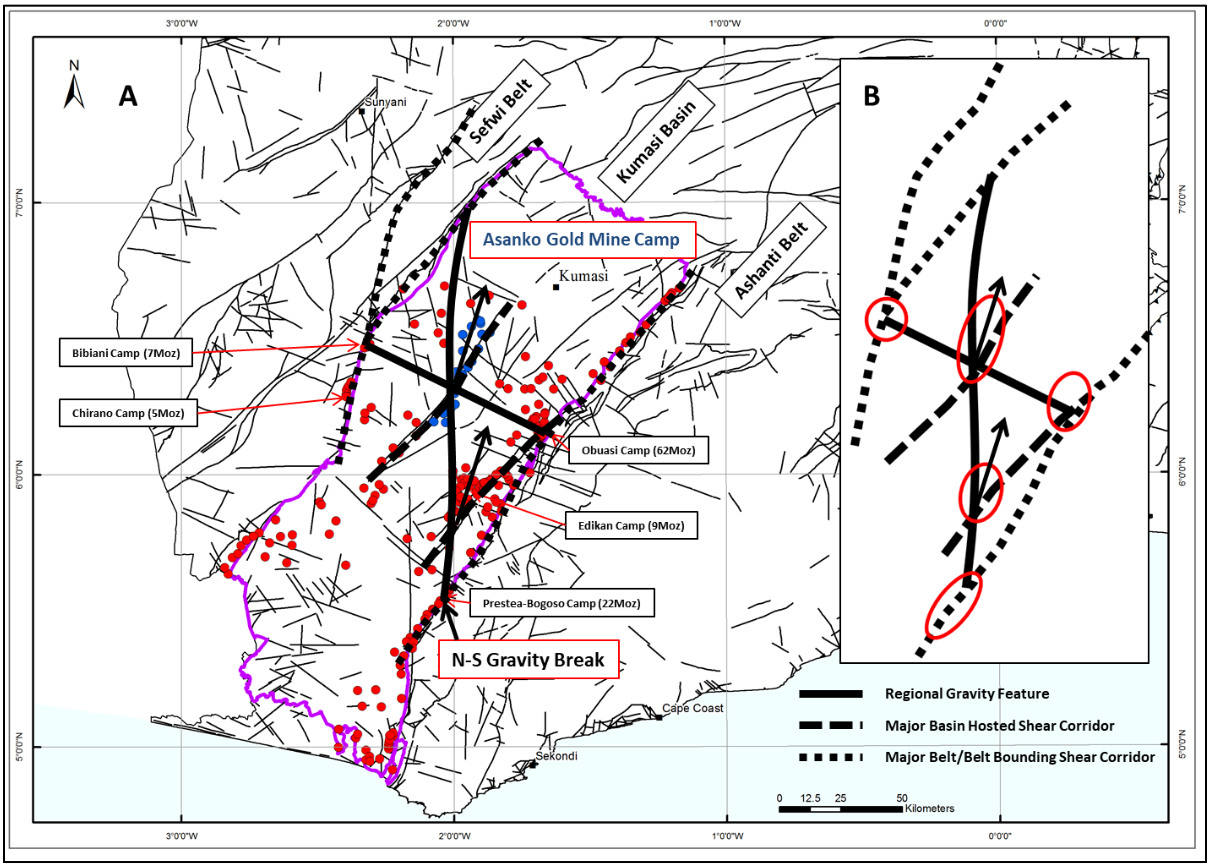


**Figure 55: Structural interpretation map showing trend of gold deposits in the Asanko Gold Mine camp and Edikan camp indicated by black arrows. Both camps display a zone of fertility between the N-S and NE-SW structural trends. Modified from Agyei Duodu, et al., (2009)**

## 7.3 Conclusions

All deposits within the Kumasi Basin study area share a single genetic model for orogenic gold mineralisation. NNE-SSW compression during D4 deformation caused reverse sinistral reactivation of D3 NE-SW second order structures. Brittle third order ENE-WSW structures formed either as conjugate sets to the NE-SW structures during D3 deformation, or directly in response to the D4 deformation were introduced or reactivated at this time to relieve compressional stress within the rock mass, and the intersection between these two structural orientations plays a critical role in providing zones of dilation needed for deposition of gold in economic quantities. The basement structure architecture was also reactivated at this time and play a vital role in connecting the permeability network between the source region and the upper crust. This permeability connection allowed upward migration of mineralising fluids into the upper crust to where they were deposited in broad brittle dilation zones. The identification of these features at all scales has allowed robust targeting criteria for gold deposits to be developed for the Kumasi Basin.

A general summary of the important findings of this study is presented here. The usefulness of the methods documented in this study were demonstrated by applying them to the Asanko Gold Mine camp and resulted in the following conclusions:

(i) The Zipf's Law results indicate that there is potential for a large amount of residual endowment in the Asankrangwa Belt. The analysis estimates that 39% of the predicted endowment in the belt has been discovered and there is potentially >19 Moz including 12 undiscovered deposits >0.4 Moz. This indicates a relative immaturity of the Asanko Gold Mine camp and is important to establish in any exploration area in order to provide the basis for developing a business case for further examination and justify additional exploration spend.

(ii) The Kumasi Basin was formed during a D2 extension event. NW-SE D3 crustal shortening during the Eburnean Orogeny isoclinally-folded basin sediments and reactivated basin growth structures along volcanic belt boundaries as first order shear corridors. Deeply penetrating second order shear corridors formed within the basin sediments and adjacent to first order structures near the belt-basin boundaries. The NNE-SSW D4 compression event reactivated the first and second order structures and formed brittle third order structures to compensate for compressive stress in the rock mass. This connected the permeability network between the source region of the gold bearing fluids and the upper crust allowing deposition of all the gold deposits within the Kumasi Basin and SW Ghana.

(iii) The Fry analysis results suggest that different mineralisation controls act on the regional and district scales compared to the camp scale. Some of the mineralising controls correspond to surficial features which can be observed in the field and some that cannot, indicating that there are cryptic controls on gold deposit location that are not obvious in rock or mine outcrop or in drill core. At the regional and district scale the dominant control is a NE-SW trend with secondary controls in the N-S, NW-SE, and ENE-WSW orientations. The NE-SW and ENE-WSW orientations correspond to the D3 and D4 deformation events from the

Eburnean Orogeny geodynamic history. The N-S and NW-SE trends do not fit into the D3 and D4 deformation events but may correspond to basement features formed to compensate for extension during the D2 basin forming event. The camp scale is dominated by a strong NNE-SSW trend in deposit spatial distribution. This trend may be caused by the interaction between the N-S basement lineament and the NE-SW structures of the Asankrangwa shear corridor or by a belt scale jog and results in a very strong control on deposit location at the camp scale.

(iv) Analysis of regional gravity geophysical data sets indicates the presence of two major lineaments visible at the resolution of the data used. These lineaments are in an N-S and NW-SE orientation and correspond to the cryptic trends observed in the Fry analysis. These lineaments, or breaks in the gravity data, are interpreted to be basement structures that exert a direct control on gold camp location at the regional scale and proximity to these structures is fundamental for camp and deposit formation. Analysis of belt scale 2D airborne EM and magnetic geophysical data was used to map the belt/camp scale structural architecture. Major D3 second order NE-SW and D4 minor third order ENE-WSW structures were mapped in detail. 3D inversion modelling of airborne EM and magnetic data indicated the presence of cryptic structures cross cutting lithology that do not correspond with the D3/D4 second and third order structures previously identified. These structures were modelled and observed to be primarily in a NW-SE orientation. It is proposed that these are upward propagating basement structures caused by countless reactivations of the basement structure architecture throughout the Eburnean Orogeny.

Orogenic gold deposits globally are commonly associated with fault flexures, jogs, intersections and splays (Robert & Poulson, 2001). While the current study is in agreement, it suggests that using only surficial information leads to the introduction of many false positive targets. This study proposes that gold deposits in the Asanko Gold Mine camp have a structural signature that is critical for ore deposit formation and Identifying this signature is critical for maximising exploration efficiency and success.

In summary, the significant conjunction of structural elements needed for gold deposit formation in the Kumasi Basin and Asanko Gold Mine camp are:

(1) At the regional scale intersections of N-S and NW-SE regional gravity lineaments with first and second order NE-SW major first and second order D3 shear zone corridors are fundamental for gold camp formation.

(2) At the camp scale triple intersections between NE-SW major second order D3 shear zones, brittle D4 third order ENE-WSW structures, and cryptic NW-SE upward propagating basement structures are fundamental for deposit formation.

(3) At the camp scale deposits fall within a 4-5 km wide zone with a strong NNE-SSW trend.

The systematic mineral system concept approach for target criteria generation in this study, namely utilising a quantitative analysis for assessing residual endowment, using a unified genetic model, a spatial distribution analysis for structural trend detection, combined with interpretation of regional to camp scale geophysical datasets could have implications for the assessment of other emerging to mature goldfields worldwide. This holistic approach can be used to assess, justify, and plan exploration projects across jurisdictions and commodities with the aim of making resulting exploration projects more successful and efficient.

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