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Sequence stratigraphy of the Vaal Reef facies associations in the Witwatersrand foredeep, South Africa

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Abstract

Facies analysis and sequence stratigraphic methods resolve the correlation and relative chronology of Vaal Reef facies associations at the Great Noligwa and Kopanang mines in the Klerksdorp Goldfield, Witwatersrand Basin. Four depositional sequences, separated by major erosional surfaces, build the Vaal Reef package. Lowstand, transgressive and highstand systems tracts (HST) are identified based on stratal stacking patterns and sedimentological features. The core of the Vaal Reef deposit is represented by a Transgressive Systems Tract (TST), which is built by shoreface (proximal) facies at Great Noligwa and inner shelf (distal) facies at Kopanang. The proximal TST includes the G.V. Bosch reef and the overlying MB4 quartzites. These facies are correlative to the Stilfontein conglomerates and quartzites, respectively, at Kopanang. The overlying Upper Vaal Reef is part of a Lowstand Systems Tract (LST). It is only preserved at Kopanang, with a thickness that equals the difference in thickness between the proximal and distal transgressive facies. This suggests that the Upper Vaal is an erosional remnant that accumulated on a gently dipping topographic profile. Traditionally, the MB4 quartzite has been considered the hanging wall relative to the Vaal Reef. We infer that these quartzites are merely associated with the G.V. Bosch conglomerate, and interpret that they are coeval with the Stilfontein quartzites, and older relative to the Upper Vaal facies. From a genetic viewpoint, the true hanging wall to the Vaal Reef begins with the Zandpan gravel lag that extends across the entire study area. Paleocurrent analysis of shoreface and fluvial systems indicate a curved shoreline and a northern elevated source area. The coastline underwent north–south transgressive and regressive shifts during Vaal Reef time. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Vaal Reef; Sequence stratigraphy; Witwatersrand foredeep; Shoreline shifts

1. Introduction

Sequence stratigraphy, currently one of the most actively evolving disciplines in sedimentary geology, is a powerful tool for explaining the relationships of allostratigraphic units that analyzes the sedimentary response to base-level changes. Through the recognition of bounding surfaces, genetically related facies (systems tracts) can be identified. Lithofacies can then be correlated according to where each unit is positioned along an inferred curve that represents base-level fluctuations. Application of sequence stratigraphic principles can be important for evaluating the origin of sedimentary-hosted mineral deposits. In the present study, we examine deposits in the Klerksdorp Goldfield along the northwestern margin of the Witwatersrand Basin (Fig. 1). Data were obtained from three contiguous mines (Great Noligwa, Kopanang, Moab Khotsong; Fig. 1) operated by Anglogold. Most data

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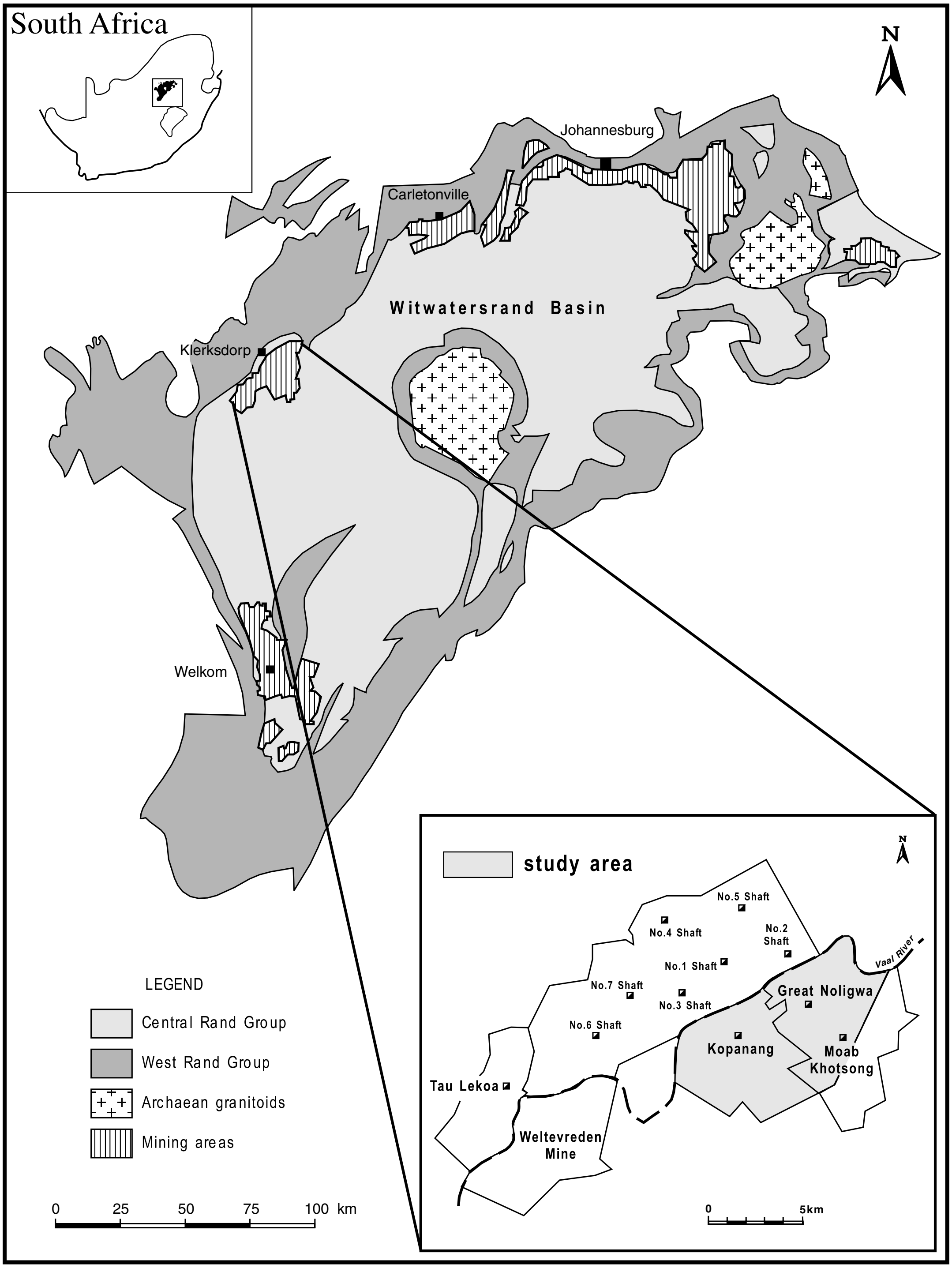

Fig. 1. Area of study in the context of the Witwatersrand Basin.

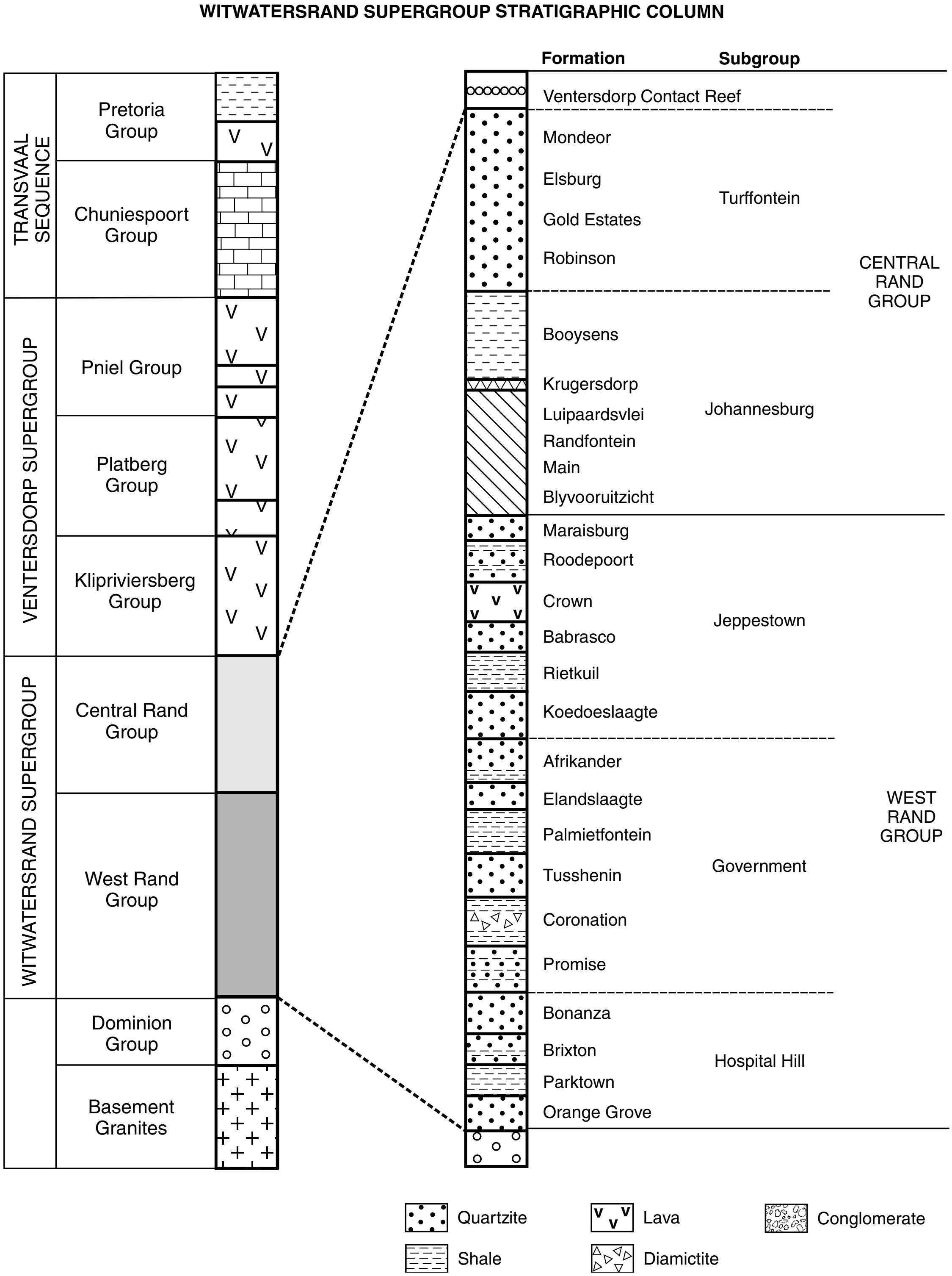

Fig. 2. Generalized stratigraphy of the Witwatersrand Supergroup in the context of the overall Precambrian geology of central South Africa.

are from Great Noligwa and Kopanang mines as the Moab Khotsong Mine deposit is currently being developed and is only scheduled to begin production in the year 2003.

Gold bearing conglomerates of the Witwatersrand Basin have generally been regarded as alluvial fan and fluvial in origin (e.g. Pretorius, 1976, 1981; Minter, 1978), a view that has persisted in part because the overall genetic stratigraphic setting has not been fully considered. Herein, we focus on the Vaal Reef deposit, preserved as a relatively thin (few meters) laterally continuous, mature placer, split into a number of facies. Based on existing and new data, we use sequence stratigraphic methods to correlate between the Great Noligwa and Kopanang mining areas, and to suggest a new model for the chronology of events leading to the formation of the preserved stratigraphic architecture.

2. Sequence stratigraphic concepts

Comprehensive discussions of sequence stratigraphic concepts and their application to the Precambrian rock record are provided by Christie-Blick et al. (1988) and Catuneanu and Eriksson (1999). Briefly summarized below are key concepts relevant to this study.

2.1. Systems tracts

Lowstand Systems Tract (LST) form during early stages of base-level rise, when rates of base-level rise are outpaced by sedimentation rates. As a result, a 'normal' regression of the shoreline occurs. Typical products for LSTs include amalgamated channel fills overlying subaerial unconformities, and lowstand deltaic deposits. Protected from subsequent erosion by the aggradation of overlying transgressive and highstand deposits, these have a high preservation potential.

Transgressive Systems Tract (TST) form during accelerated base-level rise, when rates of base-level rise outpace sedimentation rates. As a result, a transgressive shift of the shoreline occurs, and retrogradation and vertical aggradation in both fluvial and shallow marine environments results.

Highstand Systems Tracts (HST) form during late stages of base-level rise, when sedimentation rates outpace rates of base-level rise. 'Normal' regression of the shoreline occurs, resulting in aggradation and progradation of both fluvial and marine deposits. Highstand deltaic deposits, bounded above by subaerial unconformities, are typical products. Highstand strata may have a low preservation potential due to erosion accompanying subsequent base-level falls.

2.2. Bounding surfaces

Subaerial unconformities develop in the nonmarine portion of the basin due to fluvial or wind degradation during stages of base-level fall. They may overlie fluvial or marine strata, but are overlain by nonmarine deposits.

Regressive surfaces of marine erosion are the marine equivalent of the subaerial unconformities. They are also formed during the 'forced' regression of a shoreline accompanying a fall in base-level, and are represented by scoured surfaces cut by waves in an attempt to re-establish an equilibrium shoreface profile. They usually separate underlying deeper marine strata from overlying shallower marine strata.

Transgressive surfaces of erosion, also known as 'ravinement surfaces' (RS), are scours cut by shoreface waves during the transgression of a shoreline. They are highly diachronous surfaces, separating fluvial strata below from shallow marine facies above.

Maximum flooding surfaces represent the boundary between a TST and an overlying HST.

3. Geological overview

The Witwatersrand Basin is underlain by a 3.1 Ga and older granite-greenstone basement that comprise the Kaapvaal Craton (Fig. 1; Barton et al., 1986; Myers et al., 1990; Hartzer et al., 1998). The age of the Witwatersrand Supergroup (Figs. 2 and 3) is constrained by U–Pb zircon ages obtained from volcanic rocks in the underlying Dominion Group (3074 ± 6 Ma; Armstrong et al., 1991) and the overlying Ventersdorp Supergroup (2714 ± 8 Ma; Armstrong et al., 1991). Only one age (2914 ± 8 Ma) has been determined for the Witwatersrand Basin itself (upper West Rand Group (Armstrong et al., 1991; Hartzer et al., 1998). Despite low-grade regional metamorphism (Stevens et al., 1996), primary sedimentary features are well preserved.

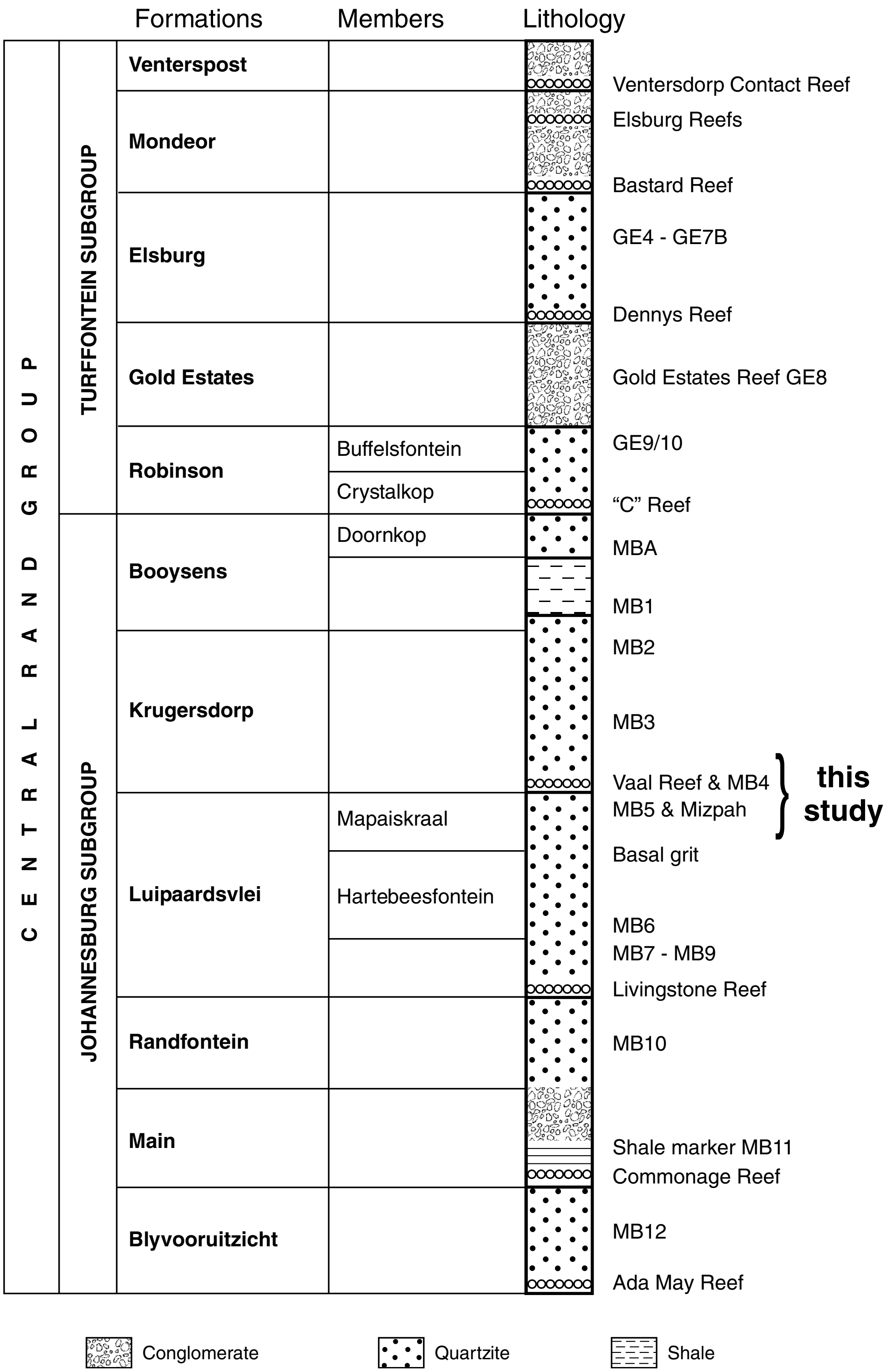

Fig. 3. Generalized stratigraphy of the Central Rand Group, showing the position of the Vaal Reef at the base of the Krugersdorp Formation, Johannesburg Subgroup.

An enormous database relating to the basin's sedimentology, stratigraphy, tectonics, and economic geology has accumulated over the last century owing to rich gold deposits associated with the coarser Witwatersrand facies. Early workers (e.g. Pretorius, 1976, 1981) envisaged an intracratonic extensional half-graben tectonic setting, and suggested that the basin was flanked by an active normal fault-bounded northwestern margin, and a relatively passive southeastern margin. In contrast, more recent studies link basin evolution to convergence and collision between the Zimbabwe and Kaapvaal Cratons, suggesting that the Witwatersrand Basin formed through flexural deflection in a retroarc foreland setting, in response to thrust loading along the northern margin of the Kaapvaal Craton (Fig. 4; Burke et al., 1986; Winter, 1986, 1987, 1995; Hartnady and Stowe, 1991; Robb et al., 1991; Stanistreet and McCarthy, 1991; Coward et al., 1995; Robb and Meyer, 1995). The strike of the basin follows a NE–SW trend, with the distal margin towards the SE. The preserved sedimentary fill extends 390 km along the strike and 130 km along the dip from the orogenic front (Pretorius, 1986).

The basic subdivision of the Witwatersrand stratigraphy includes a lower West Rand Group and an upper Central Rand Group (Figs. 2–4). The former represents the underfilled phase of the foreland system, and contains predominantly marine deposits,

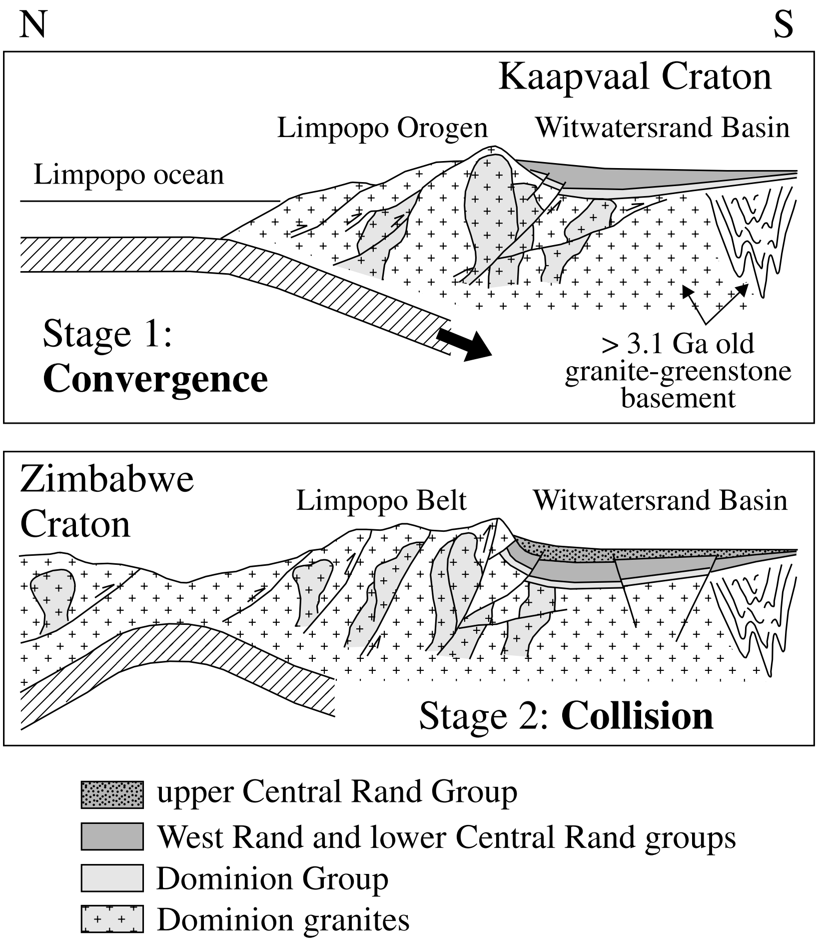

Fig. 4. Tectonic setting of the Witwatersrand Basin in relation to the convergence between the Zimbabwe and Kaapvaal cratons during the Late Archaean (modified from Robb et al., 1991; Robb and Meyer, 1995). Deformation along the northern margin of the Kaapvaal Craton led to supracrustal loading and the development of a retroarc foreland system. Not to scale.

whereas the latter corresponds to the overfilled phase of the foreland system and contains predominantly nonmarine deposits. Superimposed on this overall trend, the evolution of both units is punctuated by various hierarchical orders of transgressive and regressive events, with the core of an interior seaway being placed along the distal margin of the foredeep. The main economic horizon exploited within the study area, the Vaal Reef placer, is part of the Johannesburg Subgroup of the Central Rand Group (Figs. 2 and 3).

4. Methods

Investigations regarding allostratigraphy and facies interpretations of the Witwatersrand Supergroup in the Vaal River region have been undertaken by Minter (1972) and, as reported in numerous 'in-house' papers, by Anglogold employees (see Acknowledgements). This paper focuses on the application of modern sequence stratigraphic methods for the correlation of facies between the Great Noligwa and Kopanang mining areas. Detailed sedimentological profiles were collected from current underground workings. A total of 40 detailed logs were compiled, and over 200 stratigraphic profiles were measured to establish unit thicknesses across the area. Seven boreholes drilled and logged during the study, as well as information from older boreholes, old reports and stope maps provided additional sources of information. In conjunction with the compilation of a number of detailed sedimentological logs of surface boreholes that traverse the study area from west to east (Fletcher, pers. comm., 1999), these data permit a detailed analysis and comparison of facies types.

5. Sedimentary facies and environments

The Witwatersrand Supergroup displays transgressive and regressive facies shifts superimposed at different scales. This case study deals with a small fraction of the basin fill, and investigates a relatively high frequency succession of base-level changes and shoreline shifts. The Vaal Reef and its bounding sedimentary units were deposited in a marginal marine setting, where the stratal stacking patterns were controlled by the interplay between fluvial, deltaic, shoreface and shelf environments. This is an ideal setting for the application of sequence stratigraphic methods.

The Vaal Reef package comprises an association of vertically stacked facies that display distinct lateral variations from the Kopanang Mine in the west to the eastern boundary of the Great Noligwa Mine. The facies included in the Vaal Reef package at the Great Noligwa Mine incorporate the channelized Zaaiplaats conglomerates and quartzites, and the G.V. Bosch conglomerate (Fig. 5). At the Kopanang Mine, the terms Witkop, Grootdraai, Stilfontein and Upper Vaal Reef facies are used to refer to the Vaal Reef (Fig. 6). The Main Bird quartzites (MB5's), locally overlain by the Mizpah conglomerates and quartzites, form the footwall to the reef across the entire study area. The MB4 quartzites form the hanging wall to the reef in the Great Noligwa area. The latter are overlain by the Zandpan Marker conglomerate, which extends across both mining areas.

The sedimentological features that define the Vaal Reef and its adjacent sedimentary units are presented below. The paleo-depositional environments are interpreted from sedimentary structures, textures, and the geometry and architecture of the preserved deposits. Limiting factors for these interpretations include the effects of low-grade metamorphism and hydrothermal fluid circulation, the lack of fossils or trace fossils, and restricted underground exposures.

5.1. Great Noligwa Mine facies

5.1.1. The MB5 quartzite unit

The MB5 quartzite unit (60 m thick) consists of light gray, medium to coarse grained orthoquartzites and argillites (Biddulph, 1998). Minter (1972) recognized two coarsening-upward subunits. At the base of both subunits, argillites are interbedded with quartzites. The proportion of argillite decreases upsection and each subunit is capped by cross-stratified quartzites. The MB5 unit is overlain by channelized fluvial conglomerates (Mizpah facies, described below). We consider that the coarsening-upward subunits record aggradation and progradation of delta lobes that were in turn prograded by delta-plain fluvial deposits (Mizpah facies).

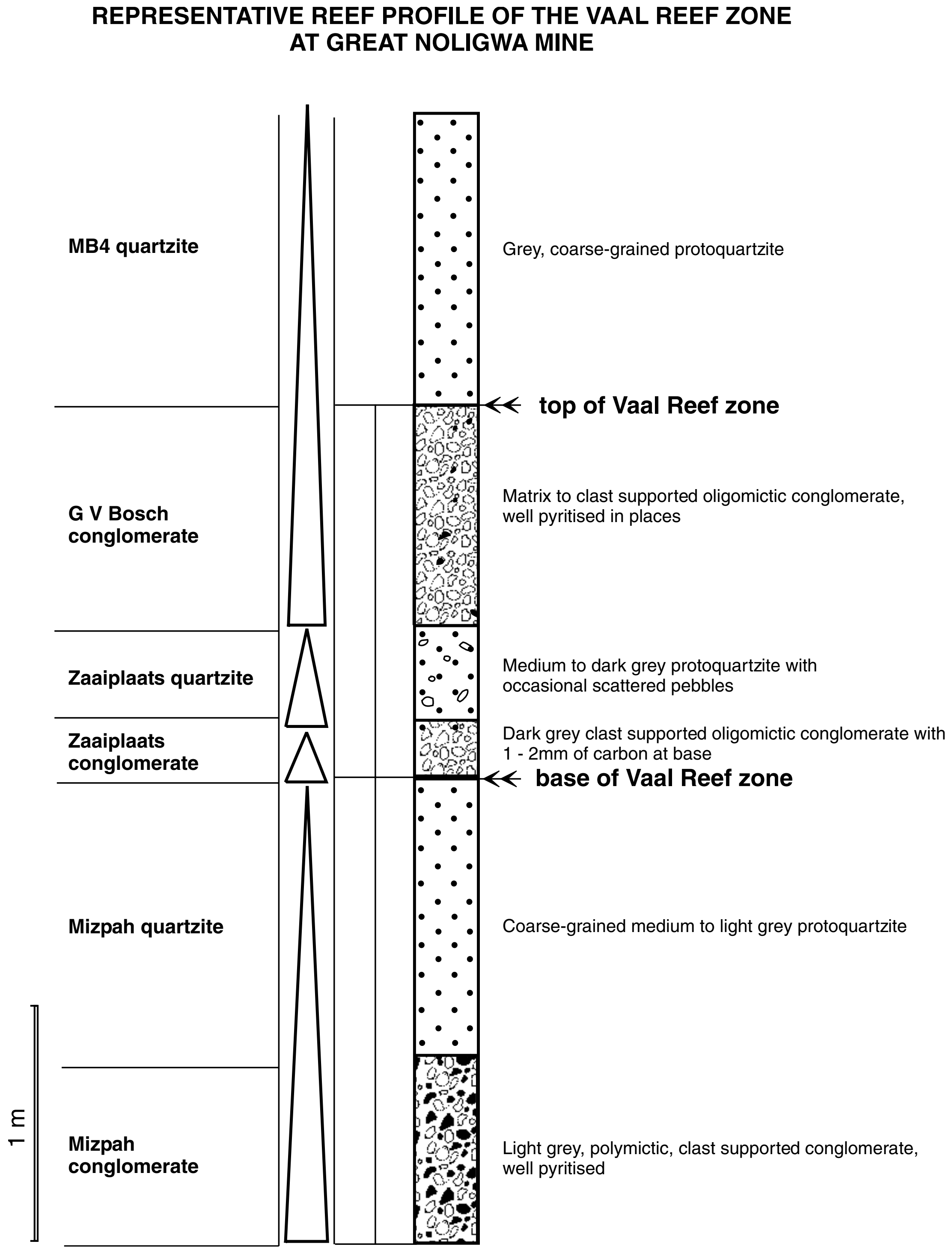

Fig. 5. Generalized profile of the Vaal Reef zone at the Great Noligwa Mine.

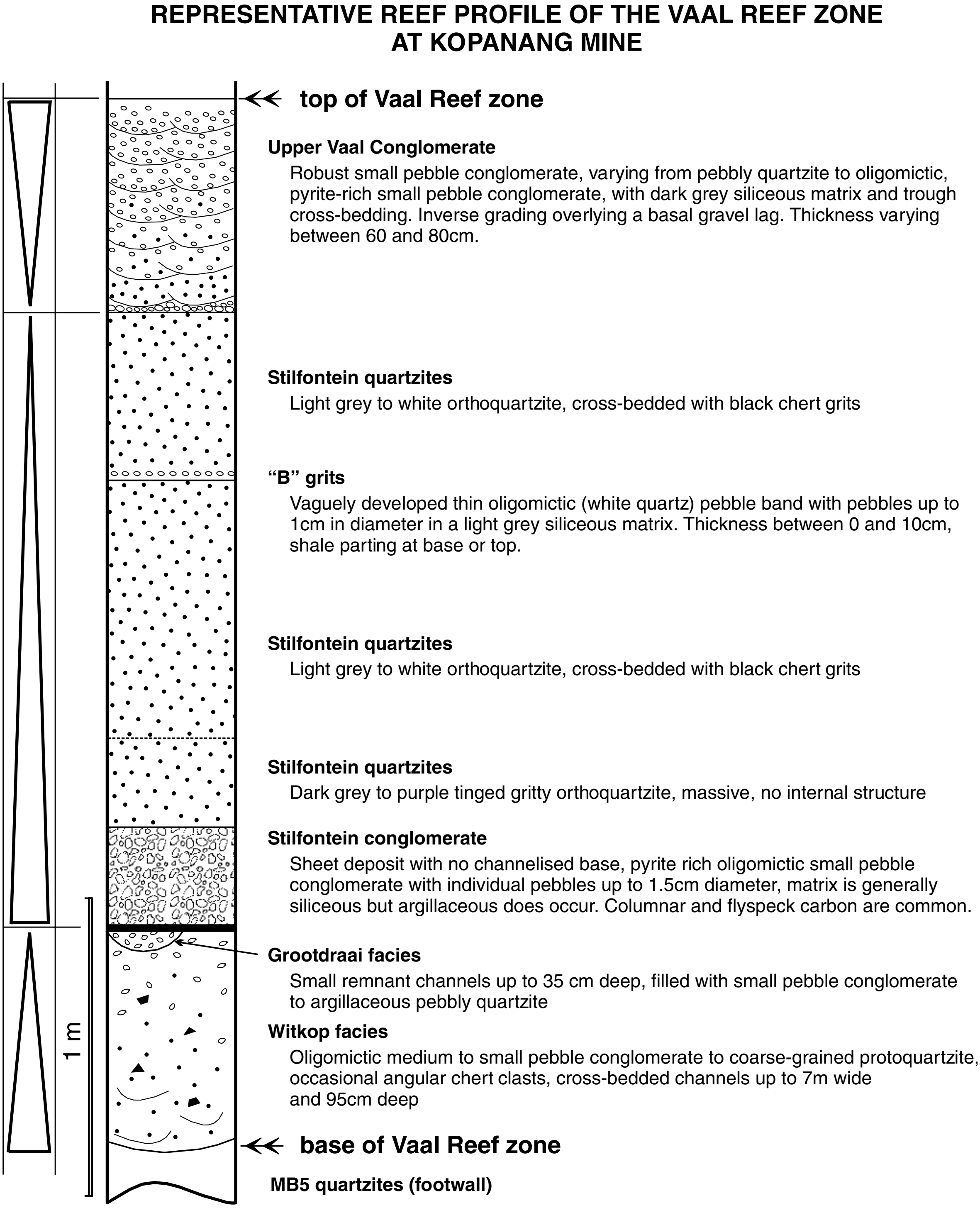

Fig. 6. Generalized profile of the Vaal Reef zone at the Kopanang Mine.

5.1.2. The Mizpah conglomerate

The Mizpah conglomerate comprises two well-defined channel fills with a south–southwest palaeocurrent trend (Biddulph, 1998). The unit thickens southwards from 1.1 m at the Great Noligwa Mine to ca. 2.7 m south of the study area. The conglomerate is moderately sorted and consists of self-supporting pebbles (8–16 mm apparent long-axes). It contains a diverse clast suite including: predominantly sub-angular to sub-rounded white and smoky quartz, scattered sub-angular black chert and local subrounded gray porphyry clasts. The matrix comprises light gray to yellow gray, moderately sorted medium- to coarse-grained orthoquartzite, and locally contains a high percentage (up to 50%) of pyrite. This gives the unit a distinctive yellow-brown color, particularly where it has been oxidized in underground exposures. The pyrite is found disseminated throughout the unit, but is also concentrated as stringers along the foresets of planar and trough cross-bedded gravels.

The Mizpah conglomerate is characterized by fining-upward cycles in which a basal lag passes through planar to trough cross-bedded arenites. These vertical profiles, together with channel forms suggest deposition in a high-energy, gravel-dominated fluvial system. The transition between the Mizpah conglomerate and the overlying Mizpah quartzite is gradational, and the two units define one overall fining-upward succession.

5.1.3. The Mizpah Quartzite

The Mizpah Quartzite unit consists of moderately mature to immature, medium to coarse grained, yellow-gray orthoquartzites, generally <1 m thick. Locally, the unit is represented by protoquartzites containing small, angular to sub-angular scattered pebbles and grit bands. Trough cross-stratified beds locally grade upward to those with planar cross-bedding. The quartzites are inferred to represent the lower energy component of the Mizpah fluvial system. The Mizpah facies are overlain by the Zaaiplaats fluvial channel fills, the two units being separated by the regional unconformity that marks the base of the Vaal Reef package. Where the Mizpah quartzites are absent, presumably due to subaerial erosion, the Zaaiplaats conglomerate and quartzites or G.V. Bosch conglomerate lie directly on the Mizpah conglomerate.

5.1.4. The Zaaiplaats conglomerate

The Zaaiplaats conglomerate facies locally comprises two separate sub-units that likely represent stacked channel fills. Where both are developed, the lower unit is typically preserved as small remnants erosionally cut out by the upper unit. The lower unit (up to 0.4 m thick) is restricted to the central portion of the study area. The upper unit contains basal conglomerates (rarely more than 0.4 m thick) that are capped by 10–15 cm (locally >40 cm) of dark gray orthoquartzites ('Zaaiplaats quartzite', see Section 5.1.5). Clasts comprise mainly rounded white and smoky vein quartz clasts (85–95% of clast assemblage) and sub-angular black chert clasts. The conglomerate has a very dark gray glassy matrix ($\sim$375 μ), which contrasts to the light gray matrix observed farther to the north.

The depositional environment is interpreted as a braided channel system (Biddulph, 1998). The unconfined character of the braided channels led to the development of unconformable contacts between the individual channel fills. Where the Mizpah facies are missing, the Zaaiplaats conglomerates rest unconformably upon the MB5 quartzites.

5.1.5. The Zaaiplaats quartzite

The Zaaiplaats quartzite is a fine to medium grained, mature, and dark gray orthoquartzite that separates the Zaaiplaats conglomerate from the overlying G.V. Bosch conglomerate. It is locally found as a pebbly quartzite that displays a gradational contact with the underlying Zaaiplaats conglomerate unit. Where the Zaaiplaats quartzite is absent, the G.V. Bosch conglomerate lies directly on the Zaaiplaats conglomerate, above an erosional contact. Local trough cross-beds, with foreset heights that range from 8 to 30 cm, record paleoflow directions of 210–220° in the southwest part of Great Noligwa Mine, and 180° in the northern part of the mine (Biddulph, 1998). The Zaaiplaats quartzites are inferred to represent the upper, low energy facies of the Zaaiplaats fluvial system.

5.1.6. The G.V. Bosch conglomerate

The G.V. Bosch conglomerate is a laterally extensive unit, up to 1.7 m thick, consisting of medium to light gray, small to medium pebble, clast-supported oligomictic conglomerate set in a medium-grained quartzite matrix. In contrast to the channelized nature of the underlying Mizpah and Zaaiplaats facies, the G.V. Bosch unit displays a sheet-like morphology. It is locally found as planar cross-bedded conglomerate or as clast-supported conglomerate intercalated with light gray, planar cross-bedded, quartz arenite. The clast assemblage comprises mainly (~85–95%) spheroidal, sub-rounded to rounded white and smoky vein quartz 8–15 mm in size. Significantly, clast sizes do not vary across the extent of the G.V. Bosch unit. Sub-angular black chert clasts are present throughout the unit and were likely derived from reworking of the underlying Mizpah and Zaaiplaats units. Such reworked clasts are readily identifiable as they are an order of magnitude larger than the other clasts. Isopach plans within the Great Noligwa lease area indicate that, where the G.V. Bosch unit is thick, the underlying Zaaiplaats is thinly developed, consistent with reworking during G.V. Bosch deposition. The G.V. Bosch unit conformably grades upwards to the MB4 quartzites; together these two units form a fining-upward succession. Locally the unit is cut-out due to sub-Zandpan Marker erosion.

The environmental conditions leading to the accumulation of the G.V. Bosch conglomerate appear to have been markedly different relative to underlying units. In agreement with Minter (1972), the morphological and sedimentological features point towards a transgressive shallow marine setting. The low-relief and laterally extensive scour surface at the base of the unit is interpreted to represent a RS (transgressive surface of marine erosion) cut by shoreface waves during shoreline transgression. The texture, clast types, uniformity of clast sizes, sheet-like geometry and gradational transition to the MB4 quartzites displayed by the conglomerates suggest high-energy shoreface deposition, as a transgressive gravel lag above the RS.

5.1.7. The MB4 quartzite

The MB4 quartzite consists of well sorted, light gray, medium- to coarse-grained protoquartzites (1–2 m thick) conformably overlying the G.V. Bosch conglomerate. The unit is characterized by planar cross-bedding with forset concentrations of heavy minerals. Minter (1972, 1976) inferred that the quartzites were deposited by longshore drift in a transgressive shallow-marine environment, and suggested that unimodal paleocurrents (vector mean ca. 077°) indicated transport from the west. The upward transition from the G.V. Bosch conglomerates is consistent with an overall decline in energy levels as water depth increased during transgression. The MB4 quartzites are bounded above by an unconformity at the base of the Zandpan Conglomerate. The latter forms a lithological marker that is developed across the entire study area, and consists of poorly sorted, clast-supported polymictic conglomerate.

5.2. Kopanang Mine facies

Minter (1972) subdivided the Vaal Reef into two main facies: the Witkop and the Stilfontein. Subsequent work by Anglogold geologists added further subdivisions and herein we group facies at the Kopanang Mine into six assemblages (Fig. 6): MB5 quartzites (footwall); Witkop conglomerate; Grootdraai facies; Stilfontein facies; Upper Vaal facies; and Zandpan conglomerate (hanging wall).

5.2.1. MB5 quartzites

MB5 quartzites are the same as those at Great Noligwa Mine, except that siliceous bands are more common at the Kopanang Mine. The MB5 quartzites form the footwall relative to the Vaal Reef facies across the entire study area.

5.2.2. Witkop conglomerate

Witkop conglomerate remnants are preserved filling channels ca. 1 m deep and up to ca. 7 m wide cut into underlying MB5 deltaic deposits. The conglomerates are clast- to matrix- supported and contain a light gray medium- to coarse-grained siliceous matrix (Britz, pers. comm., 2000). Small to medium (ca. 10 mm diameter) pebbles include: rounded vein quartz (95–100%); angular to sub-angular black chert (0–5%); lithic (quartzite) fragments (0–2%) and in places, light gray porphyry (up to 3%). Large (1–4 m wide) trough and epsilon cross-beds indicate palaeocurrent directions of 233°. This facies is inferred to record deposition in a high-energy fluvial environment.

5.2.3. The Grootdraai facies

The Grootdraai facies is present across the Kopanang lease area as remnant, shallow (35 cm) fluvial channel fills. These generally cut into MB5 quartzites, but are locally developed above remnant Witkop deposits. The Grootdraai facies is generally found varying between a pebbly quartzite and a well mineralized medium to large pebble (15–35 mm) conglomerate lag (Britz, pers. comm., 2000), with a light gray, medium- to coarse-grained sub-siliceous to argillaceous matrix. There is conspicuously less pyrite within this unit in comparison to the amount of mineralization in the overlying Stilfontein facies. The clast assemblage comprises predominantly sub-rounded to rounded vein quartz, with lesser proportions of sub-angular to sub-rounded black chert. Light gray porphery and jasper clasts are locally found. Palaeocurrent directions of 161° have been recorded for this unit. Together, the Witkop and Grootdraai units are inferred to represent multi-storey channel fills that display several internal scour surfaces related to the lateral shift of fluvial channels.

5.2.4. The Stilfontein facies

The Stilfontein facies forms a laterally extensive sheet-like deposit that erosionally cuts out underlying units. It wedges out to the east and is truncated by the overlying Upper Vaal Reef. The unit consists of a basal small pebble (<10 mm diameter) conglomerate 2–36 cm thick, overlain by fine- to medium-grained siliceous to sub-siliceous light gray quartzite. Clasts include: sub-rounded to rounded quartz (85%); sub-angular to sub-rounded black chert (12%) and sub-angular to sub-rounded gray porphyry (0.2%; Minter, 1972). Carbon is widespread at the base of the unit. Pyrite can constitute between 50 and 100% of the matrix of the conglomerates. The Stilfontein conglomerate is the main gold bearing horizon at Kopanang Mine.

Planar cross-bedding in the lower portion of the quartzites, pass upward to hummocky cross stratification toward the top (De Vries, pers comm., 1999). This suggests a marine origin for the Stilfontein facies, within an overall transgression in which shoreface deposits were onlapped by inner shelf deposits. The low-relief and laterally extensive scour surface at the base of the Stilfontein facies is interpreted as a RS associated with the shoreline transgression.

5.2.5. The Upper Vaal facies

The Upper Vaal facies (0.6–0.8 m thick) varies from a pebbly quartzite with pyritic grits west of the Kopanang lease area to a light gray, small to medium pebble (ca. 10–15 mm), clast-supported, oligomictic (~85–95% white and smoky vein quartz clasts ± sub-angular black chert clasts) conglomerate in the east. Above a thin basal gravel lag, the unit defines a coarsening-upward trend in which pebbly quartzites pass to conglomerates. The upper contact of the Upper Vaal facies, with the Zandpan Marker, is unconformable. We interpret that this coarsening-upward reflects deposition in a regressive, marginal marine setting, possibly in a prograding delta front environment.

5.3. Zandpan Marker

The Zandpan Marker is a relatively thin, (<1 m), clast- to matrix-supported polymictic conglomerate that caps the Vaal Reef stratigraphy across the study area. This layer represents a gravel lag associated with a strongly erosional surface, which truncates in places through the MB4 quartzites into the GV Bosch conglomerate. Zandpan conglomerate conformably grades upward to the MB3 unit, which comprises a sub-siliceous quartzite interbedded with scattered polymictic grit and conglomerate bands.

6. Sequence stratigraphy

Herein, we establish the chronology of events leading to the accumulation of the individual packages that comprise the Vaal Reef, as well as the correlation and relative chronology between the facies mapped at the Kopanang and Great Noligwa mines. The stratigraphic position of the Vaal Reef facies associations is well constrained between sedimentary packages with regional lateral extent: the MB5 quartzites in the footwall of the Reef at both mines; and the Zandpan Marker and the overlying MB3 quartzites in the hanging wall of the Reef. The main obstacle to overcome in the correlation of Vaal Reef facies is the lack of time control, a problem common to most case studies involving Precambrian sequences (see Catuneanu and Eriksson, 1999 for a discussion). Therefore, the paleoenvironmental interpretations, summarized above, represent a key element in unraveling the succession of depositional events that led to the stacking patterns preserved in the study area.

We infer that the G.V. Bosch is a shallow marine transgressive deposit, and the Upper Vaal facies a delta front, regressive deposit. This suggests that the two reef horizons are not of the same age, and therefore not part of one laterally continuous sedimentary wedge of genetically related strata. We correlate the G.V. Bosch conglomerate and the overlying MB4 quartzite with transgressive counterparts at Kopanang (the Stilfontein conglomerate and overlying quartzite facies Figs 7 and 8), and thus infer that the MB4 quartzite at Great Noligwa is older than the Upper Vaal conglomerate at Kopanang. The transgressive facies are separated from the underlying sediments by an unconformity interpreted here as a RS (i.e. transgressive surface of erosion), cut by shoreface waves during the transgression of the shoreline. The conglomerates are interpreted as lag deposits associated with the ravinement erosion, and they conformably grade upwards into marine quartzites. The variation in thickness, as well as differences in sedimentary structures between the eastern and western reaches of the study area, indicate different positions relative to the paleo-shoreline. The transgressive facies at Great Noligwa (G.V. Bosch and MB4) are thicker, both in terms of the lag conglomerate and the overlying quartzite, suggesting shallower water and proximity to the shoreline. The Stilfontein facies are thinner, and the hummocky cross-stratification in the upper quartzites suggests deposition close to storm wave base. This implies a shoreface into the inner shelf transition from east to west. The recognition of this transgressive unit across the entire study area is the key element to understanding the facies relationships in the Klerksdorp goldfield. The remaining facies associated with the Vaal Reef have clear stratigraphic relationships relative to these transgressive strata, and can be placed into a genetic framework. We envisage the following succession of events (Fig. 7).

1. *Late base-level rise*: aggradation and progradation of deltaic and fluvial systems, leading to the accumulation of the MB5 quartzite and the overlying Mizpah facies, respectively. This deposit formed during a normal regression of the shoreline, and is interpreted here as a HST. The upper boundary of this footwall wedge is represented by a subaerial unconformity (SU) (SU #1 in Fig. 7), cut by fluvial and/or wind degradation during the subsequent forced regression of the shoreline.
2. *Base-level fall*: SU (SU #1 in Fig. 7), separating the MB5 quartzites from the overlying facies.
3. *Early base-level rise*: low rates of fluvial aggradation, resulting in amalgamated high-energy fluvial channel fills. This succession includes the Zaaiplaats, Witkop and Grootdraai facies, and is interpreted as a LST (LST 1 in Fig. 7). This multistorey fluvial deposit is bounded by a SU at the base, and a RS at the top.
4. *Accelerated base-level rise*: TST. This includes marine deposits across the entire study area. The shallow-water proximal (relative to the paleo-shoreline) facies is represented by the G.V. Bosch conglomerate and the overlying MB4 quartzites and the deeper water distal facies is represented by the Stilfontein conglomerates and quartzites. This marine deposit is underlain by a RS, and bounded at the top by a regressive surface of marine erosion (RSE).
5. *Late base-level rise*: The HST that would have been produced by aggradation during this stage is not preserved and was likely eroded during subsequent base-level fall.
6. *Base-level fall*: forced regression of the shoreline, associated with erosional processes in both the nonmarine and marine portions of the basin. The study area was most likely seaward of the paleo-shoreline because the overlying lowstand deposits are deltaic. The marine erosion associated with this forced regression likely removed the entire underlying HST, as well as the top of the TST, as suggested by the lack of a preserved maximum flooding surface. The resulting RSE truncates into the transgressive quartzites (Stilfontein and MB4), separating them from the overlying facies. This surface is associated with a gravel lag preserved at the base of the Upper Vaal facies.
7. *Early base-level rise*: aggradation and progradation in a delta front environment within the study area. The only product of this depositional stage is the coarsening-upward Upper Vaal facies preserved as an erosional remnant saved from subsequent truncation at the Kopanang Mine. The original Upper Vaal deposit probably extended across the entire study area, and was subsequently eroded from the eastern region. The localized preservation of this LST (LST 2 in Fig. 7), restricted to the western part of the

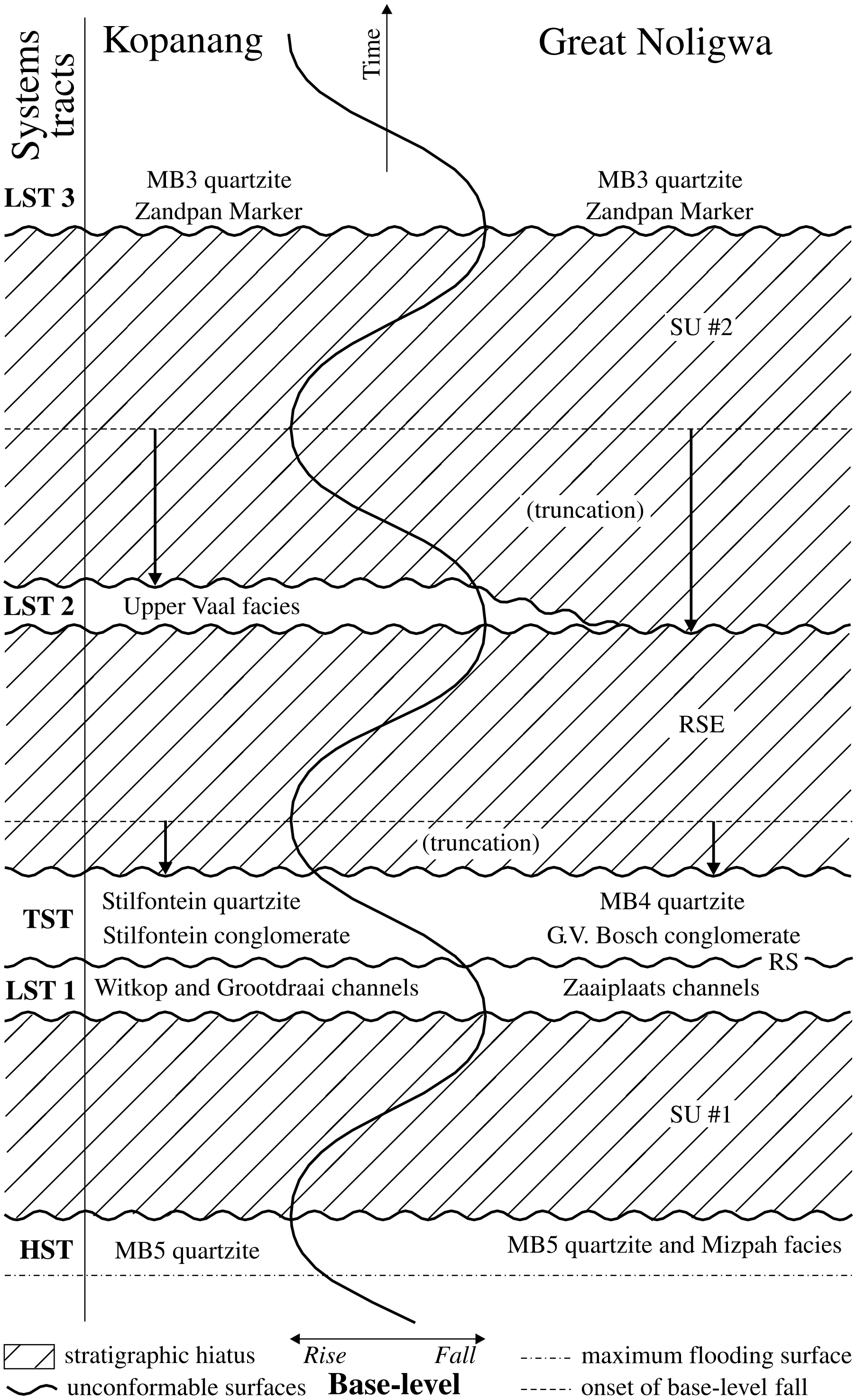

Fig. 7. Relative chronology and systems tracts of the Vaal Reef facies associations. Vertical arrows pointing downwards indicate truncation. Abbreviations: HST = Highstand Systems Tract; LST = Lowstand Systems Tract; TST = Transgressive Systems Tract; SU = subaerial unconformity; RSE = regressive surface of marine erosion; RS = ravinement surface.

study area, is possibly related to a lower topographic elevation associated with the thinner (distal) underlying transgressive facies in the west. The SU at the top of the Upper Vaal facies at Kopanang, as well as the MB4 quartzites at Great Noligwa, generated incised valleys with relatively flat inter-channel areas, as suggested by the cumulative thicknesses recorded at the two mines: the Stilfontein and Upper Vaal facies add up to an average thickness of 2.5 m, which coincides with the average thickness of the G.V. Bosch and MB4 facies in the east (Fig. 8).

8. *Accelerated and late base-level rise*: nothing is preserved from the rest of this stage of base-level rise. This suggests strong and prolonged subsequent erosion, also implied by the well-developed gravel lag (Zandpan Marker) that caps the Vaal Reef stratigraphy across the entire study area.
9. *Base-level fall*: strong subaerial erosion (SU #2 in Fig. 7) associated with truncation, valley incision, and the development of the Zandpan gravel lag. The erosion manifested during this stage was apparently stronger on the eastern side of the study area, where the Upper Vaal facies was completely removed, and localized incised channels downcut through the MB4 and G.V. Bosch facies (Fig. 8).
10. *Early base-level rise*: LST, leading to the accumulation of the MB3 quartzites that overlie

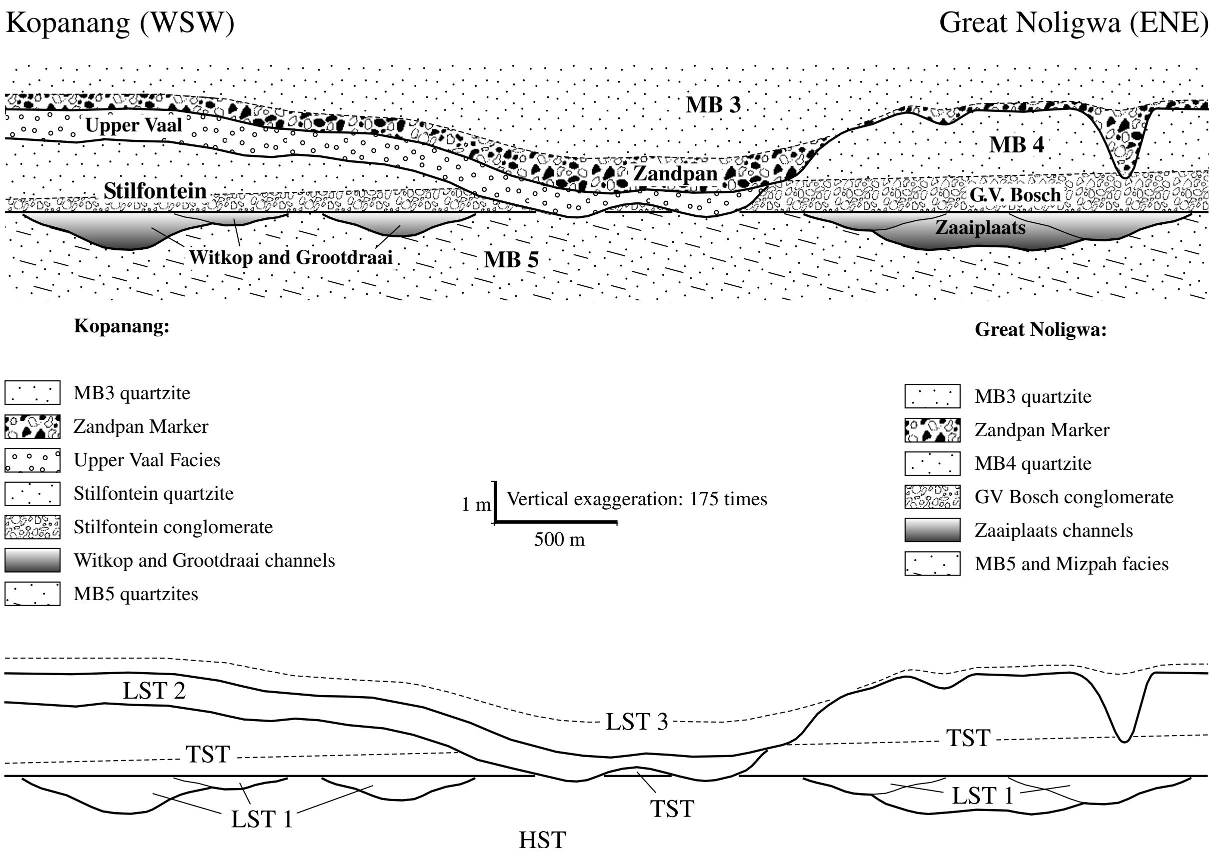

Fig. 8. Generalized cross-sections showing facies relationships and systems tracts in the Kopanang-Great Noligwa area. The RS underlying the transgressive facies is taken as the datum. The width of the amalgamated channels (i.e. LST 1) is exaggerated for clarity. The cumulative thickness of the Stilfontein and Upper Vaal facies at Kopanang matches the cumulative thickness of the G.V. Bosch and MB4 facies at Great Noligwa. This explains the better preservation potential of the Upper Vaal reef in the western part of the study area. Solid lines indicate unconformities, dashed lines indicate conformities. From a genetic prospective, the Vaal Reef includes all facies between the MB5 (footwall) and the Zandpan Marker and overlying MB3 (hanging wall).

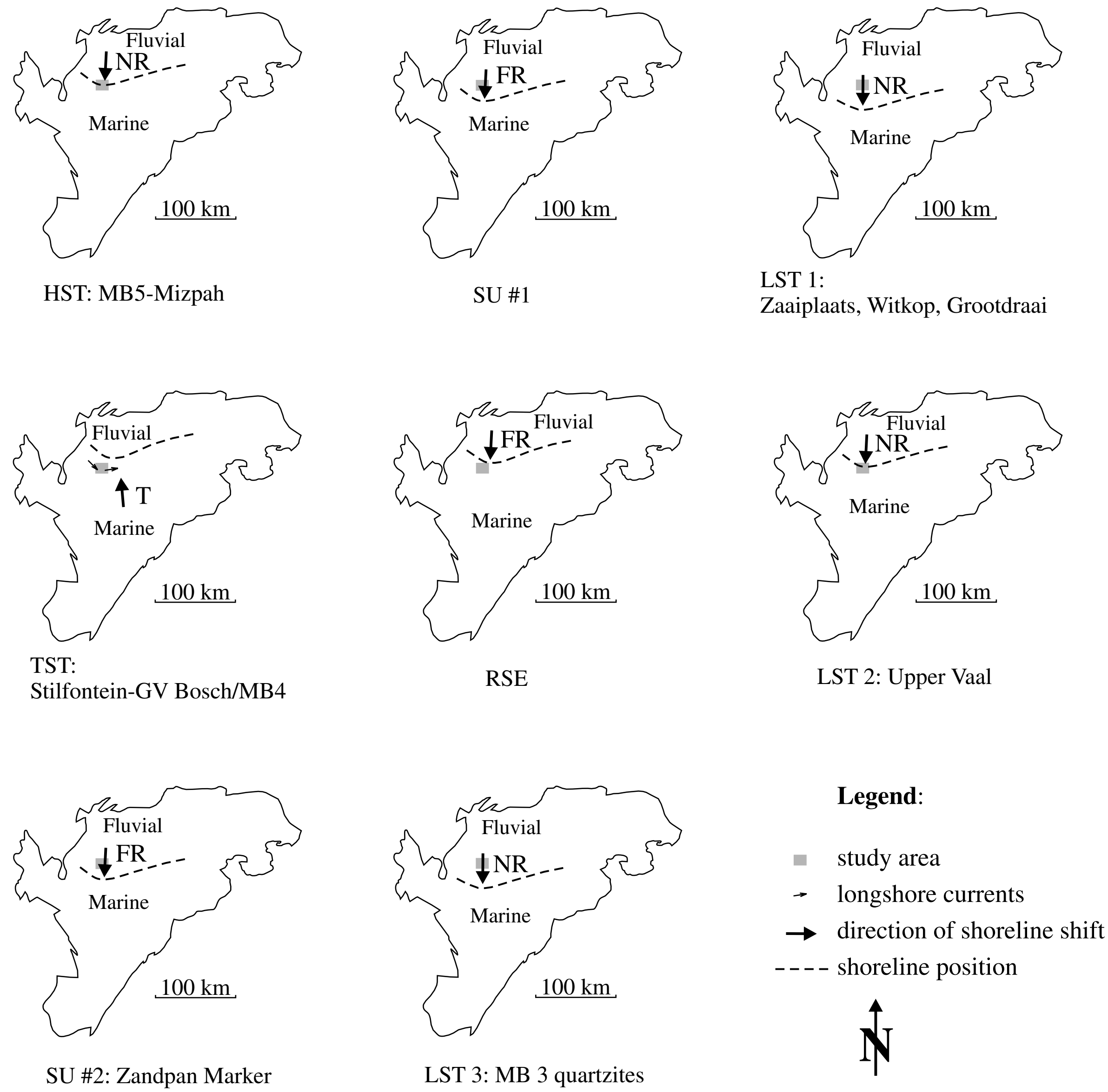

Fig. 9. Paleogeographic reconstructions indicating the shoreline position in relation to the study area for consecutive time slices during the Vaal Reef time. Note the curved trajectory of the shorline, which explains the deeper marine facies at Kopanang relative to their coeval counterparts at Great Noligwa. This shoreline trajectory is in agreement with the paleoflow directions measured for longshore currents and fluvial systems.

confomably the Zandpan Marker in the hanging wall of the Vaal Reef.

The series of maps provided in Fig. 9 represent a preliminary attempt to reconstruct the paleogeography surrounding the study area for consecutive time slices during the accumulation of the Vaal Reef facies. The suggested positions of the paleoshoreline are represented with dashed lines. The deeper marine facies recorded at Kopanang (western part of the study area) relative to their correlative facies at Great Noligwa indicate a curved shoreline in plan view (Fig. 9). Our suggested shoreline position parallels the directions of paleocurrent data inferred to represent longshore currents from the Stilfontein (154°) and MB4 (77°) marine facies. The fluvial paleocurrents measured for the Zaaiplaats (180–220°), Witkop (233°) and Grootdraai (161°) channel fills, with a mean azimuth of 180°, are consistent with this interpretation. The apparent divergence of the fluvial drainage system from north to south suggest curved topographic contours closing around the northern source area. Further research efforts from other mining areas are needed to better constrain the evolution of the shoreline position during the Vaal Reef time. A good knowledge on the position and evolution of the coastlines of the Witwatersrand seaway will be a valuable asset for future production activities, because the lateral development of the various types of gold-bearing gravel reefs is most likely controlled by the environmental conditions established relative to the paleo-shoreline.

7. Conclusions

1. A succession of highstand, transgressive and LSTs has been identified relative to an inferred curve of base-level changes (Fig. 7). The entire succession of facies associated with the Vaal Reef may be assigned to four different depositional sequences, separated by erosional surfaces (subaerial unconformities and/or correlative regressive surfaces of marine erosion) formed during stages of base-level fall.
2. The upper portion of the first (oldest) depositional sequence is represented by the MB5 quartzites and the overlying Mizpah facies. Displaying normal regressive features and capped by a SU, these rocks are assigned to a HST.
3. The second depositional sequence includes two preserved systems tracts: a LST (amalgamated Zaaiplaats, Witkop and Grootdraai fluvial channel fills) and a TST (the marine Stilfontein, G.V. Bosch and MB4 facies). The two systems tracts are separated by a transgressive surface of marine erosion.
4. The third depositional sequence only preserves the lower portion of the LST, represented by the Upper Vaal facies in the western part of the study area.
5. The fourth (youngest) depositional sequence starts with the Zandpan Marker and the overlying MB3 quartzites, and is attributed to a LST.
6. Assuming that a symmetrical sine curve is representative for the pattern of base-level changes, the rock record of the Vaal Reef preserves less than half of the stratigraphic time. This is also suggested by the poor degree of preservation of the identified depositional sequences (Fig. 7).
7. Our results indicate that the Upper Vaal and G.V. Bosch reef horizons at the Kopanang and Great Noligwa mines, respectively, are of different ages. They may however be found in direct physical contact due to the erosion and truncation that preceded the accumulation of the Upper Vaal facies (Fig. 8).
8. The MB4 quartzite was traditionally considered the hanging wall relative to the Vaal Reef, based on gold grade criteria. Our model shows that these quartzites are merely associated with the G.V. Bosch conglomerate. We suggest that the MB4 quartzites are coeval with the Stilfontein quartzites, and are older than the Upper Vaal facies. From a genetic viewpoint, the true hanging wall to the Vaal Reef starts with the Zandpan gravel lag that extends across the entire study area (Fig. 8).
9. Paleoflow directions of longshore currents and fluvial systems indicate a curved shoreline (Fig. 9). This coastline underwent cyclic transgressive and regressive shifts along a north–south direction during the Vaal Reef time.
10. The two main gold-bearing reefs at the Kopanang mine (Stilfontein conglomerates) and the Great Noligwa mine (G.V. Bosch conglomerates) are of the same age. They represent the distal and proximal facies of one laterally extensive transgressive lag associated with a RS.

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