Regional dome evolution and its control on ore-grade distribution: Insights from 3D implicit modelling of the Navachab gold deposit, Namibia

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ABSTRACT

We introduce a novel approach to analyse and assess the structural framework of ore deposits that fully integrates 3D implicit modelling in data-rich environments with field observations. We apply this approach to the early Palaeozoic Navachab gold deposit which is located in the Damara orogenic belt, Namibia. Compared to traditional modelling methods, 3D implicit modelling reduces user-based modelling bias by generating open or closed surfaces from geochemical, lithological or structural data without manual digitisation and linkage of sections or level plans. Instead, a mathematically defined spatial interpolation is used to generate 3D models that show trends and patterns that are embedded in large drillhole datasets. In our 3D implicit model of the Navachab gold deposit, distinctive high-grade mineralisation trends were identified and directly related to structures observed in the field. The 3D implicit model and field data suggest that auriferous semi-massive sulphide ore shoots formed near the inflection line of the steep limb of a regional scale dome, where shear strain reached peak values during fold amplification. This setting generated efficient conduits and traps for hydrothermal fluids and associated mineralisation that led to the formation of the main ore shoots in the deposit. Both bedding-parallel and highly discordant sets of auriferous quartz-sulphide veins are interpreted to have formed during the later lock-up stage of the regional scale dome. Additionally, pegmatite dykes cut across and remobilise gold mineralisation at the deposit scale and appear to be related to a younger joint set. We propose that kilometre-scale active folding is an important deformation mechanism that influences the spatial distribution and orientation of mineralisation in ore deposits by forming structures (traps and pathways for fluids) at different preferred sites and orientations. We also propose that areas that experience high shear strain, located along the inflection lines of folds can act as preferred sites for syn-deformational hydrothermal mineralisation and should be targeted for regional scale exploration in fold and thrust belts. Our research also suggests that examination of existing drillhole datasets using 3D implicit modelling is a powerful tool for spatial analysis of mineralisation patterns. When combined with fieldwork, this approach has the potential to improve structural understanding of a variety of ore deposits.

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changing history of brittle and ductile deformation for economic mineralisation. These changes are important because they influence fluid flow and control the formation of dilatational sites that can act as traps for hydrothermal fluids (Leader et al., 2011). It follows that the shape, size, orientation and spatial distribution of ore bodies contain important information about the deformation history of an ore deposit and the associated interactions between host rock types, fluid flow and structures (Blenkinsop and Kadzviti, 2006). Work by Blenkinsop (2004) on two lode gold deposits from the Zimbabwe craton, studies by Bauer et al. (2014) on VMS deposits in the Swedish Skellefte district, 3D modelling and analysis of nickel sulphide shoots at the Kambalda dome (Western Australia) by Stone et al. (2005) and investigations on the vein-hosted gold ore body at Sunrise Dam (Western Australia) by Hill et al. (2013) demonstrate that shapes and orientations of ore bodies or mineralised zones contain important information about the evolution of ore deposits. The analysis of structures that transport and trap hydrothermal fluids is therefore of major scientific and economic significance. By understanding the genetic relationship between (mineralised) structures and associated physical processes, we can potentially predict areas with a greater potential for mineralisation in similar tectonic environments. In this paper, we present a structural interpretation workflow that uses 3D implicit modelling to visualise and analyse geochemical and geological trends from an extensive drillhole dataset from the Navachab gold deposit, Namibia (provided by AngloGold Ashanti Ltd). Such drillhole data are normally used to compute block models for the economic assessment of a project. For each block of these models, important key values and properties are either assigned or calculated, such as net present value, metal content, density or rock type. Block models are powerful and well-established tools for resource estimation, grade control and scheduling, where the main purpose is to evaluate, maximise and optimise the economics of a project. However, they are less valuable for understanding the geology and structural framework of a deposit.

Recent developments in geological modelling software (e.g., 3D implicit modelling) allow for the precise and objective generation of spatial representations of lithological contacts, mineralisation (grade shells) and structural trends in data-rich environments. Instead of labourious manual cross-section digitisation, spatial interpolations of geological data are employed to produce models with minimised user-induced modelling bias. In our case study of the Navachab gold deposit, initial 3D implicit modelling was followed by structural fieldwork and data collection in the Main Pit and Eastern Zone 1 of the mine. Field observations and structural data were compared to the orientation, size and spatial distribution of implicitly modelled ore bodies and host rock stratigraphy. Additionally, a 3D implicit structural trend model computed from regional bedding orientation measurements was used to calculate and visualise the spatial distribution of shear strain related to the amplification of a regional scale domal structure. This structural trend model allowed us to evaluate the regional structural context of gold mineralisation, suggesting that auriferous ore shoots within the Navachab deposit were controlled by the regional-scale, non-tectonic trend model allowed us to evaluate the regional structural context of gold mineralisation, suggesting that auriferous ore shoots within the Navachab deposit were controlled by the regional-scale, non-tectonic trend. In our case study of the Navachab gold deposit, initial 3D implicit modelling was followed by structural fieldwork and data collection in the Main Pit and Eastern Zone 1 of the mine. Field observations and structural data were compared to the orientation, size and spatial distribution of implicitly modelled ore bodies and host rock stratigraphy. Additionally, a 3D implicit structural trend model computed from regional bedding orientation measurements was used to calculate and visualise the spatial distribution of shear strain related to the amplification of a regional scale domal structure. This structural trend model allowed us to evaluate the regional structural context of gold mineralisation, suggesting that auriferous ore shoots within the Navachab deposit were controlled by the regional-scale, non-cylindrical folding responsible for the formation of the Karibib dome.

Our case study illustrates how 3D implicit modelling in conjunction with selective fieldwork can aid in the extraction of additional structural and ore-genetic information from existing datasets. At the Navachab gold deposit, it improved and extended understanding of the structural framework that controlled syn- and post-deformational mineralisation, pointing towards a strong relationship with regional scale folding.

2. Regional geology

The Navachab gold deposit is situated approximately 10 km SW of the town of Karibib (Namibia). The current open pit activities represent the only fully operating gold mine in Namibia. However, in recent years new discoveries of gold mineralisation have been reported approximately 20 km and 150 km NE of the present mine site (Helio Resources, 2012; Lombard et al., 2013) as part of B2Gold’s Otjiokoto project (formerly operated by AurouxGold) and Damara Gold Corp.’s Gold Kop target (formerly Helio Resources). These have both been described as having a similar style of mineralisation to that at the Navachab gold deposit.

The Navachab gold deposit is located in the S part of the Central Zone of the Damara belt, also known as the Southern Central Zone. The Central Zone is one of several tectonostratigraphic domains within the Pan-African Damara orogen (Miller, 1983) (Fig. 1). The majority of mineral deposits are located in the Central Zone and are associated with rocks that have been subjected to medium- and high-grade metamorphism (Pirajno and Jacob, 1991).

The Damara belt extends to the NE and links with the Lufilean orogen in Zambia–Angola–Congo (Pirajno, 2008). The Pan-African orogeny is commonly used to describe magmatic, tectonic and metamorphic activity during the Neoproterozoic (~870 Ma) to early Palaeozoic (~550 Ma) orogenic episode (Kröner and Stern, 2004).

The tectonic evolution of the Damara belt started with the initiation of an intracontinental, asymmetric rift between the Congo craton and the Kalahari craton during the break-up of Rodinia around ~780–750 Ma (Barnes and Sawyer, 1980; Miller and Frimmel, 2009; Miller et al., 2009). The sedimentary fill of the newly opened graben in the S (Nosib Group) exceeds 6 km in thickness and consists of feldspathic sandstones, playa lake and evaporitic sabkha deposits (Miller et al., 2009). Rifting led to siliciclastic and carbonate sedimentation before and during the subsequent formation of an oceanic basin (Khomas sea). The final width of the Khomas sea is estimated to about 1200–1500 km (Miller et al., 2009). The Matchless Amphibolite is the metamorphosed remnant of oceanic crust (sea-floor basalt) which formed during that time, and is host to several VMS and (epigenetic) copper deposits (Breitkopf and Maiden, 1988).

Reversal of plate motion and formation of a N dipping subduction zone led to the closing of the Khomas sea and the collision of the Kalahari craton in the S with the Congo craton in the N around 540 Ma to 520 Ma. Convergence culminated in the formation of the Cambrian supercontinent Gondwana and caused thrusting and folding within the Damara belt. In the Karibib area, the thrusting and folding at 560–540 Ma is related to an early phase of crustal thickening owing to continent–continent collision (Longridge, 2012).

Navachab is located in deformed, primarily metasedimentary rocks (calcisilicates, marbles, schists and metapelites) of the several km thick Neoproterozoic Damara Supergroup, which is floorby Mesoproterozoic (~2.0 to ~1.7 Ga) gneisses of the Abbabis Metamorphic Complex (Jacob et al., 1978; Kisters, 2005). Syn- and post-tectonic granitic magmatism is widespread and voluminous in the Damara belt and is reflected as post-tectonic thermal peaks in thermochronological data (Miller and Frimmel, 2009; Tack and Bowden, 1999). Slab breakoff caused asthenospheric upwelling and heating of the lower crust and provided heat for the metamorphism and melting of the crust around 540–535 Ma to produce anatetic red granite (Longridge, 2012). Several diorite and leucogranite intrusions are located within 5 km of the Navachab deposit, but there is no direct contact between the mineralised system and any major intrusive body (Steven et al., 2011).

Metamorphic conditions within the Southern Central Zone decrease towards the NE (along strike) from granulite facies (P ~ 5 kbar, T ~ 700–800 °C, Nex et al., 2001; Masberg, 2000; Masberg et al., 1992) with partial melting (Toé et al., 2013) in the SW coastal regions to lower amphibolite-facies (P ~ 3 kbar, T ~ 560–650 °C, Puhak, 1983; Steven, 1993) in the Karibib district, as progressively shallower stratigraphic levels are exposed (Kisters et al., 2004). The temperature-dominated metamorphism in the Karibib district has been associated with periods of voluminous intrusions (Jung and Mezger, 2003; Miller, 1983), which led to pervasive recrystallisation and obliteration of tectonic fabrics, especially in marbles throughout the Southern Central Zone (Kisters, 2005).

The Southern Central Zone is bound by two roughly parallel, NW trending, major lineaments which coincide with large-scale facies...
The Okahandja lineament (Okahandja shear zone) was the locus of continental break up and represents the N bounding fault of the S graben during rifting as well as the leading edge of the overriding Congo craton during perges (Miller et al., 2009, 2010). The Omaruru lineament (Omaruru shear zone) forms the S boundary of the N graben and has been interpreted to have acted as a growth fault throughout the spreading phase, associated with substantial sedimentary-exhalative activity (Miller et al., 2009). The Navachab deposit lies between these two first-order, major crustal structures (Fig. 1).

Elongated, kilometre-scale NE trending domal structures define the regional structural grain of the Southern Central Zone. One such dome is the Karibib dome, which hosts the Navachab gold deposit at its steep NW limb, formed by SE-NW shortening (Fig. 2). Kisters et al. (2004) suggested that a blind thrust led to the formation of the Karibib Dome as a tip-line fold. The moderately steep dipping S limb of the Karibib dome is overridden from the SE by the Mon Repos thrust zone, where top-to-the-NW movement pushed crystalline gneisses of the Abbabis Metamorphic Complex over the younger Damara Sequence (Kisters et al., 2004).

SHRIMP U–Pb dating of single zircons from syn-kinematically intruded, foliated diorites and granodiorites (Mon Repos diorite-granodiorite, 546 ± 6 Ma and 563 ± 4 Ma) and post-tectonic, undeformed monzogranites (Rote Kuppe granite, 543 ± 5 Ma) has provided constraints on the timing of this regional thrusting event (Jacob et al., 2000; Kisters et al., 2004).

3. Main characteristics of the Navachab gold deposit

The Navachab gold deposit has been owned and operated by AngloGold Ashanti Ltd since 1998, but was acquired by QKR Corporation Limited in 2014 (G. Bell 2014, pers. comm.). At the end of 2012, Navachab had gold mineral resources of 4.4 Moz and reserves of 2.1 Moz. The mine produced 46,000 oz of gold in the first nine months of 2013. The Navachab gold deposit can be divided into three main areas: Main Pit, North Pit and Eastern Zone 1 (Fig. 3).

3.1. Lithostratigraphy

The Navachab gold deposit is hosted within NE striking, steeply NW dipping amphibolite facies marbles and schists of the Damara Supergroup, which form the NW limb of the kilometre-scale Karibib dome (Fig. 2). The Karibib dome is a shallowly doubly-plunging, NW verging asymmetric antiform with a length of about 12 km and a width of approximately 4 km. The oldest rocks in the area around the Navachab gold deposit are Palaeoproterozoic gneisses, schists, amphibolites and pegmatitic rocks of the Abbabis Metamorphic Complex (Jacob et al., 1978; Tack and Bowden, 1999), which are exposed in the core of the Karibib dome (Kisters, 2005), but do not crop out at the Navachab mine. The Damaran metasedimentary rocks unconformably overlie the Abbabis Metamorphic Complex starting with arkoses, quartzites, conglomerates and minor metavolcanic rocks of the Etusis formation.

![Geological map of Namibia showing tectonostratigraphic domains of the Damara belt after Miller (1983). The Navachab gold deposit is located within the Southern Central Zone of the Panariftic Damara belt, between the Omaruru Shear Zone in the N and the Okahandja Shear Zone in the S.](image-url)
The up to 1500 m thick Etusis formation can be observed as dominant ridges to the SE of the Navachab gold deposit (Kitt, 2008), but is only exposed within the oxidised zone of the Eastern Zone 1 at the mine site. It consists of highly oxidised and weathered, interbedded layers of sandstone and siltstone. Stratigraphically higher is the Chuos formation, which also crops out in Eastern Zone 1 and consists mainly of metaquartzites in the upper part and a diamictite in the lower part. These have been interpreted as glaciomarine in origin and related to the late Neoproterozoic (746 $\pm$ 2 Ma) Sturtian glaciation (Hoffmann et al., 2004). Finely distributed, bedding-parallel sulphides (mainly pyrrhotite) have been observed in the Chuos formation. The Chuos formation is overlain by the biotite-schist and calcsilicate rock dominated Spes Bona formation. The contact of the Chuos formation with the overlying Spes Bona formation has been mapped in Eastern Zone 1. The Spes Bona formation has a true thickness of up to 220 m and is overlain by the up to 160 m thick Okawayo formation, which mainly consists of marbles and also hosts the auriferous semi-massive sulphide ore shoots at its footwall contact. The latter part is dominated by a cm to dm banded sequence of calcsilicate rocks and marbles. The uppermost part of the Okawayo formation comprises greyish massive and brecciated (dolomitic) marbles. The marble-dominated Karibib formation lies on top of the Oberwasser formation, which is up to 180 m thick in the Main Pit. The Oberwasser formation is compositionally very similar to the Spes Bona formation.

Overlying the Okawayo formation are metasedimentary and minor calcisilicate rocks of the Oberwasser formation, which is up to 180 m thick in the Main Pit. The Oberwasser formation is compositionally very similar to the Spes Bona formation. The marble-dominated Karibib formation lies on top of the Oberwasser formation and is followed by metapsammitic and metapelitic rocks of the Kuiseb formation. The latter represents the uppermost formation of the Damara Supergroup, but it does not crop out at the Navachab mine.

The Okawayo formation is intruded by meta-lamprophyre sheets and dykes. U–Pb SHRIMP analyses of titanite grains from a meta-lamprophyre dyke yielded an age of 496 $\pm$ 12 Ma, which probably records a metamorphic overprint (Jacob et al., 2000). At the Navachab gold deposit, the youngest igneous activity occurs as bedding-parallel and mainly highly discordant, subvertical pegmatite dykes of unknown age.

### 3.2. Gold mineralisation

Mineralisation at the Navachab gold deposit is associated with pyrrhotite and minor amounts of pyrite, chalcopyrite, arsenopyrite, sphalerite, maldonite, bismuthinite, native bismuth and bismuth tellurides (Dziggel et al., 2009; Nörtemann et al., 2000; Wulff et al., 2010). Gold occurs mainly as native gold, but is also present in minerals such as maldonite (Au$_2$Bi) and as a solid solution with bismuth (Nörtemann et al., 2000). Stable isotope (O, H, C, S) analyses by Wulff et al. (2010) suggest that gold precipitated from a metamorphic, mid-crustal fluid derived from Damaran metapelites that underwent prograde metamorphism under amphibolite (ca. 550 °C and 2 kbars) to granulite-facies conditions.

At the Navachab gold deposit, mineralisation occurs in two main styles: 1) bedding-parallel semi-massive sulphide bodies, referred to as ore shoots (or massive skarns, Miller, 1983), and 2) bedding-parallel and highly discordant sets of auriferous quartz-sulphide veins. The ore shoots are discrete, elongate zones within a planar contact surface that contain higher metal contents than the adjacent parts of the host rock (Peters, 1993a). The two known ore shoots in the Navachab gold deposit are economically defined by relatively high gold grades of 3–7 ppm (Steven and Badenhorst, 2002). One major ore shoot (main shoot) is located in the Main Pit, the second, smaller and less extensive
ore shoot (2nd shoot) is located at a structurally higher level and is mined in the North Pit. Both ore shoots are defined by numerous, mineralised semi-massive sulphide lenses that can be up to 5 m high and 1.5 m wide in cross-section (Kisters, 2005). The semi-massive sulphide lenses are aligned to form a shallowly NNE plunging, high-grade gold trend with a down-plunge extent of at least 1800 m. The semi-massive sulphide lenses are elongated to typically rhomb-shaped bodies that are parallel to the compositional layering and locally show evidence for hydraulic brecciation (Wulff, 2008). The semi-massive sulphide lenses consist of pyrrhotite (up to 50 vol.%), garnet (10–30 vol.%), clinopyroxene (5–10 vol.%, mainly diopside), minor chalcopyrite, sphalerite, bismuth, bismuthinite, bismuth-tellurides, arsenopyrite, as well as quartz, biotite and K-feldspar (Dziggel et al., 2009; Nörtemann et al., 2000).

The ore shoots are located in the marble and calcisilicate rock dominated, approximately 30 m thick MC unit at the base of the Okawayo formation, near the contact with the underlying (partly silicified) biotite-schist rich Spes Bona formation. Studies of the calcisilicate minerals (Dziggel et al., 2009; Wulff, 2008) as well as structural evidence (Kisters, 2005) support a relatively late stage and alteration-related origin for the most of the calcisilicate banding within the MC unit.

The second style of gold mineralisation is hosted in flat-lying, vertically stacked, quartz-sulphide veins that crosscut the subvertical bedding of the host rocks at high angles. In marble host rocks, quartz-sulphide veins can mostly comprise pyrrhotite with minor quartz, whereas in biotite schist and banded calcisilicate host rocks quartz-sulphide veins mainly consist of quartz with up to 30 vol.% sulphide minerals such as pyrrhotite (Dziggel et al., 2009). Additionally, a relatively subordinate quartz-sulphide vein set occurs parallel to bedding, particularly in well-bedded units such as the Oberwasser Formation and Spes Bona Formation (Kisters, 2005).

Several genetic models for mineralisation at the Navachab gold deposit have been suggested. The close spatial and temporal association of the deposit to Pan-African granitoids (Nörtemann et al., 2000; Pirajno and Jacob, 1991), the presence of skarn-type alteration assemblages, as well as an unusual metal association of Au–Bi–As–Cu–Ag (Dziggel et al., 2009) have been used to suggest an origin as an
intrusion-related gold deposit (Thompson et al., 1999). However, recent structural studies by Kisters (2005), Kitt (2008), and Creus (2011) and geochemical investigations by Wulff et al. (2010) point to formation as an orogenic gold deposit.

3.3. Structural history

Three main phases of deformation have been described in the Central Zone of the Damara belt (Barnes and Sawyer, 1980) affecting both pre-Damaran basement (Abbabis Metamorphic Complex) and the metasedimentary rocks of the Damara Supergroup. However, only two main deformation phases have been recorded in Damaran rocks within the Navachab deposit. The oldest deformation is expressed by a bedding-parallel or bedding-subparallel S1 foliation defined by the preferred orientation of mica in metasedimentary rocks, visible within the Spes Bona and Oberwasser formations. Flattened clasts in diamictites of the Chuos formation observed in Eastern Zone 1 are also parallel to S1. Transposition of bedding (S0) into the S1 fabric impedes a full characterisation of S1. However, as also observed by Kisters (2005), rare isoclinal intrafolial folds mapped in banded marbles and calcsilicates of the Okawayo formation within the Main Pit indicate that S1 is a composite S0,1 fabric. S0,1 is most probably related to an early D1 low angle thrusting event (Kisters, 2005).

The main deformational phase is D2, which is characterised by upper-right, km-scale NE trending folds with doubly-plunging fold axes, such as the Karibib dome. The NE striking axial planar foliation (S2) of the Karibib dome dips steeply SE and indicates an asymmetric, NW verging fold geometry that formed during NW-SE shortening. Consequently, the NW limb of the Karibib dome dips more steeply than the SE limb.

4. 3D geological modelling

Selecting an appropriate modelling technique not only depends on the geological complexity and the available data (Guillen et al., 2008), but also on the intended function or purpose of the model (Stachowiak, 1973). The two main methodologies used for 3D geometrical modelling of ore deposits, termed explicit and implicit modelling (Cowan et al., 2003; Jessell et al., 2014; Ledez, 2003) are reviewed briefly below.

Before the advent of modern software and hardware, geological findings were hand drawn and stored on paper (2D) as sections and maps. Even though routinely transferred into digital formats, such sections and maps still form the foundation of traditional 3D explicit geological models (Cowan et al., 2003). Explicit models rely on manual definition of geological boundaries by digitisation of sections that are later linked to generate 3D bodies and surfaces. The data are stored digitally and can be visualised in 3D, which provides major advantages (Vollger and Kasl, 2010). It does, however, still underutilise the inherent possibilities of 3D modelling. The basic concept of this methodology emerged out of computer aided design (CAD) applications. CAD programmes were originally developed for industrial design purposes, where the manual (explicit) drawing approach is appropriate because the shape and dimension of objects are precisely defined and known beforehand. However, this does not necessarily apply to 3D geological modelling in data-rich and geometrically complex geological environments. The manual definition of each element makes explicit modelling workflows time consuming and also introduces a strong bias inherited from geological interpretation during digitisation and linkage of cross-sections, resulting in unique and non-reproducible models (Cowan et al., 2002, 2003, 2011; Jessell et al., 2010; Lindsay et al., 2012, 2013a, b). Additionally, manual linking of cross-sections with complex geometries regularly forces the modeller to adapt and simplify the model to stay within a practical timeframe (Cowan et al., 2003), hence inhibiting the graphical representation of the full structural and geological complexity of the ore deposit. In summary, the manual approach used in explicit geological modelling is a subjective, time-intensive and a non-reproducible process in which geological interpretation is inherited from the outset; hence its application for purposes of structural interpretation must be viewed with caution.

Alternatively, implicit modelling is a technique where surfaces and volumes (= closed surfaces) are not explicitly defined, but mathematically described as isovalues of a volumetric scalar field (Calcagno et al., 2008; Carr et al., 1997; Caumon et al., 2013; Frank, 2006; Jessell et al., 2014; Maxelon et al., 2009; McInerney et al., 2005) (Fig. 4). Scalar fields are computed based on a global interpolation function (e.g., radial basis function; RBF) that is fitted to data points. Early applications of the RBF interpolation scheme were employed by Hardy (1971) to calculate elevation contour lines based on irregular topographical data. However, the main development of this scalar field-based technique originated from developments in computer graphics, where the aim was to reconstruct solids and surfaces from scattered point data for applications in tomography, LIDAR, animation and visualisation of complex shapes (Carr et al., 1997, 2001; Savchenko et al., 1995; Turk and O’Brien, 2002). The first time scalar-field based modelling was used in a geological context was by Lajamie et al. (1997), who referred to it as implicit form and used it to spatially interpolate structural data. Another geological application of this interpolation method was by Billings et al. (2002), who used so-called continuous global surfaces to interpolate geophysical datasets. Cowan et al. (2002) first introduced rapid geological modelling using Leapfrog, a software package that employs RBFs to spatially interpolate large drillhole datasets to build 3D geological models of ore deposits. This RBF-based interpolation is computationally expensive and was initially considered to be impractical (Sibson and Stone, 1991). However, mathematical advances resulted in the ability of RBFs to rapidly interpolate large datasets (Beatson et al., 1999). Cowan et al. (2003) introduced the term implicit modelling to the mining industry and highlighted the advantages that arise from an implicitly defined 3D model compared to traditional explicit 3D modelling methods that rely on manual digitisation. Other implicit modelling schemes have been referred to as implicit surface representation, potential field interpolation or potential field method (not to be confused with geophysical modelling of potential field data) in subsequent publications (Calcagno et al., 2006; Chiles et al., 2004; Lane et al., 2007; Ledez, 2003; McInerney et al., 2007; McInerney et al., 2005).

The proliferation of terminology for 3D geological modelling methods that share a common mathematical approach has led to an inconsistent understanding of the term implicit modelling. To clarify, in implicit modelling, an implicit function (generic format f(x, y, z) = 0) is computed and fitted to a set of spatial data (points, lines, structural data) (Fig. 4a). This implicit function describes a volumetric scalar field, which assigns a scalar value to every point in space (Fig. 4b). Isovalues of this field can be extracted and used to define open or closed 3D isosurfaces, which can be envisaged as 3D analogues of 2D contour lines (Fig. 4c). Since the term implicit modelling refers to the mathematical description of a surface, it should only be applied in geological models that comprise surfaces obtained from a scalar field. To visualise these surfaces an independent step, that commonly includes the marching cubes algorithm (Lorensen and Cline, 1987), is necessary to generate triangulated meshes that can be rendered on a screen. Theoretically, a surface of any resolution could be extracted from an implicit function. However, practical and computational limitations will impact the final resolution of the rendered surface.

In general, implicit modelling can be used to spatially interpolate numerical (e.g., assay) and non-numerical (e.g., lithology) data points to define scalar fields. In the case of non-numerical data so-called signed distances are calculated for each data point, which describe the distance to a surface of interest (e.g., the contact between two geological formations) (Carr et al., 2001; Cowan et al., 2003). This boundary is then represented by an isosurface that smoothly fits all data points with a signed distance value of 0. In addition to isosurfaces based on lithological data, geochemical data (assay data) can be used to compute isosurfaces (referred to as grade shells) at various threshold grade values. Moreover,
when dealing with multi-element datasets, various grade shells for each element can be rapidly computed and visualised.

Implicit modelling also permits the direct integration and processing of planar structural measurements, producing structural isosurfaces by adjusting the gradient of the scalar field, as described in detail by Hillier et al. (2013). Computed surfaces are referred to as structural trend surfaces and can be used to visualise the structural grain of an area in 3D. An important characteristic of implicitly defined (iso-) surfaces is their ability to describe complex geometries, such as overturned folds or domes (Cowan et al., 2003; Jessell et al., 2010, 2014; Wellmann et al., 2010).

The direct link between data and the 3D model is a major advantage of the implicit modelling method; updates and changes are straightforward to make when additional or new data becomes available, which is an attribute that has partly driven its development (McInerney et al., 2007). This direct link also eliminates the directional bias that is inherent in traditional, manually defined explicit models, which are commonly based on a series of parallel cross-sections that are often complemented by additional long-sections, surface and level maps. Geological trends or structures oriented parallel or at low angles to these sections are commonly overlooked and become under-represented in such models. Therefore, in geologically complex and poly-deformed environments where mineralisation and structures are expected to have various orientations, an implicit modelling approach should be preferred.

Implicit modelling removes the need for time-consuming rebuilding of wireframes, allowing the continual development of geological models throughout the life of a project (Mortimer, 2010). In addition, it also supports the testing of multiple hypotheses (Jessell, 2001) in a reasonable amount of time by modifying parameters (e.g. isotropic versus anisotropic interpolations), applying structural trends (directly calculated from structural measurements) or by adapting boundaries or trend. Concatenated files are automatically updated, keeping the model coherent and giving the geologist more time to focus on geological issues and to evaluate the plausibility of different interpretations. Furthermore, implicit modelling is attractive because it makes 3D geological modelling a reproducible task, which is required for the quantification of geological uncertainty in 3D models (Ailleres et al., 2010; Chilès et al., 2004; Lindsay et al., 2010, 2012, 2013a,b; Wellmann et al., 2010).

There are, however, some limitations in using an implicit modelling workflow. Computed surfaces will always try to achieve a smooth fit due to the nature of the RBF-based spatial interpolation. In data-rich environments with large amounts of control data this is a less relevant problem. However, with sparse datasets the resulting model will become over-smoothed and will not reflect sudden changes or steps such as fault offsets. The lack of control data is generally problematic for all types of 3D modelling (explicit or implicit). In such under-constrained environments, additional data are commonly manually introduced based on knowledge and experience to generate a model that complies with the geological understanding at the time of creation. To avoid any bias that may be inherited from models that have been modified based on assumptions instead of measured data, the modelling workflow described in this paper is limited to data-rich environments, where high-data density allows direct computation of boundaries and surfaces without manual, knowledge driven digitisation. For objects with a narrow geometry such as dykes, this criterion is rarely met and unaided implicit modelling without manually introduced constraints do not deliver satisfactory results. Another shortcoming is that RBF-based spatial interpolation tends to generate balloon-like grade shells in areas where insufficient control data are available, such as the outer edges of a model (e.g., Fig. 8, long section). Furthermore, the type of RBF (Gaussian, multiquadric, or polyharmonic spline) used for the spatial interpolation will affect the resulting model (Jessell et al., 2014). However, in dense data environments the impact of the chosen RBF appears to be minimal (Hillier et al., 2014). Nevertheless, care must be taken when interpreting such models and also when using the calculated grade-shell volumes for an economic assessment of an ore deposit.

Several 3D mining and geological modelling software packages such as GOCAD (Paradigm, 2014), earthVision (Dynamic Graphics Inc., 2014), GeoModeller (Intrepid Geophysics, 2014), Vulcan (Maptek, 2014), Surpac (Geovia, 2014), Micromine (Micromine, 2014) and Petrel (Schlumberger, 2014) have incorporated (semi-) implicit modelling engines.

4.1. 3D implicit modelling of the Navachab gold deposit

In our study we aim to structurally interpret a 3D geological model of the Navachab gold deposit, based on available drillhole data and structural data extracted from geological maps and collected in the field. It is therefore important to generate objective 3D models that delineate geological boundaries, geochemical anomalies (ore bodies, mineralised zones) and structural trends. Our 3D implicit modelling workflow is confined to areas of high drillhole data density which allows us to directly compute 3D models without manual interaction (e.g., digitisation). This is quite different from a traditional explicit modelling approach, where 3D models are based on cross-sections that have assumptions about the geological and structural framework of the deposit already embedded. The aim of our workflow is to identify and analyse trends in large drillhole datasets and relate them to structures observed in the field. We also test the hypothesis that if mineralisation is structurally controlled or influenced, modelled ore-body geometries, orientations and spatial locations will outline and reveal associated first- or lower-order structures and contribute to the understanding of the processes that formed them.

For this study, the implicit modelling software package Leapfrog Mining 2.6 (ARANZ Geo, 2014) was chosen because it has the capability to process large amounts of data (several thousands of drillholes,
millions of samples) using an RBF-based algorithm on ordinary computing hardware. Data for implicit modelling were extracted from a drillhole database provided by AngloGold Ashanti Ltd in 2012. It included gold assay data, lithological data (drillhole logs), collar data and survey data for boreholes drilled between May 1986 and January 2012. Maps of the regional geology and digital elevation models (DEM) of the region and the mine were also provided and incorporated into the 3D implicit model. For the 3D implicit structural trend model a regional topographic model was generated based on SRTM 90 m digital elevation data (source: http://srtm.csi.cgiar.org/).

Data verification and error checking are the first important steps of a 3D implicit modelling workflow and are essential for the robustness of the resulting 3D geological model. Automated procedures during data import and 3D visualisation helped to identify inconsistencies within

Fig. 5. 3D implicit modelling workflow applied to drillhole data (a & b lithology, c & d gold assays) and regional structural data (e & f). All datasets were processed using an isotropic interpolation (no trend applied) without any manual digitisation of contacts or cross-sections. In a subsequent step, the three resulting models were used for visual data analysis. These geometric models were combined with field observations to develop a conceptual model, which aims to explain the structural evolution and control of mineralisation within the Navachab gold deposit.
the extensive drillhole dataset from the Navachab gold deposit (i.e., duplicate samples, missing samples, missing survey information, incorrect positioned drillholes). In summary, 20 out of 2,908 reverse circulation and diamond core drillholes were discarded, providing a total usable drillhole length of 388.5 km. Three implicit models were computed based on lithology codes, gold assay values and bedding measurements $S_{0/1}$.

4.1.1. 3D implicit lithological model

The six main geological formations that make up the host rocks of the Navachab gold deposit (Section 3.1) were used to generate the 3D lithological model (Fig. 5a and b). The known age relationships of the formations were also incorporated into the model. The youngest, overlying sediments (including alluvium, calcrite and calcritised alluvial conglomerates) were grouped into a unit called cover sediments. Meta-lamprophyre sheets and pegmatite dykes were not included in the 3D implicit model due to their narrow geometry, which requires manual adjustments and must be modelled separately. However, drillhole intercepts were used to investigate and visualise the spatial relationship between pegmatite dykes and gold mineralisation.

The lithological model is exclusively based on drillhole data, without any manual digitisation or adjustments that could reflect a subjective interpretation. An isotropic interpolation (i.e., no anisotropic trend applied to the interpolation) was chosen to minimise any bias. A radius of 60 m (adjusted to the drillhole spacing) was applied to generate a visualisation buffer along every drillhole trace (Fig. 5b). The model is only visualised inside this buffer, which means that the distance to a sample or data point is 60 m at most to guarantee that subsequent visual interpretations were constrained to an area or volume of confidence. The 3D implicit lithological model revealed that 1) bedding strikes NE and dips 70°–75° to the NW, but steepens to 85°–90° at depth and rotates slightly to a more E orientation in the NE; and 2) the true thickness of the marble-dominated Okawayo formation varies laterally and vertically from approximately 50 m to 160 m.

4.1.2. 3D implicit assay model

A total of 190,255 gold assay samples from reverse circulation and diamond core drillholes, sampled from 2 m core segments (99%) and sub-metre segments (1%), were processed into 4 m composites to reduce the number of data points, resulting in 88,580 composites (Fig. 5c). These show a maximum Au grade of 336 ppm, median of 0.1 ppm, mean of 0.5 ppm, 90 percentile value of 1.1 ppm and 95 percentile value of 2.1 ppm (ppm equivalent to g/t). The histogram of 4 m gold composites revealed a positively skewed distribution, which means that the frequency of low Au values is much higher than the frequency of high Au values, and that there are some samples with extreme values. This is very common for gold assay distributions, but is unfavourable when modelling grade values with an interpolant that uses a weighted sum of the data, which is the case for implicit modelling. This is because it will place too much emphasis on what are essentially exceptional values. A nonlinear transformation (log transformation) was applied to the gold assay data to reduce this effect.

To minimise any bias in the 3D assay model, an isotropic interpolation (i.e., no imposed trend) was used to calculate ore grade shells for cut-off grades of 0.5 ppm, 1.1 ppm and 2.1 ppm, based on the descriptive statistical values of the 4 m composites described above (Fig. 5d; for clarity only the 1.1 ppm grade shell is shown).

Subsequent analysis of the 1.1 ppm gold grade shell in combination with the 3D implicit lithological model revealed that 1) most gold mineralisation is located in the Okawayo and Spes Bona formations;
The highest grade and most extensive high-grade gold zones occur close to lithological contacts; and three geometrically and spatially distinct high-grade mineralisation trends can be defined within the 1.1 ppm grade shell (Fig. 6). One prominent high-grade mineralisation trend that can be linked to the semi-massive sulphide lenses is parallel to bedding, located near the contact between the Spes Bona and Okawayo formations and has a width of about 30 m and height of 190 m in cross-section. In long-section, it has a 1900 m long shoot-like appearance that plunges shallowly at higher levels, steepening slightly at depth (Fig. 8). Additionally, the 1.1 ppm grade shell outlines more bedding-parallel but less extensive gold mineralisation within the stratigraphically lower Spes Bona Formation. This trend resembles the orientation of bedding-parallel quartz-sulphide veins that have been observed in the field (for more details, see Section 5).

The second high-grade gold trend dips shallowly ENE, crosscuts the subvertical Okawayo and Spes Bona formations at a high angle and is located in both the hanging and footwall of the aforementioned shoot-like mineralisation trend (Fig. 6). Laterally, this shallowly ENE dipping trend completely crosscuts the Okawayo formation and continues 50 m into the Oberwasser formation. The flat-lying trend terminates to the SE within the Spes Bona formation and has a maximum horizontal extent of about 100 m. In long section, this mineralisation type appears to be less voluminous and extensive compared to the shoot-like style of mineralisation. In the field, this type of mineralisation is observed to be hosted in packages of sheeted, shallowly ENE dipping quartz-sulphide veins that crosscut subvertical bedding at high angles (for more details, see Section 5).

4.1.3. 3D implicit structural trend model

Planar structural data (bedding S0,1) within an area of about 11 km x 17 km around the Navachab deposit, covering the Usakos dome and Karibib dome have been digitised from a georeferenced geological map compiled by Kisters (2005) and height adjusted using a digital elevation model (DEM), based on SRTM 90 m digital elevation data (Fig. 5e and f). Leapfrog Mining’s interpolation of planar structural data works best for relatively uniformly sampled data points in geological environments that are gently, openly or closely folded (i.e., most domal structures), but is limited when dealing with tight to isoclinal folds, unless the data density is very high. In our case study, we computed structural trend surfaces solely based on regional S0,1 measurements to visualise the 3D structure of the Karibib dome and Usakos dome. Detailed, regional geological maps by Kisters et al. (2004) and Creus (2011) show no evidence for large scale faults cutting through the Karibib or Usakos dome, which could have an important influence on the topology. However, major thrust faults have been identified at the...
SE margin of the Karibib dome, within the Mon Repos thrust zone (Fig. 2), which is located at the SE edge of the 3D structural trend model. Movement within this zone is generally sub-parallel to bedding S0,1 along the SE limb of the Karibib dome, hence no significant changes in orientation of structural measurements that might influence the model are expected. Moreover, the 3D structural trend model aims to only resolve large-scale (kilometre-scale) structures, meaning that smaller-scale features such as minor thrust faults or parasitic folds are not represented. Nevertheless, the general 3D structure of the chosen model area is appropriately reflected by the computed surfaces. An isotropic interpolation of the regional bedding measurements S0,1 was chosen as to not force the interpolation to follow a manually-defined trend. The computed 3D trend surfaces were used subsequently to investigate the spatial location of the Navachab gold deposit within the regional structural context. The 3D implicit structural trend model outlines the shape and dimensions of the Usakos dome, Karibib dome and the intervening Navachab syncline (Fig. 5f). In NW-SE cross-section, the Karibib dome has an amplitude of ~5 km and a wavelength of ~10 km. On the NW limb of the Karibib dome, structural trend surfaces dip steeply at around 70° where they intersect topography, but are (sub-)vertical at deeper levels. The SE limb dips about 50° SE at the surface. The inferred fold axes of the Karibib dome are shallowly double plunging to the NE and SW, and steepen slightly at depth. The mineralised semi-massive sulphide ore shoots of the Navachab gold deposit resemble the orientation of the NE trending fold axis of the Karibib dome.

5. Structural fieldwork and links to 3D implicit models

Subsequent structural fieldwork was carried out in order to ground-truth the 3D implicit models and to link them to observed geological structures. Spatially interpolated assay data (3D implicit assay model) were overlaid onto the mine site digital elevation model (DEM) to identify key areas of high-grade mineralisation for targeted fieldwork at the Navachab gold deposit (Fig. 3). Mapping was restricted due to limited exposure and accessibility of high-grade semi-massive sulphide mineralisation as a consequence of ongoing mining activities in the Main Pit and North Pit. However, we were able to link implicitly modelled 1.1 ppm grade shells within the Spes Bona and Okawayo formation to ~24° ENE dipping packages of sheeted quartz-sulphide veins with sub-metre spacing located in the Main Pit. Approximately 50% of all quartz-sulphide veins mapped within the Spes Bona Formation have a sub-metre spacing (Fig. 7a), and about 75% of these veins have a thickness of less than 40 mm. Fire assay information from 40 veins sampled within the Spes Bona and Okawayo formation (sample size approximately 5 kg) revealed an average gold grade of 13.9 ppm with a maximum value of 97 ppm. Statistical analysis of these vein samples indicate that there is no correlation between vein thickness and gold grade.

An hypothetical 1 m × 1 m × 1 m sized block within the Spes Bona formation (biotite schist), which is crosscut by a single mineralised vein (40 mm thick, average grade of 13.9 ppm, as detailed above) roughly represents the structural setting of the economic cut-off grade
along the SE face of the Main Pit. Based on previous constraints and an assumed average density of 2900 kg/m³, this 1 m³ block would have an average grade of 0.6 ppm. Consequently, to form high-grade mineralisation, as illustrated by the implicitly modelled 1.1 ppm grade shells, the right combination of vein spacing, gold grade and vein thickness is required. However, as noted above, the lack of correlation between vein thickness and Au grade implies that vein spacing must be the governing quantity. If the frequency of veins exceeds a defined threshold, high-grade mineralisation becomes visible within the grade shells of the 3D implicit assay model, which in turn outlines areas of significant economic interest.

Auriferous veins within the Spes Bona and Okawayo formation crosscut subvertical compositional bedding and intrafolial isoclinal folds (F₁). This suggests that vein development postdates D₁ and occurred when bedding was already rotated to subvertical attitudes, pointing towards emplacement during the final lock-up stage of regional scale folding (D₂). Additionally, sheeted mineralised quartz-sulphide veins show small-scale upright folds with sub-metre amplitudes and wavelengths and shallowly NNE plunging fold axes. Quartz-sulphide veins within the Spes Bona formation are openly folded (Fig. 7b). On the other hand, veins within the Okawayo Formation are affected by tight, disharmonic folding (Fig. 7c). Both vein sets were probably emplaced contemporaneously, but rheological differences between their country rocks (relatively soft marble versus competent schist) led to variations in the intensity of folding.

Due to the fact that the amplitudes and wavelengths of these folded veins are much smaller than the sample and composite spacing (4 m) of the drillholes, these small-scale structures are not directly reflected in the 3D implicit assay model. However, the mean principal vein orientation calculated from field measurements and the attitude of the enveloping surface resemble the orientation of implicitly modelled shallow-dipping, high-grade mineralisation within the Spes Bona formation (Fig. 8, cross-section A). Because of the disharmonic tight folding of the veins and the limited exposure on the NW face of the Main Pit, we were not able to collect representative field measurements of folded veins within the marble-dominated Okawayo formation.

The horizontal extent of the mineralised quartz-sulphide veins is restricted and most probably controlled by changes in host rock lithology. An abrupt termination is not only visible in the 3D implicit assay model, but also in the field within the Spes Bona formation in Eastern Zone 1, where flat-lying veins terminate at the contact between biotite schist and interbedded calcisilicate rocks.

We also mapped a set of sub-vertical, bedding-parallel quartz-sulphide veins in the Spes Bona Formation within the Main Pit (Fig. 7d). Because these veins are oriented parallel to the pit face and are widely spaced, their recognition is limited in the field, but they have been identified in drill cores by Deltenre (2012). The geometry and orientation of the computed high-grade ore shells within the Spes Bona formation also suggests the existence of bedding-parallel gold mineralisation (Figs. 6 and 8).

The S₂ axial planar foliation related to the formation of the Karibib dome is best preserved in mica-rich rocks such as biotite schists of the Spes Bona and Oberwasser formations. S₂ strikes NE and dips steeply SE, reflecting the asymmetry of the Karibib dome. The lack of an additional (axial planar) foliation trending NW and oriented at high angles to S₂ suggests that the Karibib dome (and Usakos dome) did not form by two different deformation stages, but one non-cylindrical folding event. Intersection lineations between S₀, S₁, and S₂ are oriented parallel to fold axes of the Karibib dome and plunge shallowly NNE, and also parallel to the orientation of the semi-massive sulphide ore shoots, as indicated by the 1.1 ppm grade shell trend within the MC unit of the Okawayo formation (Fig. 8).

The least competent, marble-dominated Okawayo formation has been intruded by (meta-) lamprophyre sheets, which are generally parallel to bedding, but also show a number of bedding-oblique splayts. On the uppermost, non-accessible pit walls in the NE part of the Main Pit, such splayed meta-lamprophyre sheets have been folded. The fold vergence is converse to F₂ parasitic folds, but consistent with asymmetric folds that have formed due to the oblique orientation of the meta-lamprophyre sheets in relation to the maximum NW-SE shortening direction.

Numerous, mainly NW-trending subvertical pegmatite dykes (dm to several metre thick) intruded into the metasedimentary rocks at Navachab and crosscut auriferous quartz-sulphide veins, semi-massive sulphide ore shoots and the meta-lamprophyres sheets and dykes, therefore postdating gold mineralisation and the mafic intrusions (Fig. 7e). Additionally, it is noticeable that the abundance of pegmatite dykes is greater in the S and N of the Main Pit as well as in the North Pit. Occasionally, remnants of flat-lying quartz-sulphide veins are preserved within the crosscutting pegmatite dykes in the field, confirming that the dykes postdate vein hosted gold mineralisation (Fig. 7e).

Several young, brittle, shallow SE-dipping faults with minor displacement (<1 m) have been mapped on the NW face of the Main Pit. We interpret these to be related to the post-folding relaxation of the Damara orogen or an even younger deformational event. They do not seem to play a significant role in the mineralisation or the main structural framework at Navachab.

6. Discussion and interpretation

One of the most complex structural attributes of many ore deposits is folding, which is a prevalent feature at macro and micro scale and often described to influence mineralisation (Aerden, 1993; Blenkinsop and Doyle, 2014; Cox et al., 1991; Leader et al., 2010; Morey et al., 2005, 2007; Richard and Tosdal, 2001; Wilson et al., 2013). However,
associated regional scale folding is frequently overlooked as a major structural control on mineralisation. Additionally, folding is a rather under-appreciated control on ore emplacement compared to faults and shear zones, even though the formation of these structures is often a consequence of strain localisation during regional scale folding.

6.1. Relationship between folding and mineralisation

In compressional tectonic settings such as fold and thrust belts, active folding (buckling) initiates when multilayered rock packages of different viscosities are shortened parallel to layering (Fossen, 2010). The development of a buckle fold can be divided into four main stages (Fig. 9), namely (1) initial layer-parallel shortening, (2) nucleation or birth of buckling instability, (3) growth or amplification of the buckle-fold and (4) decay or locking-up (Cobbold, 1976; Ramsay, 1974; Schmalholz, 2006). Mineralisation, on the other hand, is commonly classified as pre-, syn- or post-deformational based on structural relationships, petrographical analysis and/or geochronological evidence. This temporal classification of mineralisation can be linked to the four main stages of folding, which are thought to influence the spatial distribution, trends and relationship of mineralisation. Depending on the folding stage under which mineralisation occurs, geometrically distinct high grade ore zones can form at preferred sites with respect to the fold. Furthermore, due to ongoing tectonic processes these ore zones might overprint and overlap each other and can be refolded as well. Their crosscutting relationships can be used to establish the relative timing of the different generations of mineralisation.

The nucleation of folds is mainly determined by initial heterogeneities. In numerical models, initial perturbations are introduced to nucleate folds (Fernandez and Kaus, 2014; Frehner, 2014; Grasemann and Schmalholz, 2012; Mancktelow, 1999; Schmalholz, 2008; Schmid et al., 2008). Moreover, scaled analogue experiments have highlighted the importance of irregularities in localising the site of fold initiation (Abbassi and Mancktelow, 1990; Biot et al., 1961; Cobbold, 1975; Dubey and Cobbold, 1977). Such heterogeneities are manually introduced prior to experimentation to induce folding during the experiment. These two examples emphasise the importance of initial heterogeneities, which may also play a role in the development and preservation of certain types of mineral deposits. For example, in the case of VMS deposits, the typical mound shape of such deposits, accompanying faults or the relatively soft massive sulphides themselves have the potential to act as heterogeneities and favour and/or control the nucleation of folds. This might explain why VMS deposits like Kidd Creek, Canada (Richardson, 1998) or Que River, Tasmania (Large et al., 1988) are associated with fold closures, although further work is required to evaluate this hypothesis. Alternatively, sulphide-rich mineralisation can also be remodelled during deformation and metamorphism. Many sulphide ores are less competent than their host rocks (Duuring et al., 2007). When folded, one would expect stretched ore bodies along the limbs or migration and accumulation of sulphide ore in fold hinges due to mass transport towards low pressure sites.

During the subsequent fold amplification and kinematic growth stage of folding, the highest shear strain is reached along the inflection lines of folds. Maximum values of flexural shear/flexural flow are confined to these areas, which are also associated with zones of low pressure and maximum dilation. Such linear zones of enhanced permeability have the potential to efficiently transport large volumes of fluid through mid-crustal rocks, which is important for the genesis of an economic grade mineralisation. Moreover, these linear structures might not only act as favourable conduits, but also trigger the precipitation of gold because of changed physical conditions (e.g., lowered pressure), therefore acting as physical traps. As described by Peters (1993b), the location and shape of ore shoots are usually controlled by dilatant zones caused by changes in attitude, splays, lithologic contacts and intersections.

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**Fig. 10.** Topography based on SRTM90 data (grey) intersected by the regional structural trend surface for $S_{0.1}$ (structural data from Kisters (2005)). Colours refer to calculated shear strain $\gamma$ which is directly related to dip ($\gamma = \tan(\text{dip})$) of originally horizontal layers, which are deformed into upright folds (Fossen, 2010). Note the distinctive geometrical differences between the Usakos dome in the W compared to the Karibib dome in the E. The Navachab deposit is located where shear strain reaches peak values. Regional structural trend surface generated with Leapfrog Mining 2.6; shear strain calculated and visualised with Move 2013.1.
The final lock-up stage of folding occurs when folding can no longer accommodate layer-parallel shortening. This leads to the formation of veins and faulting, which is a major feature of orogenic gold deposits. Vein-hosted mineralisation that crosscuts steepened bedding and mineralisation controlled by pre-existing foliations and late thrust faults form at this stage. Famous examples are the gold deposits of the Bendigo Zone, where gold is hosted by quartz veins associated with steeply-dipping reverse faults (Leader et al., 2012).

6.2. Structural history and gold mineralisation at the Navachab gold deposit

The 3D implicit structural trend model for bedding $S_0$, shows that the Navachab gold deposit is located near the inflection line of the steep NW limb of the regional scale Karibib dome (Fig. 10). During NW-SE shortening and associated buckling of the Karibib dome, this would have been an area where shear strain reached peak values. In contrast, shear strain induced by the same process would have reached minimum values in the hinge regions. To quantify and visualise shear strain distribution along the Karibib dome, we calculated shear strain based on the layer dip. For original SW-facing layers that are folded into upright folds, shear strain $\gamma$ is directly related to layer dip ($\gamma = \tan(dip)$) (Fossen, 2010). This formula was used to determine shear strain based on local dip values of the triangulated mesh from the 3D implicit structural trend model (Fig. 10). The software package Move 2013.1 (Midland Valley Exploration Ltd, 2013) was chosen to perform advanced analyses on (triangulated) 3D meshes. It also allows colour-coding of desired properties such as dip, curvature or in our case shear strain. The results are consistent with the location of the Navachab gold deposit along the NW inflection line of the Karibib dome where shear strain reached the highest values of 4 to 5 during fold amplification (Fig. 10). Maximum layer-parallel displacements due to flexural shear or flexural flow would have been confined to these areas, potentially forming low-pressures zones such as shear veins or dilational jogs, thereby generating suitable conduits and traps for ore bearing fluids. The semi-massive sulphide lenses that delineate the auriferous ore shoots were probably controlled by this folding-related strain partitioning mechanism. This is in agreement with structural fieldwork by Kisters (2005), who relates the emplacement of auriferous semi-massive sulphide lenses to dilational jogs based on their rhomb-like geometry. Additionally, the orientation of calculated $S_0/S_2$ intersection lineations ($= F_2$ fold axes) resembles the trend of the central, slowly plunging 1.1 ppm grade shell that is related to semi-massive sulphide ore shoots, suggesting that they are structurally related to the formation of the Karibib dome (Fig. 8). No semi-massive sulphide mineralisation is reported within the hinge regions of the Karibib dome, where flexural slip-related shear strain is expected to have attained minimum values, and where the potential to form associated, dilatant structures is low. Therefore, an epigenetic, syn-deformational origin of the semi-massive sulphide ore shoots is more likely.

The potential to form such dilatant structures depends on the amount of shear strain, but also rheological properties of affected lithologies. This could explain the second order control on the localisation of semi-massive sulphide ore shoots. As seen in the 3D implicit models, the main shoot (Main Pit) and 2nd shoot (North Pit) are both located close to the contact of the Okawayo Formation with the Spes Bon Formation (Fig. 6). Generally, layer parallel shearing will not be uniformly distributed throughout a sequence (Price and Cosgrove, 1990) and strain will be preferentially partitioned close to lithological contacts due to relative differences in physical properties. In the case of the Navachab gold deposit, the rheological contrast between relatively soft marbles and competent biotite schists (partly silicified) may have controlled the ‘stratigraphic’ position of the ore shoots.

At the Navachab gold deposit, high grade mineralisation is also hosted in bedding-parallel and highly discordant quartz sulphide veins. The highly discordant veins dip shallowly to the ENE and are affected by sub-metre scale, upright folding with fold axis that are parallel to NNE plunging axis of the Karibib dome. There is no evidence that the aforementioned bedding-parallel flexural shear was active during folding of the highly discordant vein set, suggesting that they were emplaced later during the lock-up stage of the Karibib dome when host rocks have already reached steep attitudes and doming related flexural slip had mostly ceased (Kisters, 2005).

Ambiguous and mutually-crosscutting relationships between the subvertical, bedding-parallel and the discordant, flat-lying vein systems are consistent with contemporaneous emplacement during the late stages of regional fold (dome) lock-up. The highly discordant vein set is oriented sub-parallel to the horizontal principal compressive stress direction, $\sigma_1$, expected for the NW-SE regional shortening event and associated folding. In contrast, bedding-parallel veins are oriented almost perpendicular to $\sigma_1$ and were most likely generated under high fluid overpressure conditions, which are required for emplacement along planes of strong mechanical anisotropy such as bedding (Sibson, 1996). Their unfavourable orientation with respect to the main stress field might also explain their limited abundance and lower thickness. However, we cannot rule out that some bedding-parallel quartz-sulphide veins could have formed as shear veins during amplification of the Karibib dome, contemporaneously with emplacement of the auriferous semi-massive sulphide ore shoots. Bedding-parallel veins logged in drillhole N766 located within the Oberwasser Formation are boudinaged. This is consistent with the bulk strain regime that folded the discordant vein set and lamprophyre sheets during the late lock-up stage of folding. Boudinage could also explain the lenticular shape of massive-sulphide bodies that form the ore shoots.

The third type of gold mineralisation is associated with pegmatite dikes that intruded parallel to a NW trending, subvertical joint set, which is interpreted here to have formed in an extensional fracture orientation during the lock-up stage of the Karibib dome. These pegmatite dykes are responsible for local remobilisation and redistribution of gold, which has not been described previously at the Navachab gold deposit (Fig. 8). This suggests that earlier deposited gold has been locally replaced and remobilised by pegmatite intrusions and re-deposited at (mainly) higher levels in the form of dispersed mineralisation.

In summary, results from 3D implicit modelling in combination with structural fieldwork suggest that structures formed during the amplification and lock-up stage of the Karibib dome acted as conduits and traps for gold mineralisation and also controlled deposit-scale remobilisation. These deformation related structural features best classify the Navachab gold deposit as an orogenic gold deposit.

7. Conclusions

We have demonstrated that ore body geometries obtained from 3D implicit models can be accurately linked to local and regional structural patterns. First-order controls are most important for economic mineralisation and are represented in our 3D implicit models for the Navachab gold deposit. Small-scale structures that cannot be resolved in these models but have been observed in the field were used to complement and constrain our structural interpretation. Our workflow focussed on minimising the modelling bias by using an isotropic spatial interpolation in order to utilise the resulting 3D implicit models for structural interpretation purposes. The results from 3D implicit modelling in conjunction with structural fieldwork suggest that this workflow enhances the identification and (re-)assessement of structural controls on mineralisation. Our structural interpretation of the Navachab deposit builds upon work by Kisters (2005). We demonstrate that the spatial location of ore shoots at the Navachab gold deposit is systematic and controlled by different stages in the development of a regional scale domal structure (Karibib dome). Additionally, we described the role of cross-cutting pegmatite dykes in locally replacing and remobilising previous vein-hosted and semi-massive sulphide-hosted mineralisation.

The Navachab gold deposit case study highlights the importance of folding as a first order structural control on emplacement of ore bodies.
The 3D structural trend model demonstrates a geometrical dependence of shear strain that potentially controls the localisation of associated mineralised structures (ore shoots). We propose that inflection lines (where shear strain reaches peak values during fold amplification) of close, tight or even overlapped faults are preferred sites of mineralisation and represent pipe-like traps and 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 drillhole targets. Additionally, this work indicates that state-of-the-art modelling workflows can lead to a better structural insight in already developed and explored mine settings.

Acknowledgements

We thank AngloGold Ashanti Ltd for their generous support as well as AusIMM for funding S. A. V. (Bicentennial Gold Endowment). We are grateful to Jane Allen (AngloGold Ashanti Ltd Exploration Manager – Brownfields, Continental Africa Region), Frik Badenhorst and especially to Navachab’s chief geologist Graham Bell and his team for their abundant and helpful support. S.A.V. and A.R.C. also acknowledge Monash University for scholarship and research support. Stereonets were generated using Rod Holcombe’s programme GEOrient. Academic licenses for the Leapfrog Mining software package were kindly provided by ARANZ Geo Pty. Ltd. In addition, we acknowledge Midland Valley Exploration Ltd. for providing an academic license for the Move 2013.1 geological modelling software package. We are grateful to two anonymous reviewers for their comments and suggestions, which improved the quality of this paper.

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