Effective mineral exploration requires a detailed knowledge of the factors and processes which result in the formation of economic deposits. To apply this knowledge, a sound three-dimensional understanding of the geology and structure of a region is required. In most cases, surface geology can be mapped with a high degree of accuracy, however, the geology at depth has to be inferred from geophysical methods, or through drilling programs, and is therefore mapped at much lower spatial resolution. This anisotropy in spatial-data quality, coupled with the scarcity of three-dimensional geographic information systems (GIS), makes computer-based exploration at a camp- or district-scale very difficult.

The process of computer-based three-dimensional mineral exploration is being addressed at the Centre for Teaching and Research in Strategic Mineral Deposits within the Department of Geology and Geophysics at The University of Western Australia. A research project is in progress which attempts to define a three-dimensional gold prospectivity model for the Wiluna goldfield. The aim of this research is to gain a better understanding of the factors which spatially control the location of the known ore bodies, and especially of high-grade zones within these bodies. Also, the research aims to identify potential continuations of known ore bodies, and to attempt to locate new prospective areas for gold mineralisation further to the south of the present goldfield.

The Wiluna goldfield comprises a region approximately 3km x 5km, and is situated in the northern part of the Archaean Yilgarn Block of Western Australia, approximately four kilometres south of the Wiluna townsite. The area has been mined for gold since the early 1900s, and presently comprises 11 open-cut and underground gold mines. Geological information for the region includes detailed surface mapping and over 6,000 unevenly distributed drill holes, totalling in excess of 300km of core samples. The drill-core has been assayed for gold and gold-related elements, including arsenic, antimony, and sulphur. Plans and sections from mine construction activities provide detailed surface mapping and over 6,000 unevenly distributed drill holes, totalling in excess of 300km of core samples. The drill-core has been assayed for gold and gold-related elements, including arsenic, antimony, and sulphur. Plans and sections from mine construction activities provide detailed three-dimensional information for limited areas. These data have been entered into a 3D mining package, and a model of the surface and interpolated sub-surface geology and structure constructed. This model will be used as a base on which to conduct a gold prospectivity analysis.

Several GIS-based methods have been developed to as-
sess and map prospectivity on a global to district scale using datasets such as geological maps, aeromagnetic and radiometric data, topography, and satellite imagery. Prospectivity mapping methodologies can be split into two broad groups: knowledge driven and data driven. Knowledge driven methodologies involve the application of conceptual models to appropriate spatial datasets, whereas data-driven methodologies look for significant spatial relationships between known sites of mineralisation and surrounding geological features. Identified spatial relationships are quantified as mappable criteria and are ultimately integrated into a single prospectivity map. Techniques applied with varying degrees of success include Boolean logic, index-overlay, Bayesian statistics, fuzzy logic and artificial neural networks.

The majority of assessments to date have been two-dimensional in nature and normally conducted at a scale where deposits can be adequately represented as point features. This research has the additional complications in that the third dimension must be addressed, and that the scale of observation is such that ore-bodies have a definite volume, and cannot be regarded as simple point objects. Although present mining packages are good at visualising three-dimensional bodies, and are capable of measuring lengths, areas and volumes, most packages lack an in-built macro language which would allow a quantitative examination of gold prospectivity. Consequently, dedicated data handling programs are being developed to extract the spatial information from the mining software and to conduct quantitative spatial analysis techniques to identify and quantify significant spatial relationships between high-grade ore zones and the surrounding geology.

1- Objectives

Through the integration of two-dimensional surface geological maps and three-dimensional subsurface information of the Wiluna goldfield, the aim of this research is to construct a three-dimensional geological model of the area and to quantitatively analyse controls on gold mineralisation. Use of these controls to define methodology for regional GIS-based gold prospectivity analysis.

2- Data collection

Data available for this project includes:

a) a detailed geological surface map at scale 1:2 500 produced in a previous research (S. Hagemann, 1992). This map is available in digital format and was updated with more recent information. It includes main lithostratigraphic units, first-, second- and third-order structures, and measurements of azimuth and dip of faults.

b) an extensive drillhole database including exploration and evaluation records. The information contained in the database includes:
   > 6000 drillholes (RC, diamond, evaluation)
   > 375 000 meters of drill
   > 200 000 Au assays
   > 95 000 geochemical assays
   > 95 000 magnetic susceptibility of host rock measurements
   > 15 000 rock descriptions
detailed geological maps of pit and underground works and interpreted geological cross sections.

3- Data integration and 3D modelling

To achieve the best graphic visualization of the complex environment of the geological subsurface, the available information was integrated using a mining visualisation software. A 3D model was constructed correlating the surface map with the drillhole information, underground mining maps and interpreted geological sections.

A number of problems need to be addressed in the process of interpretation and integration of data. These problems are technological as well as inherent to the data. Present mining visualisation software require high specialisation and the process of updating the model according to new information is difficult and extremely time consuming. In terms of the data, good correlation is achieved in dense sampled areas but an increasing degree of interpolation and uncertainty is introduced in poorly sampled areas combined with the inherent anisotropy and complexity of the geologic subsurface.
4- Controls of the mineralisation

It is accepted that the gold mineralisation is late in the tectonic evolution of the Yilgarn craton (Groves, 1993). The fault system, along with relevant lithological contacts, is the principal control of the mineralisation. As the faults play a critical role in the siting of the ore bodies, an accurate spatial representation of this structures is required.

The traces of the faults on the surface map, their projection in the underground mining maps, and the drillhole intersection of the fault in subsurface, provide the lines and points used to create these entities in space. An empirical spatial resolution of 15 m was adopted for the basic cells that represent three dimensional geological solids. Lines and points were spatially gridded at this resolution, and a best polynomial algorithm fitted a TIN (triangulated irregular network) to these points. In all cases, control points were left without gridding to validate the interpolation accuracy. The final surfaces look smooth and realistic and serve as a basis for further spatial analysis.

5- Data extraction

In this study the kind of datasets required for analysis are dependent primarily on the type of deposit investigated. The Wiluna lode gold deposits are predominantly structurally controlled with relative lithologic control. Consequently, the solid 3D representation of faults and structures of first to third order is required to identify suitable relationships with gold mineralisation and specially of high-grade accumulations within these bodies.

From the final 3D model, the TIN representation of solid geologic entities can be exported in various formats for further analysis. For this project, ASCII files of the format \( \{x_1,y_1,z_1,x_2,y_2,z_2,x_3,y_3,z_3\} \) which represent the spatial coordinates of the three corners of the basic triangular units, were extracted for each entity.

6- Spatial analysis of the fault system

Considering that the ore bodies are mainly controlled by faults and are present in determinated sites, but not in others, it is inferred that particular geometrical features along these faults are responsible for gold deposition along with fluid-wallrock interaction and physico-chemical conditions in the time of the mineralisation. Extensional veins, dilational jogs, shear veins, divergent bends, etc., are all terms related with the geometry of the structures formed after the application of a directed regional stress to the rockmass. A measure of this deformation is the displacement along a fault, the azimuth and dip, the angle formed between faults, veins, joints, the orientation of the schistosity, etc.

In order to find relationships between gold mineralisation and the hosting structures, it is necessary a spatial discretisation of the faults into basic components, at a scale relatively similar to that of the gold assays, and to generate new variables relating the relative spatial position of gold and structure.

By construction, the fault surface is made from a variable number of ordered triangular facets connected by the sides, they represent the topology of the physical surface. The computation of the centroid (properly called hypocenter) of every triangular facet generates the points necessary for the analysis.

At the same time, operating on the normal vector to every facet it is possible to calculate its spatial orientation, in terms of azimuth and dip. Angular relations between facets or their normals, allow measures of coplanarity, convexity, bends and variability in azimuth and dip of the faults or lithological contacts. The vector equation of the plane for every single facet enables to discriminate points in space relative to this plane in terms of above and below, or in geological terms hangingwall and footwall.

The computation of the distance to the nearest facet in the fault for every gold value in space, generates a spatial variable that relates gold grade with azimuth, dip and proximity to the fault.

7- Customised software

To conduct quantitative spatial analysis to identify significant relationships between high-grade ore zones and the surrounding geology, dedicated data handling programs were developed. These specific pieces of software were created in Borland C++, to fulfill the necessity of spatial
analysis tools other than those which are standard in the mining software.

The name of each module, use and a sample of output chart is described below.

**FACET-3D:** for every facet on a fault surface, FACET-3D calculates the spatial coordinates of the centroid, azimuth, dip, dip direction, normal vector, director cosines, vectorial equation of the plane and fault identification (See Figure 1).

**DIST-3D:** for a set of spatially distributed gold assays, DIST-3D computes the shortest distance to a facet in the nearest fault. Discrimination between assays in the footwall and hangingwall is made through the sign of the relative distance. A (+) distance indicates points in the hangingwall and (-) in the footwall.

**LAG-ASSAY:** for a selected lag interval \( h \), LAG-ASSAY computes the average and frequency of gold assays within this lag distance relative to the nearest fault position, increasing the searching distance away from the fault surface until all assays are exhausted. The averages are calculated for a normally distributed population of assays as well as a three-parameter lognormally distributed population. In this case the lag \( h \) controls the amount of smoothing of the distribution and hence is called smoothing factor (See Figure 2).

**DIP-ASSAY:** for a selected dip interval of facets in the fault surface, DIP-ASSAY computes the average and frequency of gold assays associated to these facets. The averages are calculated for a normally distributed population of assays as well as a three-parameter lognormally distributed population (See Figure 3).

**AZIM_ASSAY:** for a selected azimuth interval of facets in the fault surface, AZIM_ASSAY computes the average and frequency of gold assays associated to these facets. The averages are calculated for a normally distrib-
uted population of assays as well as a three-parameter lognormally distributed population (Figure 4).

DEPTH-ASSAY: for a selected depth interval, DEPTH-ASSAY computes the average and frequency of gold assays within this interval relative to the surface level. The averages are calculated for a normally distributed population of assays as well as a three-parameter lognormally distributed population (Figure 5).

ROCK-ASSAY: for every rock-type present at the mineralised site, ROCK-ASSAY computes the average and frequency of gold assays within this rock. The averages are calculated for a normally distributed population of assays as well as a three-parameter lognormally distributed population (Figure 5).

STRIKE-BIN: for a selected portion of a fault, STRIKE-BIN splits and bins the assays at selected distances from an origin and computes the average and frequency of gold assays within these bins designed perpendicular to the fault strike. The averages are calculated for a normally distributed population of assays as well as a three-parameter lognormally distributed population (Figure 7).

DIP-AZIM: for selected intervals in dip and azimuth of facets in the fault, DIP-AZIM computes the frequency of facets within these intervals for further statistics.

8- Preliminary results

One important mine “Deposit A”, is examined using these techniques to quantify spatial relationships between gold mineralisation and structural features.

8.1- Proximity relationships

For Deposit A, a proximity relationship is identified between high-grade gold mineralisation and the portion of the fault hosting that mineralisation. Figure 2 shows that at a smoothing factor \( h \) of 10 meters, gold is concentrated in economic grades in a narrow corridor around the hosting fault. The distribution is asymmetric with the highest grades in the hangingwall up to 20 m away from the fault surface. In contrast the mineralisation in the footwall is less intense and restricted to the first 10 m, although the sampling frequency is less abundant in this portion of the fault.

For the discovery of parallel or secondary mineralised structures relatives to the main fault, the factor \( h \) has to be related to the sample size \( n \) and to the dispersion of the data. The more data available, the more precise is the search for details of the underlying density function.

Figure 8 demonstrates the effect of the factor \( h \) on a
density estimate of gold-distance to fault. \((h = 2.5\, \text{m})\). From Figure 1 it is known that the first 20 m away from the fault, in the hangingwall, is highly mineralised, using \(h = 2.5\, \text{m}\) it is possible to detect two discrete zones between 5 and 7.5 m and 12.5 and 15 m away from the fault accounting for most of the gold in the first 20 m. These peaks correlate in depth with two parallel structures hosting high grade mineralisation in the south portion of the deposit. These minor structures were not incorporated in the model, but are highlighted using the appropriate \(h\). See fig 7, bins 150.

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**Fig 4. Azimuth-assay chart**

**Fig 5. Depth-assay chart**
and 200 for the along-strike extension of this feature.

A buffer zone both sides of the fault can be distinguished according to appropriate cut-off grades to limit the lateral extension of the mineralised body.

8.2- Dip-Azimuth relationship

Identified a proximity relationship between gold mineralisation and the hosting fault, sections of the fault striking and dipping in a restricted interval of directions may be more prospective than others.

Applying an appropriate cut-off for high-grade assays, an $i \times j$ contingency table of frequency of facets within a par-
A particular interval of azimuth and dip can be constructed. Based on the relative proportion of facets in the fault, the expected number of facet related to high-grade can be calculated. These values are the expected if the position of the high-grades assays is independent of strike and dip.

For statistical reasons the expected value $E_{ij}$ for each interval should be greater than 1.0 without endangering the validity of the test (Conover, 1980). The cells in the contingency table of expected values with frequencies less than 1.0 are condensed into a fewer number of contiguous and logically arranged cells, so that no cell contains less than 1.0 expected facet. The same arrangement of cells is then applied to the observed $O_{ij}$ contingency table. The observed and expected tables can then be compared using a Chi-square test for independence with $m-1$ degrees of freedom, being $m$ the number of condensed cells.

The test statistic $c^2$ is given by

$$\chi^2 = \sum \sum \frac{(O_{ij} - E_{ij})^2}{E_{ij}}$$

where $E_{ij} = \frac{niCi}{Ni}$

$ni$ represents the number of facets for each interval of azimuth-dip in the fault, and $Gi/Ni$ the proportion of high-grade related to total facets for the deposit.

If a Dip-Azimuth to high-grade gold relationship is found to exist, the Chi-squared component of each Dip-Azimuth category can be examined to determine which particular combination of Dip-Azimuth is more prospective for high-grade values.

An example of contingency tables for a Chi-square test for independence between observed and expected facets of particular azimuth and dip associated to gold assays > 5 ppm, and critical values is shown in Figure 9.

As the statistic is larger than the critical Chi-square value, the null hypothesis that both distributions are identical is rejected at a confidence level of 95%, and consequently a high-grade dip-azimuth relationship is established.

Circular or spherical statistical analysis in case of azimuth or azimuth and dip data, is required to assess the deviation about the mean direction vector of the fault, of these more prospective sites. These departures can then be used as a predictive tool in the search for extensions of present deposits or to target new ones in similar geological conditions.
9- Conclusions
Quantification of controls on gold mineralisation at camps- scale requires a sound three-dimensional understanding of the geology and structures involved. Integration of detailed surface geological maps with subsurface underground mining and direct drilling information, lead to the construction of acceptable representations of the three-dimensional geology of the area. These models are used as a base on which to conduct gold prospectivity analysis. Dedicated data handling programs are designed to quantify and analyse spatial relationships that control known ore bodies. Characteristic features can be identified as more prospective and consequently used as a predictive tool in the location of new deposits.

References

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Fig. 9 Contingency table for Chi-square test of independence