Definition of Geotechnical Design Sectors in Structurally-Controlled Anisotropic Environments: Apparent Dip Analysis of Bedding within Fault-Bounded Blocks at Jwaneng Mine, Botswana

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ABSTRACT: This contribution describes a methodology for assessing the interaction of dominant bedding planes within anisotropic materials (laminated, quartzitic and carbonaceous shales of the Griqualand West Supergroup at Jwaneng Mine) with a design pit. Lithological contacts from implicit 3D lithological and structural models are used as proxies for bedding. Apparent dips are derived by combining the orientations of individual triangles on these contacts with orientations of individual triangles on a design surface, using a nearest-neighbour algorithm. Apparent dips may be contoured, binned into categories that show inward or outward dipping attitudes, or areas where critical friction angles are exceeded. *A priori* definition of specific design sections is minimized, design sectors are more intelligently defined and reliance on average or median dips for a simplistic, wedge-shaped design sectors, is obviated. This is particularly important where simplistic sectors contain significant changes in dip direction of the main plane of anisotropy/bedding.

1 INTRODUCTION

Data from geological, structural, rock mass and hydrogeological models provide inputs into design sectors for geotechnical models and failure modes. It is often difficult to determine the size and exent of each design sector or domain, which contains structurally-controlled and/or anisotropic materials, prior to analysis or early in the analysis process. Furthermore, geotechnical drilling, structural mapping data, scanline data and geotechnical mapping data utilizing Sirovision are either sparse or are focused in narrow windows around fixed vertical 2D design sections.

The orientation and location of these sections are predicated on the geometry of a conceptual shell or design, in turn based on an economically-driven optimization process by utilizing tools such as Whittle. Sections are typically radially-oriented around the center of a pit or sub-pit. These sections seek to show the interaction of the true dip of planes of anisotropy (e.g. bedding, foliation) with the slope. At Jwaneng, a structurally-controlled stepped path failure mechanism (interaction between bedding, joints, and rock bridges) is anticipated. Pre-defined design sectors and 2-dimensional design sections, however, limit the Geotechnical Engineer to “snapshots” of the *spatially continuous and variable interaction of geology with the existing or planned pit surface*. The analysis and slope design of volumes between these vertical sections becomes a matter of interpolation and could result in increased geotechnical risk should possibly unfavourable interaction of geology with slope geometry be overlooked.

In order to deliver practical, sector-specific design parameters as input for mine design, a methodology was derived to improve the definition of these geotechnical design sectors early in the process, thereby providing a robust *a priori* definition of potential design sectors for subsequent analysis. This contribution augments the use of vertical 2D design sections by extracting the spatial variability of the abovementioned interaction, by means of apparent dip maps. The methodology has been successfully applied at Kumba’s Sishen and Kolomela Mines (in the Transvaal Supergroup). The recent construction of a comprehensive, implicit 3D model of the country rock around the Jwaneng kimberlites has made such an analysis possible, while ongoing issues in a particular part of the pit (the NE Corner) have necessitated the extraction of as much relevant information as possible from available 3D models and existing data. The use of macros allows for any changes in design to be analysed according to the methodology presented herein, thereby resulting in both a dynamic process and a direct input into mine planning. The methodology may be applied to most planar features throughout any volume of interest.

2 GEOLOGY

2.1 *Stratigraphy*

Jwaneng Mine is in the Okavango and Shakwe Zone(s) (Carney *et al.*, 1994), covered by Palaeoproterozoic (*circa* 2300-2100 Ma) sediments of the Griqualand West Supergroup of southern Africa. The base of the sequence consists of the *c.* 2.552 Ga Malmani dolomite. The contact between the Malmani Subgroup and the Rooihoogte/Duitschland Formation has been delineated in several very deep drillholes. The overlying (Middle) Rooihoogte/Duitschland Formation consists of laminated sandstone, mudstone, greywacke and black shale. The upper and lower portions of the (Middle) Rooihoogte/Duitschland Formation are subdivided into quartzitic shale (QS2) and carbonaceous shale (CS2). A chert pebble conglomerate, consisting of angular to rounded chert clasts in a gritty matrix, separates the upper part of the Rooihoogte/Duitschland Formation from its lower part, representing an 80 Ma hiatus in the depositional history. This unit is termed the Bevets Conglomerate (BVT) on Jwaneng Mine, although Coetzee (2001) found that the *base* of the Duitschland Formation near Thabazimbi (South Africa) is occupied by a "flat" chert-pebble conglomerate, which is termed the Bevets or Bevetts Conglomerate at this location.

The upper part of the Rooihoogte or Duitschland Formation consists of fine-grained to medium-grained, poorly-sorted argillaceous quartzite, greywacke, subgreywacke and silty mudstone. Quartzitic shale (QS1) is succeeded by a diachronous, transgressive (erosional) surface. Above this erosional surface, the 2.264 Ga Timeball Hill (or Lower Ditlhojana) Formation consists of deep marine laminated sandstone, mudstone, greywacke and black shale interbedded with thin, mafic tuff bands. The upper part of the Timeball Hill (or Upper Ditlhojana) Formation consists of laminated sandstone and black, laminated shale (LS). The 2.184 Ga Boshoek Formation, which overlies the upper Timeball Hill Formation, consists of felsic volcanics and graphitic or carbonaceous shale with sandstone intercalations. Together with the Upper Timeball Hill Formation, these comprise the laminated shale unit (LS).

The Kalahari Sequence or Group consists of calcrete, sand and scree, which includes alluvial material of unspecified or undocumented origin. The lower part of the Kalahari Group in the area of interest consists of calcrete or caliche, which comprises calcium carbonate-cemented surficial gravel, sand, clay and silt.

2.2 *Deformation Events*

The deformation sequence and geometry in 3D reveal an early compressional event directed towards a bearing of 350° or almost due north (Figure 1). This event is expressed by a series of mesoscale folds and associated low-angle thrusts that show strike extents on the order of 100m. Thrusts merge laterally and down-dip into bedding, expressing "distributed" strain throughout the sequence. This early compressional event was defined by Dietvorst (1988) in the Ramotswa-Lobatse area, 120 km ESE of Jwaneng (Figure 1). In that study, regional folding around NE- to ENE-trending, gently plunging (0°-20°) open folds preceded extension and the development of normal faults. A similarly-oriented compressional event is evident in the Thabazimbi area in South Africa, approximately 250 km to the east of Jwaneng Mine. At Thabazimbi, a maximum age of thrusting is constrained by a quartz porphyry age of 2054 ± 4 Ma (essentially Bushveld Complex age), from the basal unconformity of the Waterberg Group (Dorland *et al.*, 2006). The Ramotswa-Lobatse area shows large-scale, normal faulting that sub-divides the Transvaal Supergroup into blocks showing characteristic dips and F_1 fold axis orientations (Dietvorst, 1988). Based on Dietvorst (1988), an overview of deformation in the Thabazimbi area, and mapping performed at Jwaneng Mine, regional NE- and ENE-trending faults exploited axial planar cleavage around D_1 anticlines and synclines. In effect, the orientations of D_2/D_3 are controlled by the macrostructural "fabric" imposed on the sequence due to early development of this fold-and-thrust belt. The geometry resulting from this sequence of deformation events is a series of NW-dipping, NE-SW elongated, fault-bounded, wedge-shaped blocks. These define structural domains, each with a characteristic average bedding dip, determined from robust datasets. Relatively minor E-W trending faults within these blocks may subdivide the geology into rhomboid-shaped blocks.

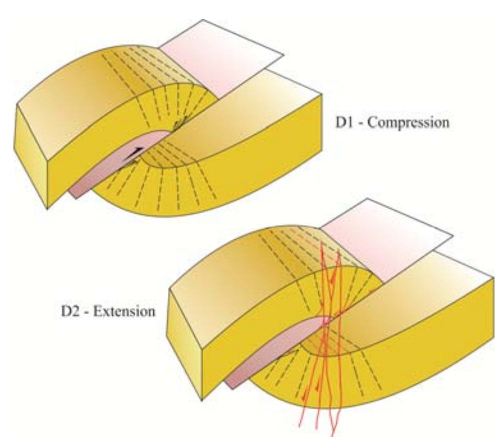

Figure 1. Schematic of the deformation events at Jwaneng Mine: D_1 compression forming breached folds and low-angle thrusts; D_2 extension exploiting fanning axial planar cleavage

3 METHODOLOGY

Standard mapping data, downhole oriented bedding from A/OTV logs and well-constrained, high-confidence 3D models, which are built using implicit modelling techniques, form the basis for the analysis. Based on well-constrained mapping and oriented geotechnical drilling, lithological contacts are predominantly parallel to bedding in their related volume(s), with the exception of volumes that have tectonic or erosional unconformities against their upper limits. Apparent dips of a given lithology, at either an existing or planned pit surface, may therefore be derived from a combination of the dip and dip direction of individual triangles on finely-triangulated lithological surfaces (*viz.* sedimentary contact orientations represent bedding orientations), with the dip direction of individual triangles on pit surfaces, on a pre-defined grid basis. The relationship between the orientation of contacts and the orientation of bedding may be tested via stereonet analysis. This produces an *apparent dip* value that represents the continuous variation in the interaction of the main plane of anisotropy with the pit surface or design surface. Several steps are adopted in Micromine to create apparent dip maps (Figures 2, 3):

- Extraction of triangle orientations (dip and dip direction) from wireframed or triangulated surfaces, assigned to structural domains (*viz.* fault-bounded blocks). Surfaces of specific lithological contacts are proven and/or reasonably assumed to be parallel or sub-parallel to bedding within their respective structural domains, thereby providing a "proxy" to bedding orientation;
- Erosional or tectonic unconformities, which violate one of the basic assumptions of the analysis, are filtered out;
- Data from triangles on the sides of fault-bounded blocks, which would provide anomalously steep dips where they run up against steep or vertical bounding faults, are filtered out;
- Using a nearest-neighbour algorithm, all surface orientation data, with respect to each structural domain, are assigned to a pit or design. The proximity over which this projection is done from off-(pit)-surface varies, but it is usually advisable to refer to the thickness, lateral extent, and internal coherence of the unit from which data are taken and, by default, through which data will be extrapolated. It was found that using true dip data within a vertical distance of 20m–50m of the pit surface was acceptable;
- Lastly, an apparent dip is calculated by spatially coinciding, on a grid basis, the proxy to bedding surface orientation (dip and dip direction) with face orientation of the design pit;
- Apparent dips are displayed only where units intersect the design pit. This was achieved by clipping modelled lithological volumes against the design pit, to show where they daylight on the design pit;
- Areas on ramps and berms are filtered out;
- Apparent dips are re-gridded using an inverse distance interpolator to give an accurate representation of the *spatial variation in apparent dip for each anisotropic lithological unit, within each fault-bounded block*. Ranges may be arbitrary or plots could show individual units with ranges or bins based on various critical friction angles, or fail/no-fail maps (e.g. see Figures 3c and d).

4 DEFINITION OF GEOTECHNICAL DESIGN SECTORS

By incorporating data obtained from apparent dip maps and utilizing various strength models according to conceptual failure models (with respect to lithological layers), geotechnical design sectors may be defined. Design sectors are first identified and grouped according to lithologies with similar strength properties, *i.e.* Hoek-Brown strength parameters (UCS, GSI, Mi, and D) to represent the rock mass strength. For instance, quartzitic shale is very different from laminated shale or carbonaceous shale at Jwaneng. Zones where the apparent dip of bedding is into the design pit, but importantly, with apparent dips regularly exceeding 37°, are considered for the delineation of separate design subsectors (Figure 3). Conversely, large areas where the apparent dip is more favourable (*viz.* away from the pit centre or into the pit face), may be delineated, which provides opportunity for optimizing the design.

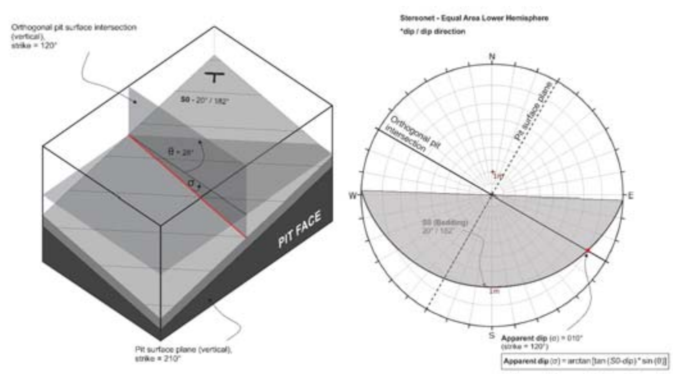

Figure 2. Schematic showing the calculation of apparent dip

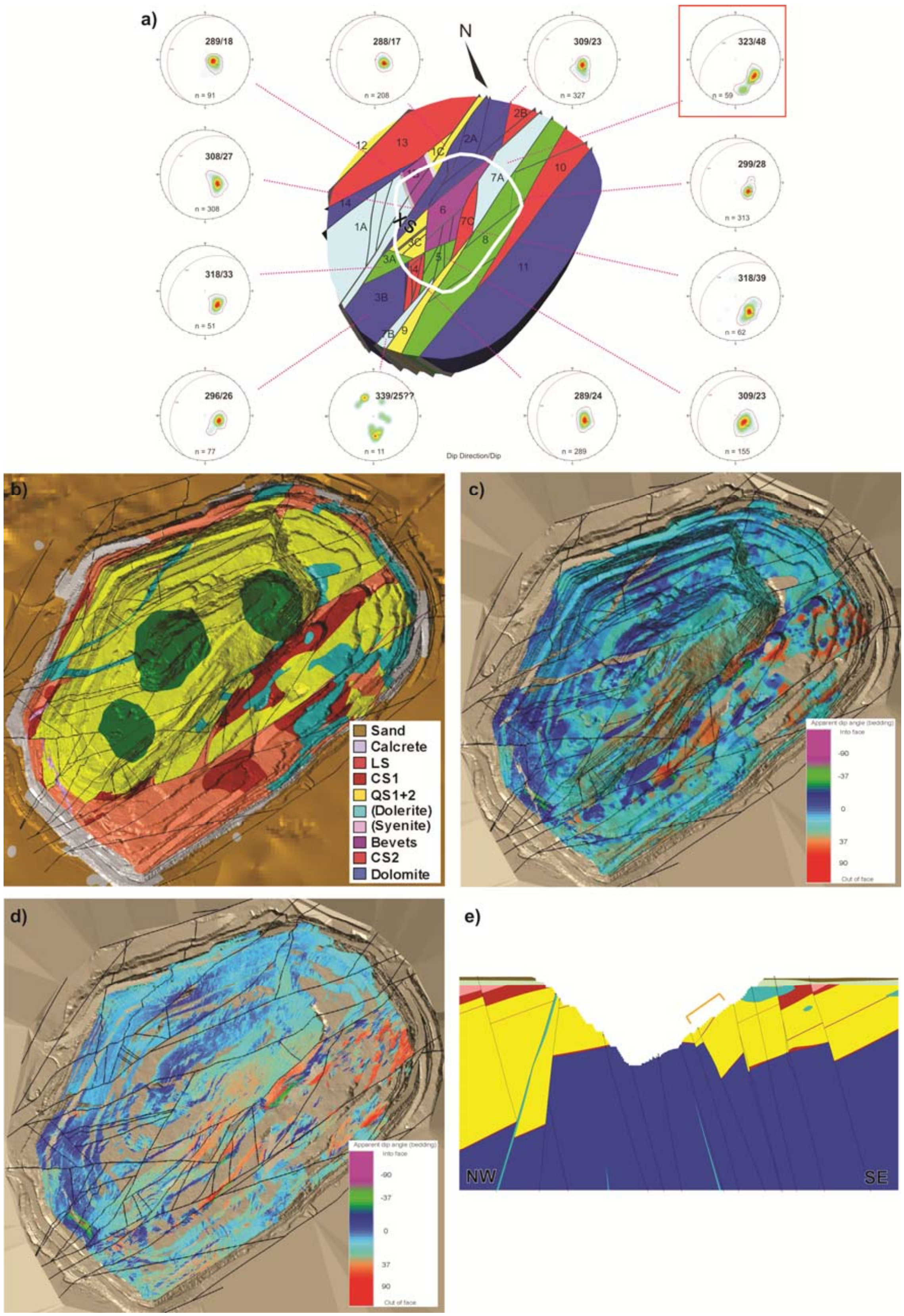

Figure 3a): Sub-domaining of bedding readings from pit mapping into fault- bounded blocks. Anomalously steeper dips from Domain 7A are highlighted. Approximate extent of the pit surface is shown; b): 3D geological model clipped to pit surface. Shows daylighting or intersecting country rock lithologies; c): Contoured plot of apparent dip for QS, CS, LS (dol. sill is excluded), binned according to average friction angle (37 deg) and sense of dip (into vs out of face). The plot highlights a zone of relatively steeper bedding, compared to the underlying design surface, within Domain 7A and trending NE-SW through Domains 8 and 9; d): Dip direction and dip symbols, binned according to the chosen friction angle and coloured according to apparent dip angle and sense of dip; e): NW-SE trending cross-section showing the 3D model clipped to the design surface and the relatively steeper bedding for Domain 7A (indicated)

This methodology allows for a significantly improved definition of design sectors without using averages or median dips of planes of bedding or other planes of anisotropy for a whole domain or sector. When combined with strength and failure criteria, this allows for the early subdivision of domains into practical design sectors as individual 3D volumes. When utilized early in the mine design process, this methodology optimizes (*viz.* usually reduces) the required number of 2D design sections that need to be analysed. Time and expense required to perform the iterative process of geotechnical stability analysis and risk assessment is also optimized and reduced.

A case in point is the NE Corner of the pit at Jwaneng Mine. An apparent dip analysis highlighted potentially problematic blocks (Block 7A and 8A) (Figures 3a, c), which appeared to show steeper bedding dips compared to adjacent blocks (an additional 8°-10°), based on an average within a DIPs stereonet window (Figures 3a, c, d and e). The identified anomalously steep bedding, highlighted by the apparent dip analysis, has over time led to planar sliding failures affecting single to double benches. The failure of such benches in planar sliding leads to pit-ward dipping bedding surfaces that extended over 3-4 benches. Particularly to the NE part of the pit, access ramps were at risk of failure due to the locally steep bedding. Using the methodology described herein, the risk to the ramp was identified early and detailed stability analysis was thereafter carried out to determine the factor of safety (FoS) and probability of failure for the area. The results of the stability analysis indicated lower than acceptable FoS and, as mitigation, slope support designs were determined. The support which was designed and successfully installed in the area comprised concrete piles primarily aimed at preventing planar sliding of the blocks (Figure 4).

The methodology has greatly assisted the early identification of the stability condition. It has allowed for forward prediction of the stability implications, based on the still-to-be-mined benches with respect to the mine design. Business risks associated with personnel and equipment safety as well as loss of the access ramps could have had devastating impacts on the mine's sustainability.

5 CONCLUSION

The methodology and example presented herein augments the use of 2D design sections by improving the early definition of design sectors, as inputs to the mine planning process or into focussing on various areas. This is particularly important where the main plane(s) of anisotropy show significant changes in dip or dip direction, across various domains.

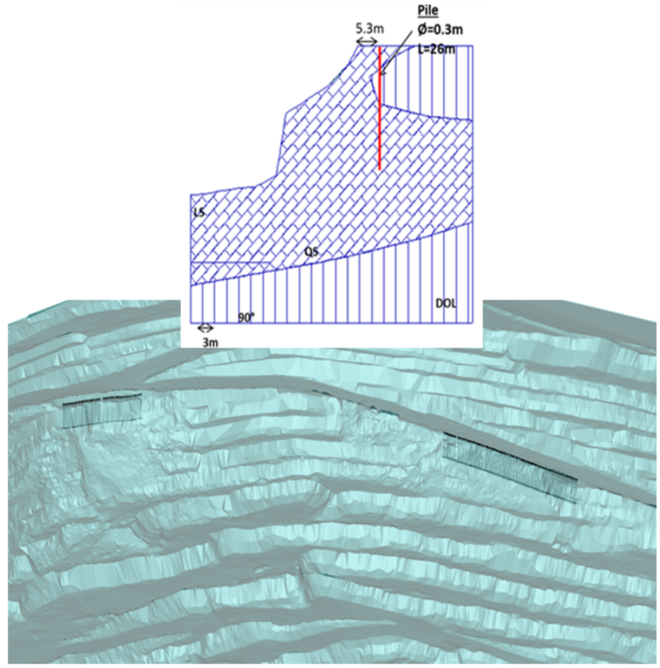

Figure 4): Pile reinforcement (slope support) installed on the ramp to ensure long term sustainability of the ramp

This is the case at Jwaneng, where each fault-bounded block exhibits its own particular dip and dip direction due to early folding and variable rotation of fault-bounded blocks. In addition, the potentially problematic Blocks 7A and 8A occurred where there is a change in trend of pit and the future design.

This methodology allows for the incorporation of data from continuous mapping of interim or final faces. In this process, mapping, scanline and Sirovision data may be incorporated directly into the grid file, ideally followed by macro-driven re-analysis, thus allowing for continuous recalibration of the geotechnical model based on mapping data which are progressively more proximal to the final layout or design. Dedicated geotechnical drillhole information, which contains oriented downhole data, may be added to further refine and optimize the design at a very early stage. Indeed, any orientation data, whether desurveyed downhole bedding or fracture readings, surface mapping, Lidar or I-Site data, which falls within the distance defined by the nearest-neighbour algorithm, may be incorporated in the analysis.

This technique also overcomes the situation wherein certain parts of the pit inevitably show a dramatic change in orientation with respect to strike or dip direction *within* a domain. This has historically been problematic when using the more traditional means of average or median dips, which inevitably are not representative of the whole design sector. Improved design sector classification highlights possible areas – of any size or shape and not just vertical “wedges” – that show unfavourable interaction with slope geometries in future pushbacks or on final faces. In turn, this results in a more robust and practical suite of sector-specific design parameters as inputs for mine design.

6 REFERENCES

Carney, J.N., Aldiss, D.T. and Lock, N.P. (1994). The Geology of Botswana. Technical Report, Geological Survey Department of Botswana.

Coetzee, L.L. (2001). Genetic stratigraphy of the Palaeoproterozoic Pretoria Group in the western Transvaal. M.Sc. Thesis (unpub), Rand Afrikaans University, Johannesburg, 206pp.

Dietvorst, E.J.L. (1988). Early Precambrian Basement uplift and block faulting along the western margin of the Bushveld Complex, Southeastern Botswana. Journal of African Earth Sciences, 7(4), 641-651.

Dorland, H.C., Beukes, N.J., Gutzmer, J., Evans, D.A.D. and Armstrong, R.A., (2006). Precise SHRIMP U-Pb zircon age constraints on the lower Waterberg and Soutpansberg Groups, South Africa. South African Journal of Geology, 109, 139–156.