POSTER

Structural Geology Meets 3D Implicit Deposit Modelling

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Introduction

Folding is a prevalent structural feature of many mineral deposits such as iron ore, lode gold and V(H)MS. Because of the geometrical complexity of folded ore deposits it is important to establish accurate, deposit scale 3D models to visualise, analyse and understand ore delineation and mineralisation processes.

The traditional explicit modelling approach utilized by many mining software packages is essentially a CAD (computer aided design) based technology. 3D models are constructed by manually linking hand-digitised 2D sections. This technique has obvious limitations, which lead to problems when dealing with structurally complex (e.g. folded) environments. Intersecting triangles and open triangulations are common technical problems, and geological models have to be simplified to overcome them. Moreover, "explicit models" are irreproducible and highly subjective due to the manual input of the modeller, hence inheriting bias from the outset. Objective structural interpretations are therefore difficult to achieve with explicitly defined 3D models (Cowan *et al.* 2002).

The alternative approach is implicit modelling, which is capable of generating internally consistent 3D geological models directly from borehole intersections, numerical data and structural measurements. Spatial interpolation calculations are performed and mathematical fitting functions are calculated to generate 3D isosurfaces of numerical (e.g. assay) and non-numerical (e.g. lithology) attributes. The resulting 3D model can be used to obtain ore body geometries and mineralisation trends, which can be linked to local and regional structural patterns observed in the field. We present results from implicit modelling and fieldwork from a case study at the Navachab gold deposit, Namibia.

3D Implicit Modelling

The implicit modelling technique allows the construction of 3D surfaces that are defined by a single mathematical volume function (implicit function). This function is calculated by spatial interpolation of numerical and non-numerical data points to define isosurfaces, which are represented graphically as triangulated meshes or wireframes with a user-defined resolution. In general, isosurfaces are 3D surfaces that embody points of a constant value within a defined volume space, and they can be used to display various types of data. Assay data is represented as isosurfaces based on metal content and are referred to as grade shells. Logged lithology information from drill core can be used to generate lithological isosurfaces that represent lithological boundaries. Bedding and foliation measurements are used to compute "structural isosurfaces", which are referred to as structural trend surfaces.

The software package Leapfrog 2.4 (AranzGeo) is used to process drill core data (assay & lithology) and structural field measurements (bedding & foliation) to generate a 3D geological model for structural interpretation purposes. Our implicit model is not used for resource estimation, although it does allow the definition of domains and search ellipsoid parameters necessary for the computation of a resource estimation block model.

Case Study: Navachab Gold Deposit (Central Namibia)

The Navachab open pit gold mine (operated and owned by AngloGold Ashanti Ltd.) is located on the steep north-western limb of the regional-scale, shallowly doubly-plunging anticlinal Karibib Dome (Kisters, 2005). Gold mineralisation occurs in several sets of auriferous quartz-sulfide veins and within bedding-parallel massive sulfide bodies (Fig. 1), hosted in Neoproterozoic, amphibolite facies metasediments of the Pan-African Damara belt. Crosscutting mafic and felsic dykes postdate and replace gold mineralisation. Several diorite and leucogranite intrusions are located within 5km of the Navachab deposit, but there is no direct contact between the mineralised system and any major intrusive body (Steven *et al.* 2011). The most likely source of the mineralising fluids are mid-crustal fluids in equilibrium with Damaran metapelites that underwent prograde metamorphism under amphibolite to granulite facies conditions (Wulff *et al.* 2010).

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Drill core logging data and assay results from RC (reverse circulation) and DC (diamond core) drill holes were used to model formation boundaries (lithological model) and assay values (grade shell model) implicitly. For both model types an isotropic interpolation was chosen to eliminate any bias or interpretation from the outset. An initial preliminary 3D model was used to identify and analyse ore delineation and ore body geometries, and to pinpoint key areas for fieldwork.

Vein Hosted Gold

Surface mapping in high grade key areas of the Navachab Main Pit (identified from the initial 3D model) reveal that gold mineralisation is hosted in stacked, folded quartz-sulfide veins that vary in thickness and form shallowly dipping packages, which have higher vein frequency and sub-meter vein spacing. Depending on host rock rheology, these vein packages are tightly to openly folded. The veins crosscut subvertical bedding at a high angle and form upright to slightly inclined folds with shallowly NE plunging fold axes. The orientation of these fold axes differs to those of the first-order regional dome structure which plunges shallowly at surface and more steeply at depth, resembling the orientation of the massive sulfide mineralisation. Consequently, the gently-dipping auriferous quartz veins must have been emplaced under different stress conditions than the bedding-parallel auriferous massive sulfides. This is in agreement with the conceptual model proposed by Kisters (2005), in which highly discordant sets of sheeted quartz veins were emplaced during the late lock-up stage of the Karibib Dome. The shallowly dipping orientation of the enveloping surface of the folded, auriferous quartz-sulfide veins coincides spatially with high-grade ore zones computed in the implicit 3D geological model. Their downward continuity has been drilled to a length of about 1000m. However, the lateral extent of the veins is restricted and is most probably controlled by changes in host rock lithology.

Additionally, subvertical (bedding-parallel) quartz and quartz sulfide veins have been mapped in the Lower Schist of the Navachab Main Pit. Their unfavourable orientation parallel to the pit face has limited their recognition in the field, but they have been identified in drill cores from subhorizontal dewatering holes. Ambiguous crosscutting relationships between the subvertical and the shallowly dipping auriferous veins suggest that their emplacement was contemporaneous. Fluid overpressure was probably able to propagate fractures perpendicular to the regional shortening direction by exploiting bedding-parallel zones of weakness and forming this subvertical vein set. The geometry and orientation of the computed high-grade ore shell within the Lower Schist suggests the existence of bedding-parallel gold mineralisation.

Massive Sulfide Hosted Gold

Mapping of the auriferous massive sulfide lenses was not possible because of limited exposure and mining activities

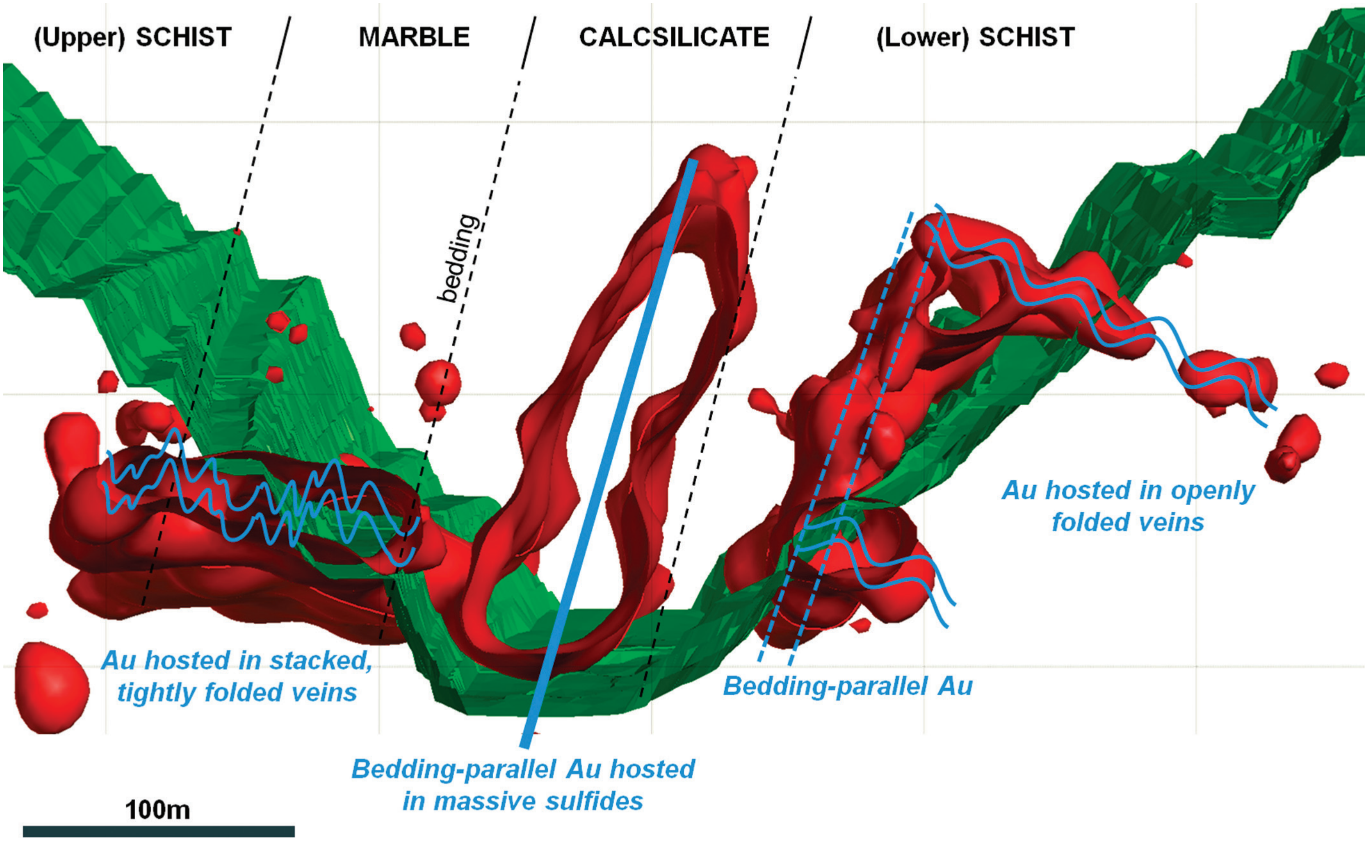

Figure 1. WNW-ESE slice through the central part of the Navachab Main Pit (green) and the isotropically interpolated high grade ore zone (red). Schematic annotation of mineralisation trends observed in the field (blue).

during our fieldwork, but we were able to improve our understanding of their occurrence based on available data. Bedding measurements extracted from regional geological maps were used to compute a regional bedding (S0/S1) structural trend surface. A calculated mean axial planar foliation (S2) value, based on field measurements at Navachab, was applied as a weak, planar anisotropy (2:1:1) to the interpolated structural trend surface in order to take into account the asymmetry of the Karibib Dome. The data suggests that the Navachab gold deposit is located on the inflection line of the steep north-western limb of the regional scale Karibib Dome. Kisters (2005) proposed that the bedding-parallel massive sulfide lenses (high-grade ore shoots) represent dilational jogs that opened during flexural flow along bedding-parallel slip planes during the amplification of the Karibib Dome.

Shear strain associated with flexural flow in a fold will reach peak values in proximity to the steep limb's inflection line during fold amplification. For originally horizontal layers folded into an upright fold, shear strain is equal to the tangent of the layer dip (Fossen, 2010). Steeply dipping beds will therefore experience higher shear strain / flexural flow than shallowly dipping ones. In the case of Navachab, the maximum bedding parallel shear was spatially confined to the inflection line of the fold, which likely controlled the generation of favourable pipe-like fluid pathways. Since a pipe-like geometry is more conducive to flow than a fracture network (Blenkinsop, 2004), this may explain why the highest gold grades at Navachab are confined to the inflection line of a regional antiform.

The lithological contrast at the contact of the marbles / calc-silicates that host the massive sulfide shoots within the silicified biotite schist unit may also have played an important role in strain partitioning. The contact represents a pronounced rheological contrast, which likely experienced greater shear strain rates during fold amplification, thereby enhancing fluid flow rates (Kisters, 2005).

Conclusion

Implicit modelling in conjunction with fieldwork allows identification and evaluation of structural controls on deposit geometries, thereby improving understanding of the relationships between mineralisation and deformation. At the deposit scale, we were able to link computed high-grade zones to shallowly dipping, stacked packages of folded quartz-sulfide veins within metasedimentary formations. Based on a regional scale bedding trend model we identified a spatial relationship between the first order domal structure and the auriferous massive sulfide mineralisation at Navachab. We propose that inflection lines of close to tight folds are preferred sites of mineralisation and represent pipe-like traps and/or conduits for ascending fluids of various origins. Our results have implications for exploration activities in similar tectonic environments and should be considered in the planning stage of drill hole targets.

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