Tectonosedimentary model for the Central Rand Goldfield, Witwatersrand Basin, South Africa

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ABSTRACT

A tectonosedimentary model is established for the Composite Reef at Far East Vertical Shaft, East Rand Proprietary Mine, Central Rand Goldfield. There the Composite Reef comprises the Main Reef and the Main Reef Leader, with the South Reef occurring sporadically in the hangingwall, redefining the Composite Reef stratigraphy for this area. Tectonic controls on sedimentation persisted throughout the deposition of the Composite Reef, influencing the nature and distribution of the conglomerates. Utilising the Composite Reef model, combined with structural and sedimentological modelling of the Central Rand Goldfield, a tectonosedimentary model for the Main Conglomerate Formation is proposed. Pre- and syn-depositional folding associated with regional basin-wide compression resulted in the formation of the Springs Monocline, the West Rand Syncline and associated DRD Anticline. This was overprinted by northwest to southeast oriented folding associated with left-lateral wrenching on the Rietfontein Fault, forming a corrugated palaeosurface, prior to Main Reef deposition, that controlled the palaeoflow direction. Brittle deformation initiated during Witwatersrand times in the form of Riedel and Riedel conjugate shears, normal faults, principal shears and P-shears associated with left-lateral wrenching caused northeast/southwest and east/west cross-cutting channel orientations and northeast/southwest oriented erosion channels. The deposition of the Black Bar, associated with a marine transgression, accumulated in topographically lower lying areas, smoothing the palaeotopography prior to Main Reef Leader deposition. This smoothing effect combined with syn-depositional folding resulted in a single Main Reef Leader channel complex associated with the Robinson Deep Syncline, and restricted Main Reef Leader deposition to an area bounded by the Springs Monocline in the east and the DRD Anticline in the west. Brittle deformation continued during Main Reef Leader deposition resulting in cross-cutting channels. The tectonosedimentary model that has been established increases the confidence of modelling the distribution of conglomerates of the Main Conglomerate Formation, thereby facilitating feasibility modelling of the down-dip, un-mined South Central Rand area.

Introduction

The Central Rand Goldfield is situated to the south of Johannesburg (Figure 1) and is host to one of the most extensive gold reserves in the world (Robb and Robb, 1998). By the late 1960's and early 1970's, most of the mining in the Central Rand Goldfield had ceased, and currently, only one mine is still operational, namely East Rand Proprietary Mines (ERPM). In the early 1980's, interest was revived in the Central Rand Goldfield because of an increase in the gold price, and mining down-dip from the old mine workings was considered. The area currently under consideration has become known as the Argonaut, South WITS or South Central Rand area, and is located as a down-dip extension, to the south, of the defunct Central Rand Goldfield. With mining projected to exceed depths of 4200m, the feasibility of this project relies heavily on the level of confidence of predicted ore resources, which, in turn, depends on a confident geological model outlining the distribution and nature of the orebody.

The Main Reef and Main Reef Leader are the primary target orebodies of the South Central Rand. These orebodies form part of the Main Conglomerate Formation of the Johannesburg Subgroup (Figures 2 and 3), and are separated by the Black Bar, except in the eastern parts of the Basin (ERPM), where they merge with the overlying South Reef to form what is referred to as the Composite Reef (Jones, 1936) (Figure 3). Jones

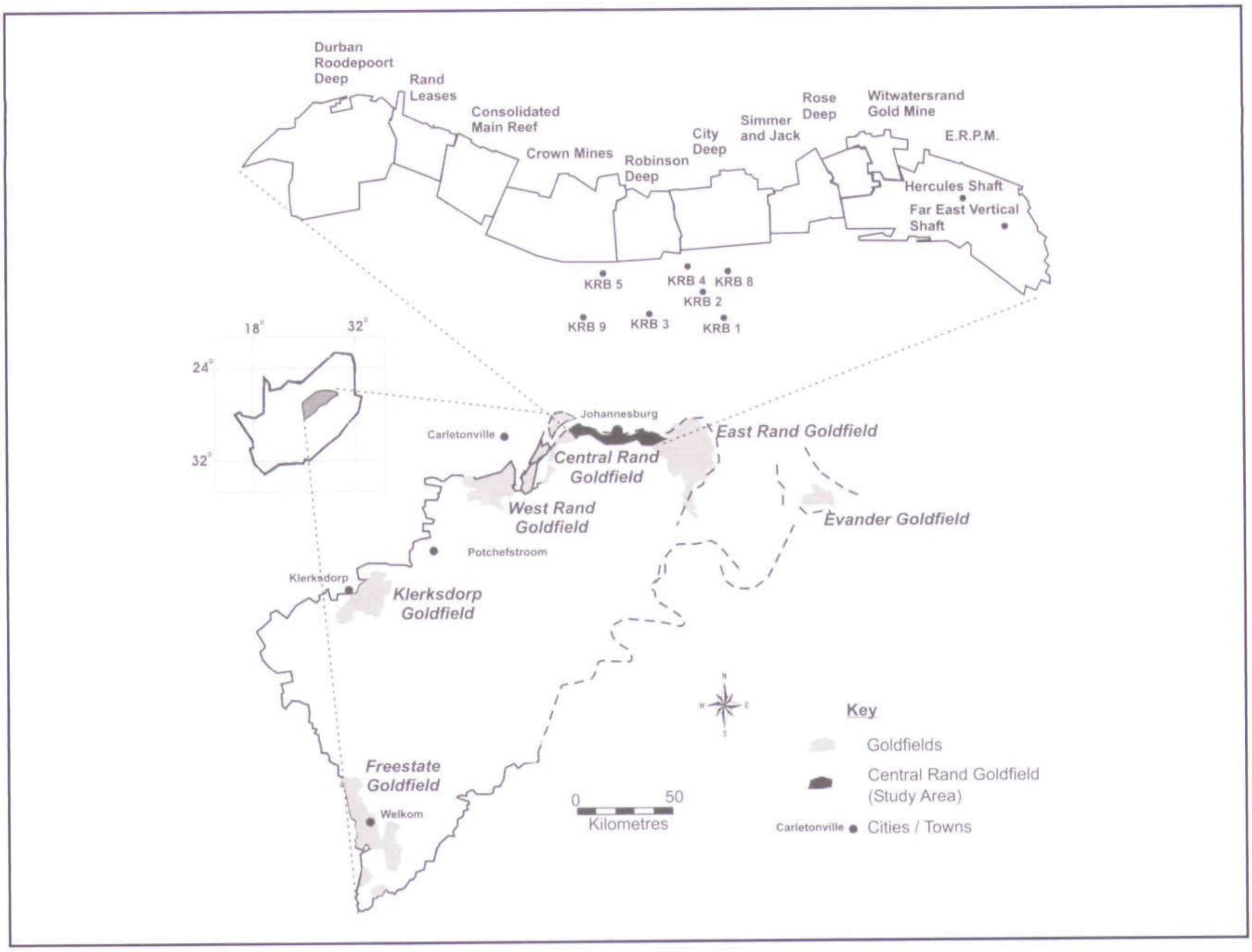

Figure 1. Locality map of the Witwatersrand Basin, showing the location of the Central Rand and other goldfields (modified after Schweitzer and Johnson, 1997). Also indicated are the mines of the Central Rand Goldfield, Far East Vertical and Hercules Shafts of East Rand Proprietary Mines (ERPM), and surface exploration boreholes drilled south of the Central Rand mines.

(1936) argued that there was no evidence for the continuation of the Black Bar (Figure 3) across the ERPM mine area and proposed that the Black Bar and Main Reef Leader diminished to such an extent that the Composite Reef was made up primarily of the Main and South Reefs.

This study considers sedimentological characteristics of the Main Reef and Main Reef Leader at ERPM Hercules Shaft, and the Composite Reef at the Far East Vertical (FEV) Shaft of ERPM (Figure 1). This information is used to propose a tectonosedimentary model for the deposition of the Composite Reef in the FEV Shaft area. The Composite Reef model is used as a basis, in conjunction with findings from regional tectonic studies, to review and refine previously proposed depositional models for the Central Rand Goldfield.

Background

Although Pretorius' (1964) fan delta model adequately explains the deposition of the Central Rand Goldfield, several researchers (e.g. Hiller and Mason, 1982; Camden-Smith *et al.*, 1989, and Stanistreet and McCarthy, 1991) have demonstrated that tectonic control was fundamental to the process of sediment deposition in the Central Rand Goldfield. Despite the significant amounts of geological modelling that has been undertaken to explain reef deposition (*e.g.* Mellor, 1917; Reineke, 1927; Wethmar, 1957; Pretorius, 1974; Weder, 1983; Stear, 1986; Stanistreet et al., 1986; Charlesworth and McCarthy, 1990; Reading and Reynolds, 1993), much of the earlier work (pre 1970's) concentrated on purely sedimentary models, not recognising the impact of syn-depositional structural features on conglomerate distribution. Wethmar (1957) first identified a regional northwest-southeast palaeoflow direction with northeast to southwest cross-cutting channels associated with both the Main Reef and the Main Reef Leader. Pretorius (1974) recognised a relationship between regional northwest to southeast oriented anticlines in the goldfield and regional palaeoflow directions, as well as east to west cross-cutting channel orientations, and based his depositional model on the fan delta model (Pretorius, 1964), with entry points from the northwest and northeast. The fan-delta model recognised normal faulting along the Rietfontein Fault (Figure 2) associated with uplift of the hinterland. During the 1980's a 2D seismic study was carried out in the South Central Rand area. From this, Weder (1983) identified a series of

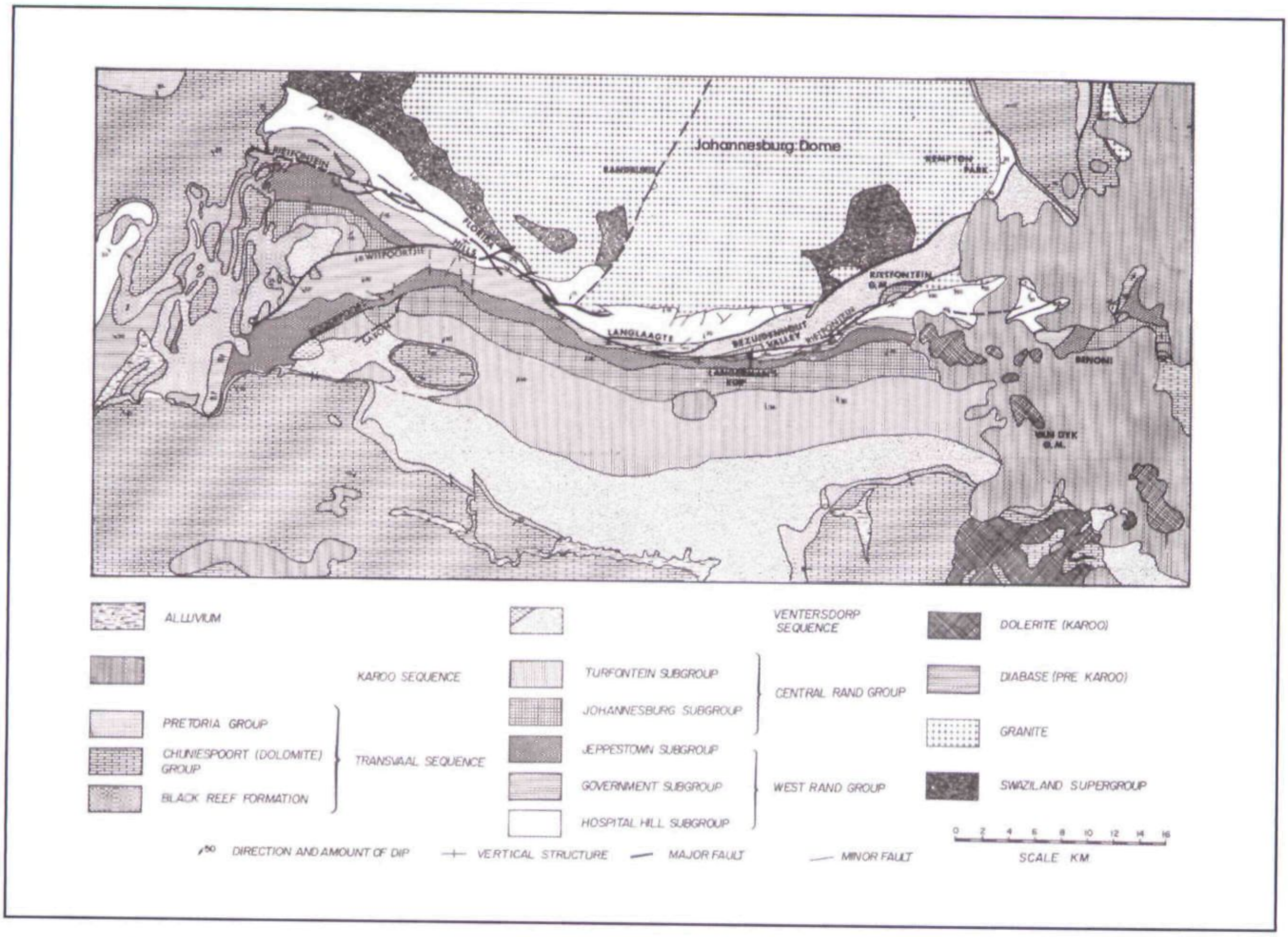

Figure 2 Surface geological map of the Central Rand Goldfield and surrounding areas (after Mellor, 1917).

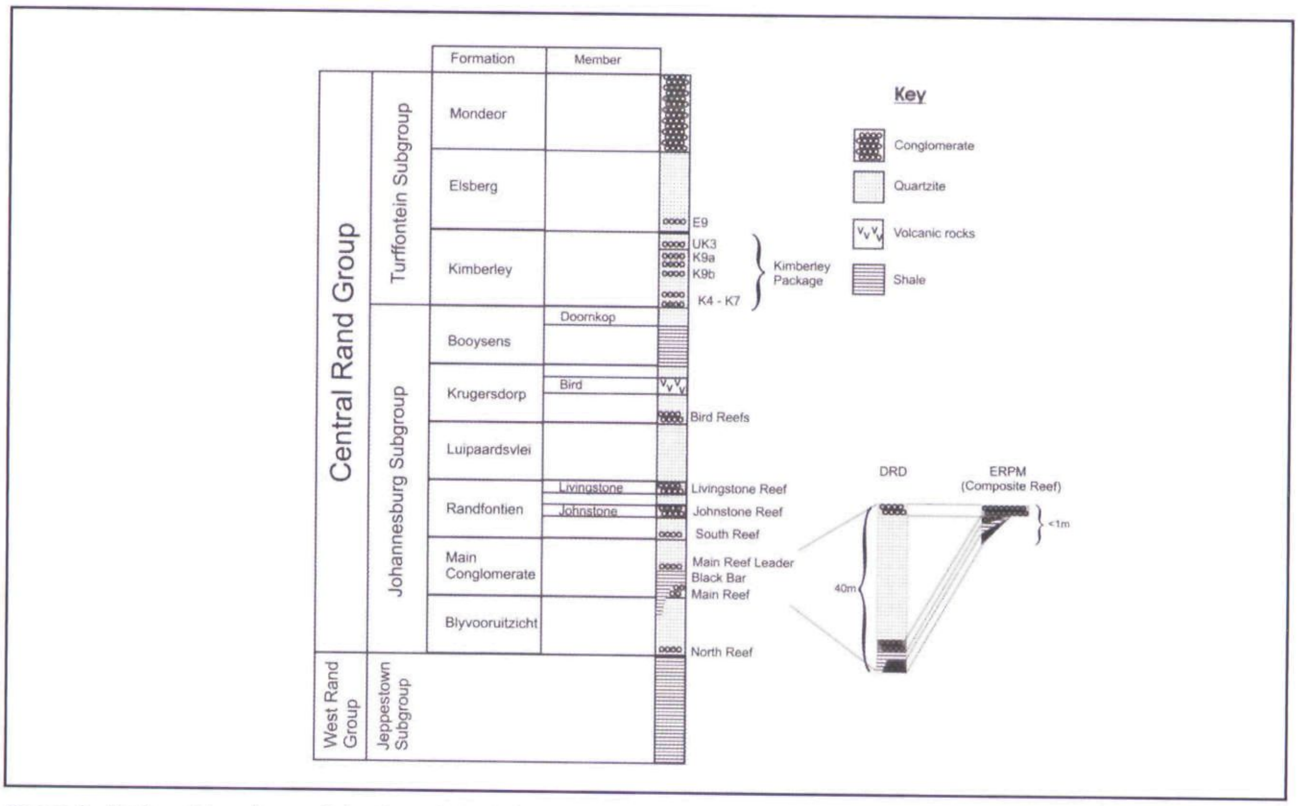

Figure 3 Stratigraphic column of the Central Rand Group as it occurs in the Central Rand Goldfield (modified after Kingsley, 1998). Also illustrated is the coalescence of the Main Conglomerate Formation and the South Reef from Durban Roodepoort Deep Mine in the west of the goldfield to East Rand Proprietary Mines in the east.

synclinal and anticlinal fold axes, which he proposed controlled the depositional patterns of the Main Reef and Main Reef Leader. Pretorius (1992) modified his model and removed the northeastern entry point.

Stanistreet *et al.* (1986) recognised that the Rietfontein Fault (Figure 2) was associated with left-lateral wrenching during Main Conglomerate deposition. Camden-Smith and Stear (1986) utilised this information, to propose a left-lateral wrenching model that controlled the deposition of the Composite Reef at ERPM. They further proposed that cross-cutting channels observed by Wethmar (1957) resulted from successive shoreline migrations. Grohmann (1986, 1988) compiled and interpreted 1:10 000 structure plans of the entire Central Rand Goldfield from 1:1 000 mine structure plans. Through this investigation, Grohmann (1988) recognized southerly dipping, east to west trending normal faults, related to the uplift of the hinterland that formed during Witwatersrand deposition. He further proposed that left-lateral wrenching along the Rietfontein Fault (Figure 2) resulted in the formation of Riedel shears, Riedel conjugate shears, principal shears and P-shears (Wilcox *et al.*, 1973), and that these shears were of Ventersdorp age, based on dyke ages identified by Jeffery (1975). Grohmann (1988) also recognized thrust and normal faulting associated with left-lateral wrenching. The rising of the Johannesburg Granite Dome resulted in the reactivation of normal faults in a reverse sense (Grohmann, 1988). Bushveld deformation was associated with east to west compression (Roering, 1986; personal communication in: Grohmann, 1988), and dyke emplacement into pre-existing fault planes occurred. Grohmann (1988) recognized that Ventersdorp-age wrenches were reactivated in a right lateral sense during this compression.

Since the late 1980's, there has been little work conducted on tectonosedimentary modelling of the Central Rand Goldfield. However, regional modelling of the tectonic development of the Witwatersrand Basin by authors such as Myers *et al.* (1990), combined with the findings by Charlesworth and McCarthy (1990) on the Rietfontein Fault (Figure 2), have provided sufficient additional information to review and refine previously proposed models.

The Main Reef, Main Reef Leader and Composite Reef at ERPM

Main Reef and Main Reef Leader at Hercules Shaft

The thickness and characteristics of the Main Reef are highly variable over distances of less than 50m. It consists of one to four distinguishable conglomerate units separated by quartzite lenses. The conglomerates are matrix-supported (approximately 30% to 50% matrix material) and are polymictic, consisting of white (90%) and smoky (5%) vein quartz clasts and chert clasts (5%) that vary from 2 to 4cm in size. Sulphide mineralisation in the conglomerates is variable, but, on average, they are moderately mineralised (10 to 15% of the matrix) by predominantly disseminated euhedral pyrite (<0.5mm) and occasionally small detrital (<1 mm) pyrite. The base of the Main Reef is a pronounced, unconformable contact with the footwall quartzite. The top contact is gradational where it is in contact with the hangingwall quartzite, and sharp when in contact with the Black Bar.

The Main Reef hangingwall quartzite is a dark grey, fine-grained (<1mm), siliceous, massive or planar cross-bedded quartzite. The Black Bar is a very fine-grained (<0.1mm) quartzite, in places grading into a siltstone. It is grey, massive and devoid of any sedimentary features. The bottom contact, and occasionally the top contact, of the Black Bar are affected by bedding-parallel faulting that is commonly associated with quartz veins.

The primary distinction between the Main Reef and the Main Reef Leader is made on the basis of average clast sizes, clast packing densities and presence of internal quartzites. The Main Reef Leader is a clast-supported (<20% matrix), small pebble (0.5cm to 2cm) conglomerate. This conglomerate is oligomictic consisting of approximately 90% white and 5% smoky vein quartz clasts and 5% blue opalescent quartz clasts. Localised (typically ranges of less than 10m) dark-grey, fine-grained quartzite matrix occurs. On average, the Main Reef Leader conglomerate is more mineralised (up to 25% of matrix) than the Main Reef. Mineralisation is predominantly euhedral disseminated pyrite (<0.5mm) and minor amounts of small (1 to mm) detrital pyrite. Quartzite lenses are absent in the Main Reef Leader.

Composite Reef at Far East Vertical Shaft

The Composite Reef mapped at Far East Vertical (FEV) Shaft consists of five distinct, discontinuous lithological units (Units 2 to 6, Figure 4). An angular unconformity (1° to 2°) exists between the conglomerates and the green footwall quartzite (Unit 1, Figure 4). This contact undulates due to the local occurrence of depressions (channels) and palaeohighs. The lowermost Composite Reef Unit, Unit 2, is a discontinuous, matrix-supported (50% matrix), large pebble conglomerate (20 to 30mm clasts) that is restricted to palaeolow or channel areas. Quartzite lenses are common in Unit 2 and comprise highly siliceous, trough cross-bedded quartzite. Unit 3 is a matrix-supported (30% matrix), medium pebble conglomerate (15 to 25mm clasts) that is more continuous than Unit 2, only pinching out on palaeohigh areas (Figure 4). Locally, Unit 3 may degenerate to a pebbly quartzite (>70% quartzite). In these areas, the quartzite is a medium-grained, siliceous quartzite that displays trough cross-bedding. D. Rolfe (ERPM, personal communication, 2000) reported herringbone cross-bedding associated with this quartzite. Unit 4 quartzite has a gradational contact with the underlying Unit 3 conglomerate, but a sharp contact with the overlying Unit 6 conglomerate. Unit 5 siltstones are restricted to palaeohigh areas (Figure 4) and lie directly on top of the green footwall quartzite (Unit 1), forming a sharp contact, on which shearing is evident and is occasionally

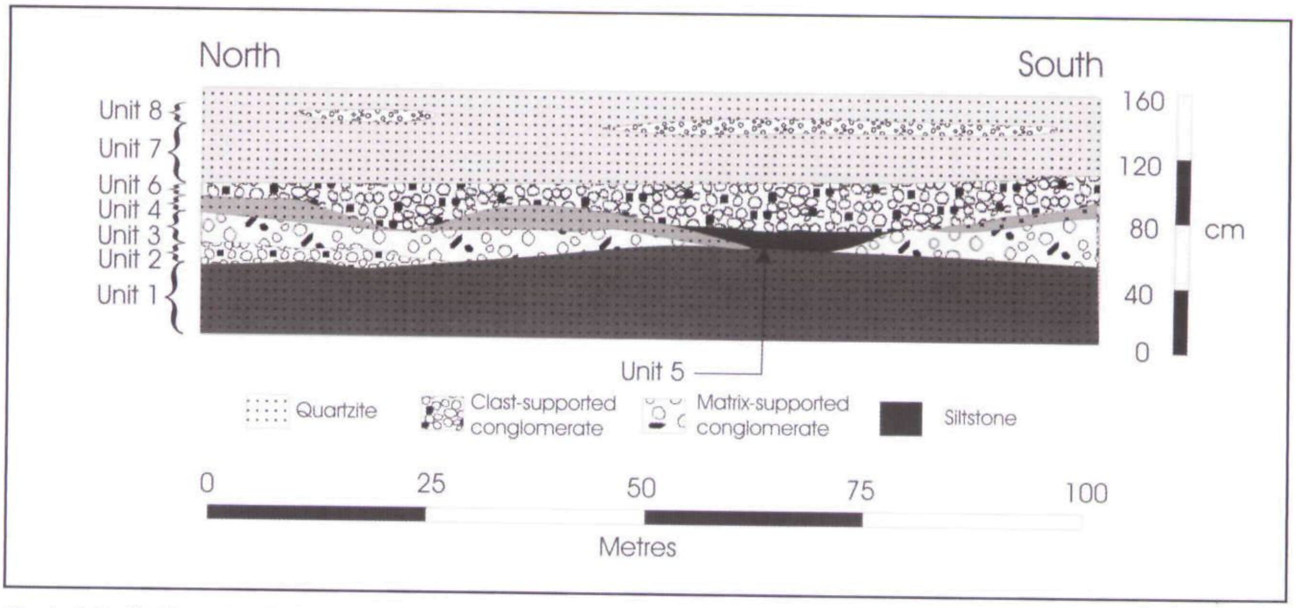

Figure 4 Profile illustrating the 8 units mapped at ERPM, Far East Vertical Shaft (Level 70, Panel 4 East), where Unit 1 represents the footwall quartzite, Units 2 to 6 the Composite Reef, Unit 7 the hangingwall quartzite, and Unit 8 the South Reef.

associated with quartz veining. Although the upper Unit 6 conglomerate pinches and swells to form minor channelised areas, it is continuous across the study area. This conglomerate is a clast-supported (<15% matrix), small pebble conglomerate (10 to 13mm clasts). The hangingwall quartzite to the Composite Reef (Unit 7) is light grey and devoid of any sedimentary structures. The small conglomerate band comprising Unit 8 is discontinuous (Figure 4) and typically consists of small clasts (<5mm), including blue opalescent quartz clasts, and is matrix-supported (50 to 60% matrix). Although no channelisation is evident in Unit 8, it only occurs in areas where the lower Unit 2 is formed (*i.e.* above palaeolow areas). The relationship between the Unit 8 conglomerate and the Composite Reef is discussed in further detail in the following sections.

Composite Reef Depositional History

Subsequent to Jones' (1936) interpretation that the Composite Reef represents a coalescence of the Main Reef, Main Reef Leader and South Reef, various authors (*e.g.* Hiller and Mason, 1982; Cousins, 1965; Wethmar, 1957) argued that the conglomerates below the South Reef (Main Reef and Main Reef Leader) were truncated by the unconformity at the base of the South Reef.

The stratigraphic units observed in the Composite Reef at Far East Vertical Shaft can be correlated with the Main Reef, Main Reef hangingwall quartzite, Black Bar and Main Reef Leader at Hercules shaft. Units 2 and 3 are matrix-supported, polymictic pebble assemblages, containing up to 15% chert clasts and discontinuous quartzite lenses, similar to the Main Reef at Hercules Shaft. The Unit 4 quartzite middling and the hangingwall quartzite of the Main Reef are similar in character, namely representing a fine-grained, siliceous, trough and planar cross-bedded quartzite. The Unit 5 siltstone is stratigraphically equivalent and lithologically similar to the Black Bar. The overlying Unit 6 conglomerate has similar characteristics to the Main Reef Leader in that it is generally a clast-supported, single and continuous conglomerate band that is oligomictic with rare occurrences of scattered chert clasts. Furthermore, both the upper conglomerate of the Composite Reef and the Main Reef Leader at Hercules Shaft are associated with higher gold grades relative to the lower conglomerate and the Main Reef (D. Rolfe, personal communication, 2000). The high proportion (15%) of blue opalescent quartz clasts in the hangingwall conglomerate band is characteristic of the South Reef (Pretorius, 1964; Reinecke, 1927).

The above interpretation of the Composite Reef stratigraphy differs from previous interpretations (*e.g.* Jones, 1936; Cousins, 1965; Hiller and Mason, 1982) in that the Composite Reef observed at FEV Shaft consists of a coalescence of the Main Reef and Main Reef Leader, with the South Reef occurring as a discontinuous grit band in the hangingwall quartzite. In accordance with this interpretation, a proposed depositional environment for the Composite Reef observed at FEV Shaft has been established. Figure 5 outlines four stages of deposition of the Composite Reef that are separated by 3 major unconformity-bounded surfaces. Within the Composite Reef, three upward-fining sequences are identified. The first upward-fining sequence includes the deposition of the Main Reef, quartzite middling and Black Bar (Units 2, 3, 4 and 5), the second includes the Main Reef Leader and the Main Reef Leader hangingwall quartzite (Units 6 and 7), and the third, the South Reef (Unit 8) and South Reef hangingwall quartzite.

A palaeosurface of low relief existed prior to the deposition of the Composite Reef. Stage 1 includes folding or warping of this surface (caused by left-lateral wrenching according to Camden-Smith and Stear, 1986), resulting in the formation of palaeolows and

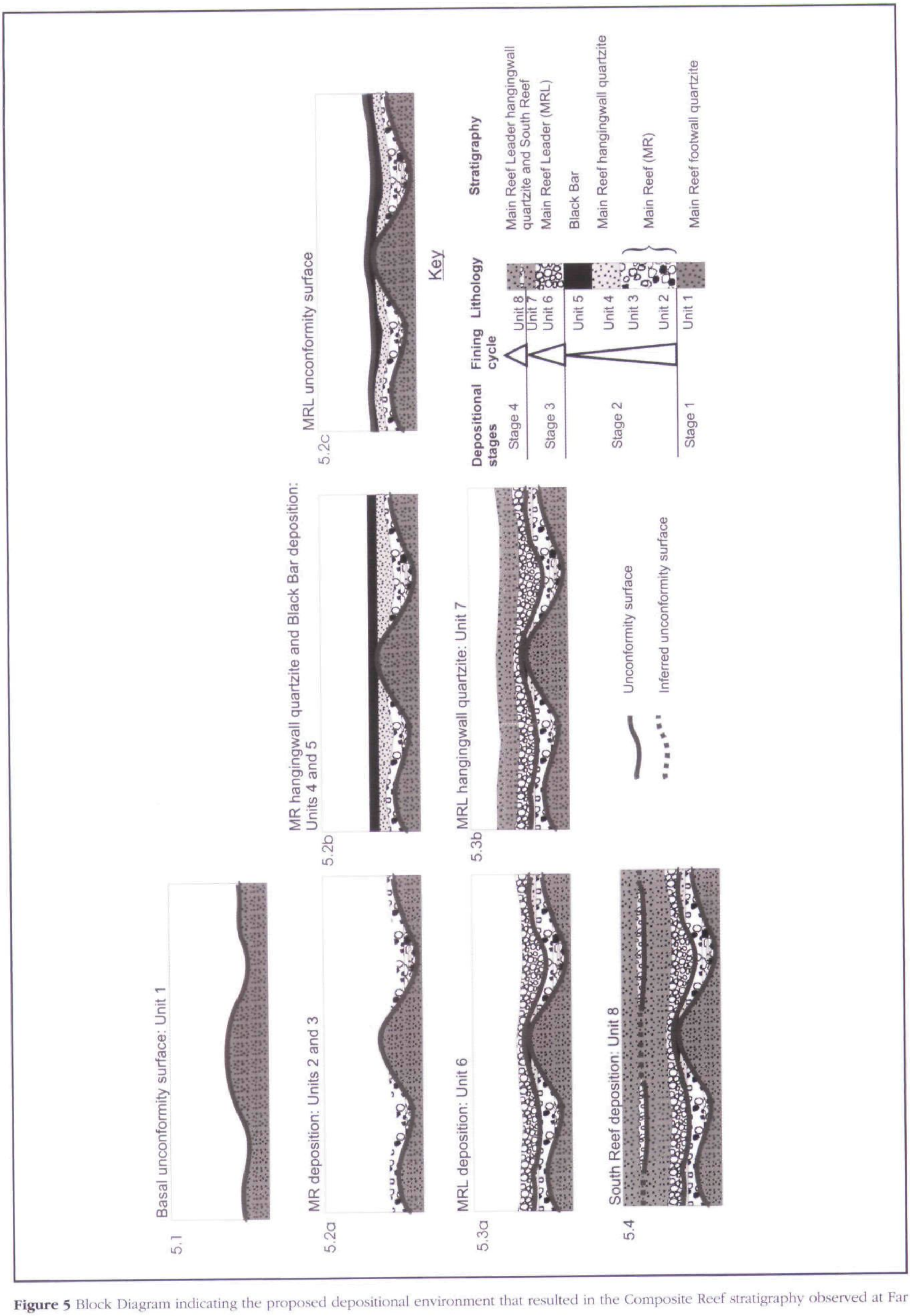

Figure 5 Block Diagram indicating the proposed depositional environment that resulted in the Composite Reef stratigraphy observed at Far East Vertical Shaft, ERPM.

palaeohighs on which the Composite Reef was deposited (Figure 5.1). Stage 2 includes the deposition of the Main Reef, Main Reef hangingwall quartzite and Black Bar (Units 2 to 5). This stage is initiated with the lower Main Reef conglomerate (Unit 2), which is a poorly sorted, large pebble conglomerate deposited in a fluvial environment. Deposition was restricted to palaeolow or down-warped areas (Figure 5.2a). The upper portion of the Main Reef (Unit 3) is a well-sorted conglomerate, indicating a degree of winnowing associated with a lower flow energy regime. The presence of trough- and herringbone cross-bedding in quartzites associated with Unit 3 indicates an interactive fluvial and marine setting. The remainder of Stage 2 deposition is associated with a waning flow deposit and the continuation of the marine transgression, during which the Main Reef hangingwall quartzite (Unit 4) and the Black Bar (Unit 5) were deposited (Figure 5.2b). The deposition of the hangingwall quartzite was fairly pervasive except for the palaeohigh areas, where the Black Bar was deposited unconformably on the footwall quartzite palaeohighs. Tectonism continued throughout Stage 2 deposition, and the Main Reef Leader palaeosurface, thus, resembled the Main Reef palaeosurface, although less accentuated (Figure 5.2c) due to deposition in palaeolow areas.

Stage 3 is the deposition of the Main Reef Leader conglomerate. The basal unconformity of the Main Reef Leader (Unit 6) indicates an increase in flow energy and a return to a fluvial environment. The deposition of the Main Reef Leader resulted in erosion of the Black Bar (Unit 5) and the Main Reef hangingwall quartzite (Unit 4), eroding these units in the down-warped areas (Figure 5.3a). The Black Bar was only preserved on palaeohighs that were not subject to extensive erosion (*i.e.* lower flow energy regimes, Figure 5.3a). Stage 3 culminated with a marine transgression, associated with the deposition of the Main Reef Leader hangingwall quartzite (Unit 7, Figure 5.3b).

Stage 4 signifies the deposition of the South Reef (Unit 8), associated with a marine regression and an increase in flow energy. In contrast to the Main Reef and the Main Reef Leader deposition, the South Reef was formed by predominantly aggradational deposition, resulting in a discontinuous small pebble conglomerate. Tectonic activity prevailed during the deposition of the South Reef, with the majority of the conglomeratic areas being confined to palaeolows (Figure 5.4). Similar to Stages 2 and 3, Stage 4 represents an upward-fining sequence with the South Reef grading into a quartzite.

Central Rand Goldfield

Sedimentological Modelling

An underground grade sampling data base (supplied by Durban Roodepoort Deep Limited) has been used to identify variations in large-scale sedimentary features of the Main Reef and Main Reef Leader. The Main Reef data encompasses individual sampling points from both development and stope sampling, and includes channel thickness measurements between Durban Roodepoort Deep (DRD) and City Deep Mines (Figure 1). The Main Reef Leader data comprises only development sampling data and has been regularised to 25m x 25m blocks. Main Reef Leader data includes channel thicknesses and percentage conglomerate information from an area between Consolidated Main Reef and Simmer and Jack Mine (Figure 1). For sedimentological modelling purposes, three lateral facies are defined, which correspond to three depositional regimes (Figure 6).

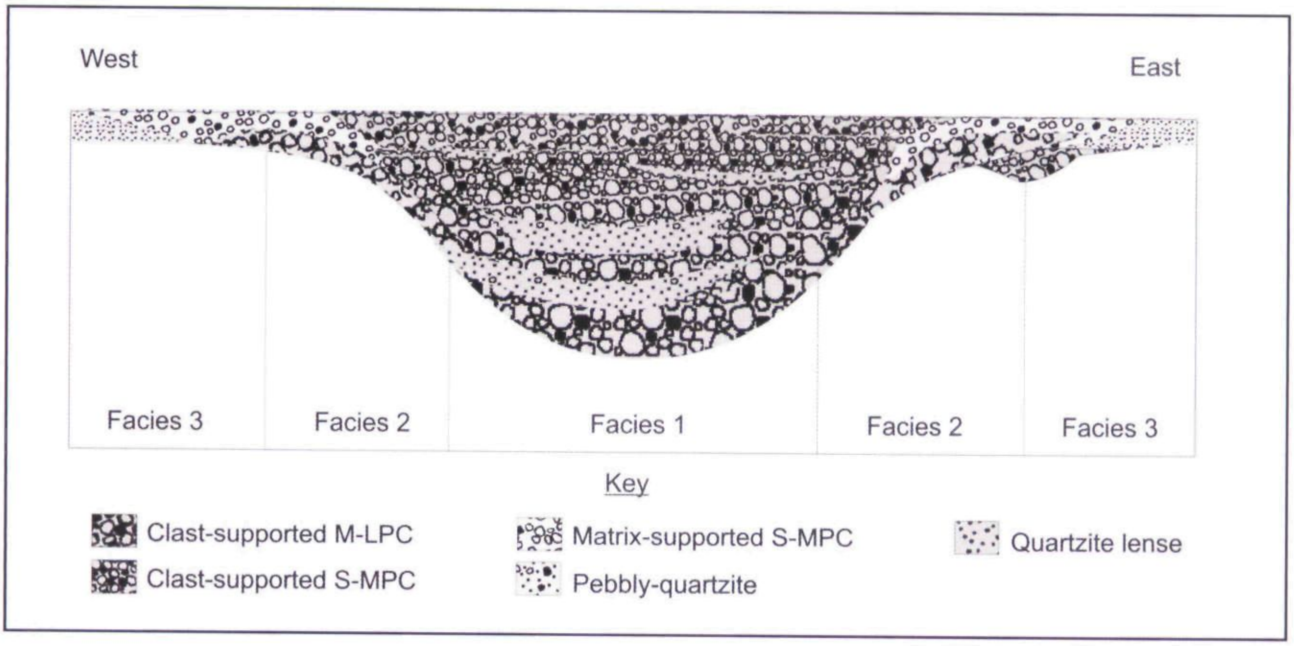

Figure 6 Schematic illustration of a "channel complex" indicating the distribution of different facies defined in this study and the rock types that comprise each facies (SPC - Small pebble conglomerate, MPC - Medium pebble conglomerate and LPC - Large pebble conglomerate).

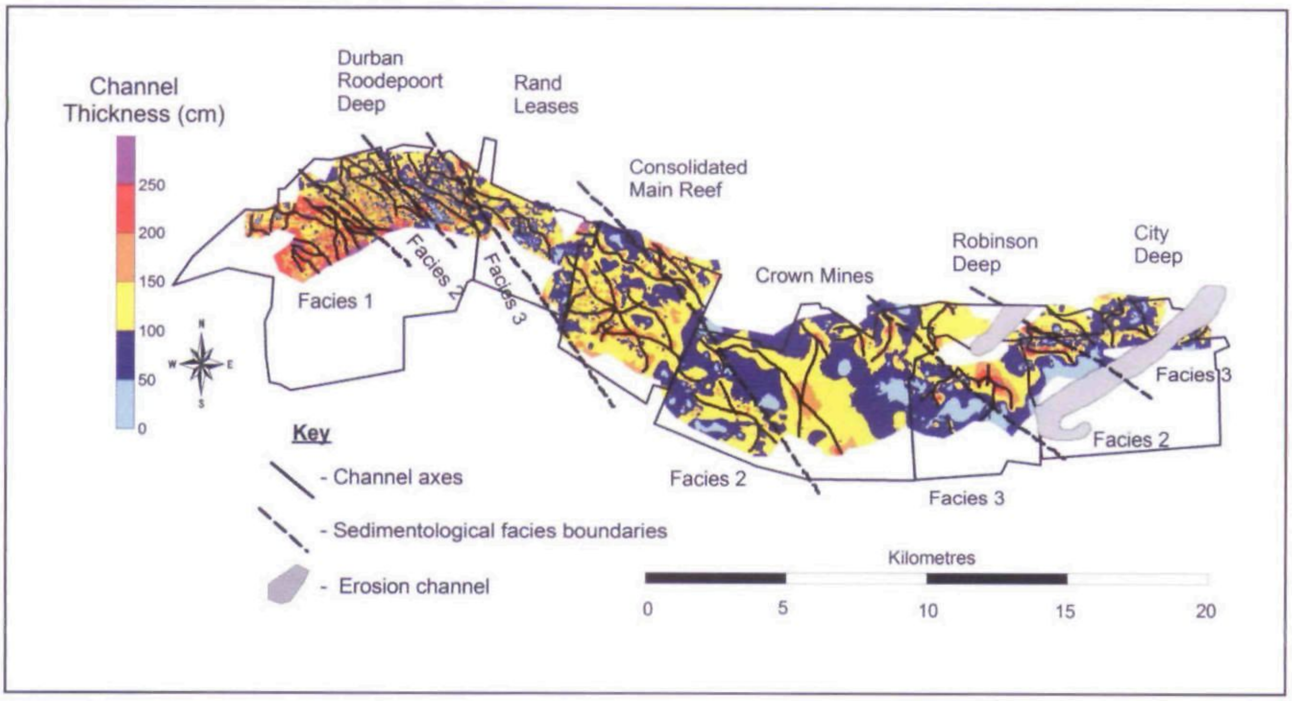

Figure 7 Isopach plan of the Main Reef conglomerate. Indicated on the isopach plan are the sedimentological facies and the channel axes as defined in the text.

Facies 1 represents the main channel complex, Facies 2 the channel flanks, and Facies 3 the overbank area. Main Reef and Main Reef Leader data were contoured to produce isopach plans, which were used to identify channel axes (defined by a line that passes through the centre of a localised area of thick conglomerate) and classify the orebodies into regional sedimentological facies (Facies 1 to 3; Figure 6).

Main Reef Sedimentology

From the isopach plans (Figure 7), Facies 1 to 3 (Figure 6) were classified according to the following scheme:

Facies 1: Average channel thickness > 150cm

Facies 2: Average channel thickness between 100 and 150cm

Facies 3: Average channel thickness < 100cm

The largest channel complex (Facies 1) of the Main Reef is situated in the DRD Mine area (Figure 7), where channel widths of up to 9m occur (W. Stear, Venmyn Rand, personal communication, 2003). The Main Reef rapidly thins to the east of DRD and then thickens gradually in the Rand Leases and Consolidated Main Reef (CMR) mine areas (Figure 7). The remainder of the goldfield consists of Facies 2 and 3 areas, with slightly thicker Main Reef developed in the Robinson Deep and City Deep area. The dominant channel orientation is northwest to southeast, conforming to palaeoflow directions measured by several authors (*e.g.* Reinecke, 1927; Wethmar, 1957; Stear 1986). In addition to the regional northwest/southeast palaeoflow direction, less prominent cross-cutting channels also occur, particularly in the eastern parts of the study area, oriented approximately north-northeast/south-southwest and east/west. These cross-cutting channels were also observed by Wethmar (1957), who noted northeast/southwest trending channels, and by Pretorius (1974), who noted east/west oriented channels.

Erosion channels (Figure 7) oriented northeast/southwest erode the Main Reef. One such channel was observed in a surface exploration borehole (KRB 4) to the south of City Deep Mine (Figure 1). The channel is stratigraphically situated beneath the Main Reef Leader and filled with Black Bar material. It is approximately 23m deep and consists of a 7m thick basal conglomerate overlain by a homogeneous, siliceous quartzite that grades upwards into a fine-grained, argillaceous quartzite. The basal conglomerate is clast-supported, polymictic and devoid of any macroscopic sulphide mineralisation.

Main Reef Leader Sedimentology

Similar to the Main Reef, isopach plans for the Main Reef Leader have been used to classify facies and to identify channel axes. The Main Reef Leader is characterised by thinner channel thicknesses relative to the Main Reef, and the facies classification is, thus, based on reduced thickness intervals:

Facies 1: Average channel thickness > 60cm

Facies 2: Average channel thickness between 30 to 60cm

Facies 3: Average channel thickness < 30cm

The isopach plan for the Main Reef Leader (Figure 8) illustrates that a channel complex (Facies 1) is situated in the Robinson Deep Mine area. Similar to the Main Reef, the regional palaeoflow direction is in a northwest/southeast orientation with cross-cutting channels oriented in northeast/southwest and east/west directions. A comparison between the channel axes and

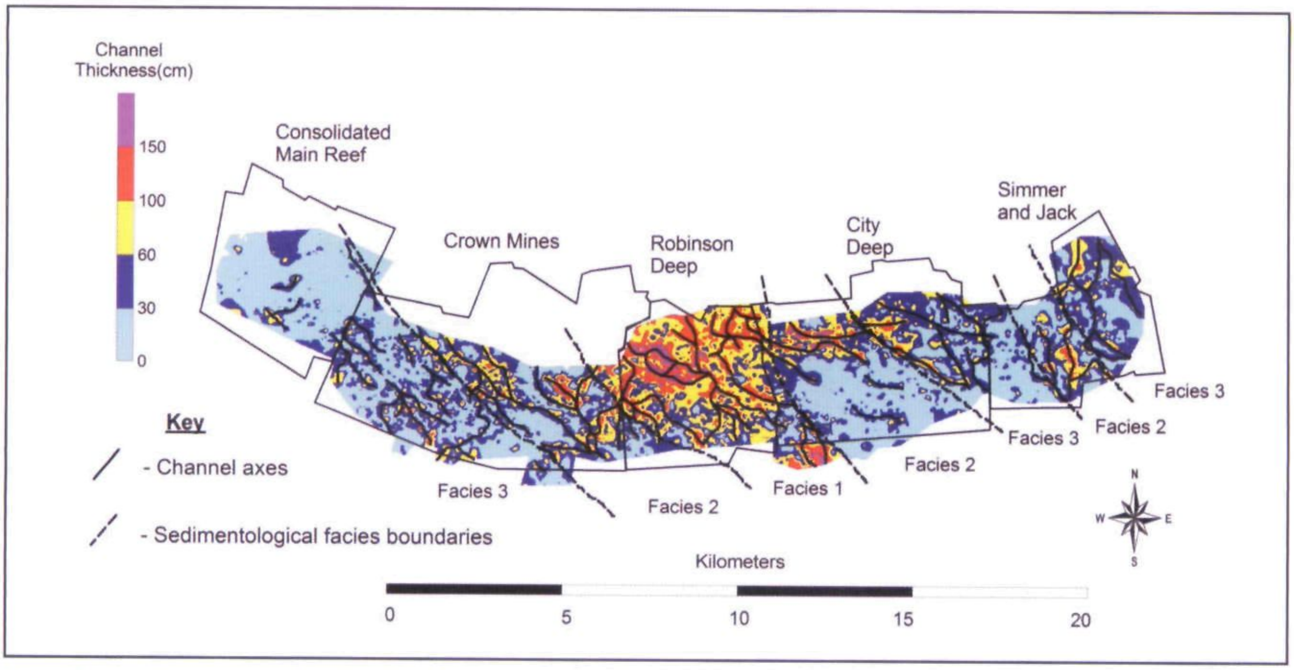

Figure 8 Isopach plan of the Main Reef Leader conglomerate. Indicated on the isopach plan are the sedimentological facies and channel axes as defined in the text.

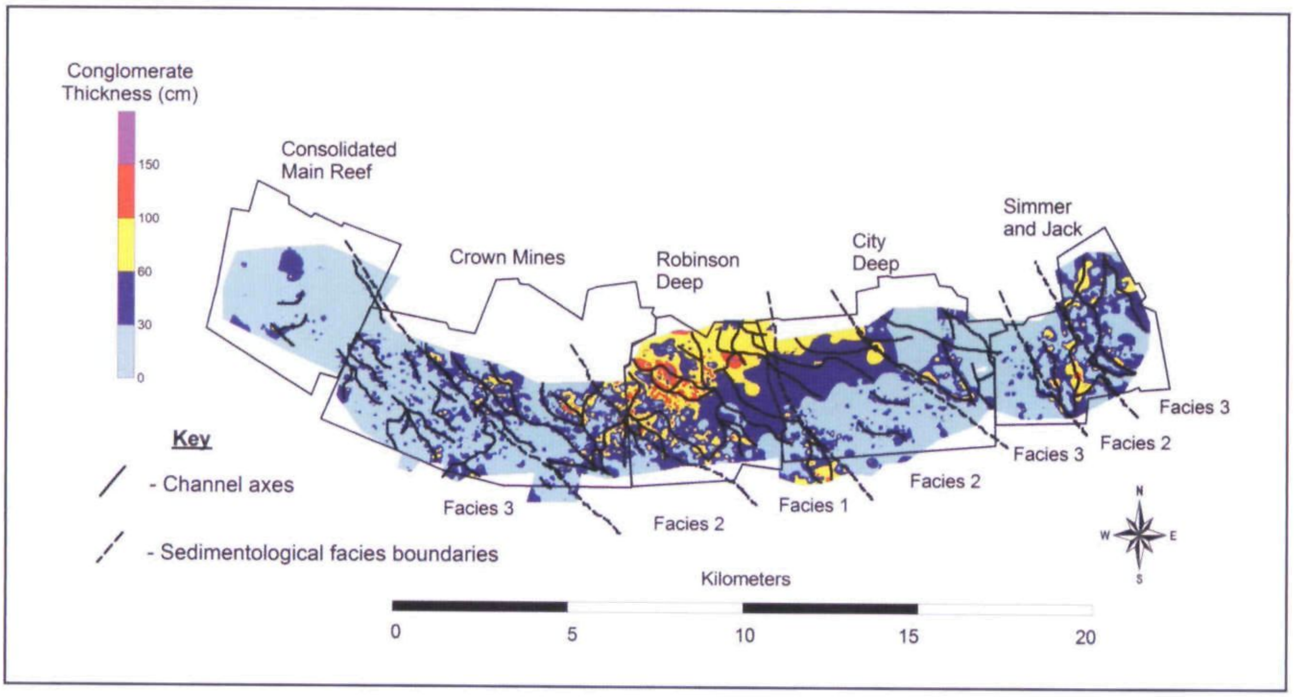

Figure 9 Distribution of the total conglomerate thickness of the Main Reef Leader (i.e. excluding internal quartzite). Also indicated on the plan are the sedimentological facies and the channel axes, as defined in Figure 8.

the total conglomerate thickness (i.e. excluding internal quartzite) confirms the position of the channel axes (Figure 9).

Structural Modelling

Pre- and syn-depositional structures are considered. Syn-depositional fold axes were identified by Weder (1994) based on the Main Bird Isopach (base of the Main Bird series defined from the top of the Jeppestown Subgroup to the top of the Booysens Shale Formation, Figure 3) determined by a 2D seismic investigation (Weder, 1983). The isopach plan (Figure 10) was also considered by Reading and Reynolds (1993), who noted that the upper portion of the Booysens Shale represents a transitional contact over 100m – therefore not representing a high density reflector. In addition, the isopach interpretation does not consider intrusives and structural gains (duplication) and losses that are observed in surface exploration boreholes. Based on the logging of boreholes, Reading and Reynolds (1993) estimated new isopach thicknesses (Table 1) that excluded intrusives and considered structural gains and losses (Figure 10).

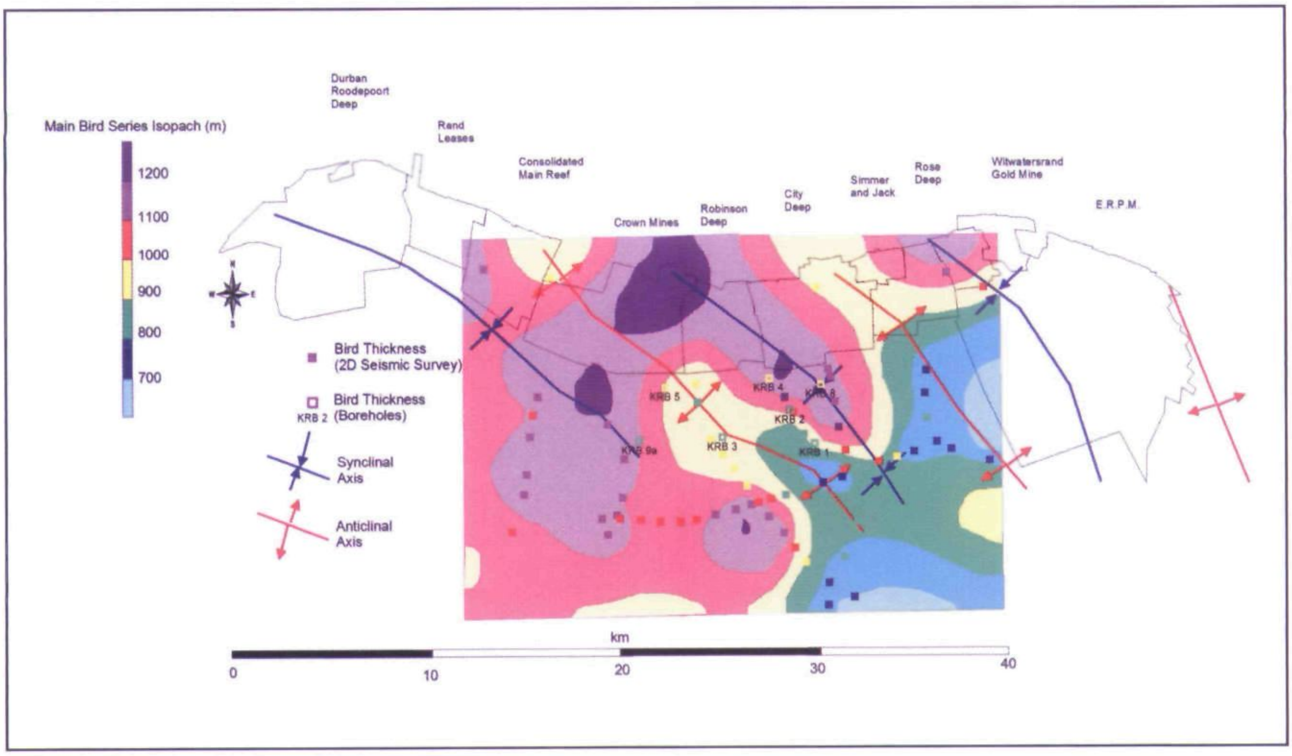

Figure 10 Syn-depositional fold axes identified by Weder (1994). Coloured filled squares indicate the Bird Series thicknesses as measured along seismic lines and used by Weder (1994) to contour the Bird Series isopach. Unfilled coloured squares represent the Bird Series thickness as measured from borehole core by Reading and Reynolds (1993).

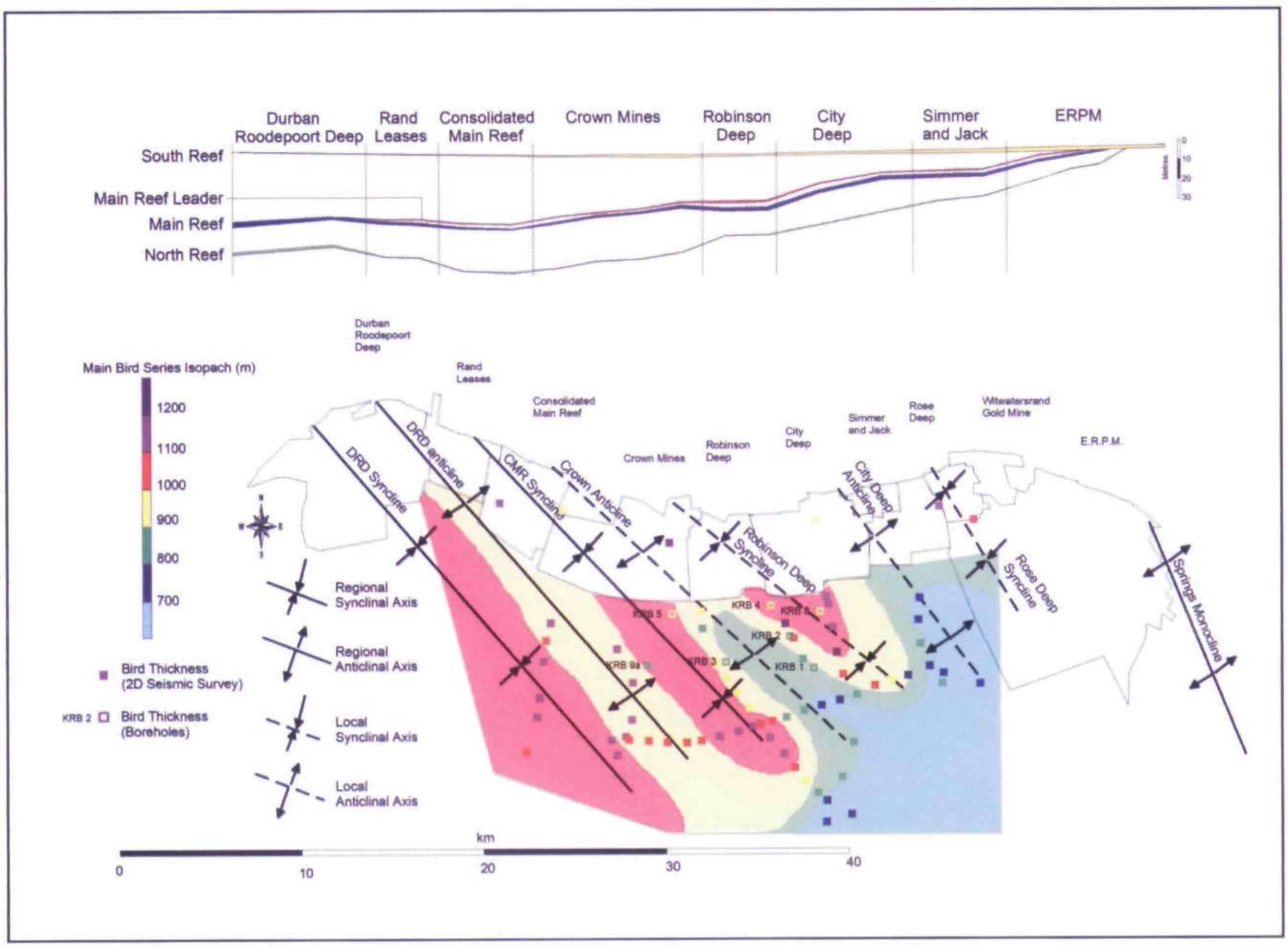

Figure 11 Regional and local folding as determined using contoured Bird Series thickness data and a cross-section through the Central Rand (Wethmar, 1957).

Table 1. Estimated isopachs of Main Bird Series (after Reading and Reynolds, 1993).

Borehole	Estimate of Isopach (excluding intrusives and including faulting, i.e. duplication and loss zones)	Original estimate
KRB 1	865	995
KRB 2	847	885
KRB 3	833	875
KRB 4	942	1080
KRB 5	954	980
KRB 8	950	1275
KRB 9	850	796

The true thickness estimates from Reading and Reynolds (1993), combined with the relative thicknesses as defined by the seismic study and a cross-section constructed by Wethmar (1957) (Figure 11), are used to re-evaluate pre- and syn-depositional fold axes.

The Bird Series thicknesses determined from the seismic data have been re-contoured, emphasising the northwest to southeast palaeoflow direction (Figure 11). This contouring illustrates an overall decrease in Bird isopach thicknesses towards the east, conforming to the proposal by Myers *et al.* (1990) that the Springs monocline (Figure 11) was an active structure during Witwatersrand deposition. A comparison between Wethmar's (1957) cross-section and the Bird Series isopach reveals that the thick Bird Series south of Crown Mines (CMR Syncline) corresponds to the thickest parting between the North and the South Reefs. The thinner Bird Series south of Rand Leases and CMR (DRD Anticline) corresponds to a thinning in the parting between the North Reef and South Reef and the area where the Main Reef Leader pinches out against the Main Reef. The thicker Bird Series south of Robinson and City Deep Mines (Robinson Deep Syncline) correlates with a thickening of strata only of the Main Reef and Main Reef Leader (and associated parting), but not between the North Reef and the South Reef (Figure 11).

Based on these correlations, the fold axes as defined by Weder (1994) are re-interpreted. Two types of folding are recognized, namely, regional and local folding (Figure 11). Regional folding is associated with larger amplitudes and is persistent throughout the Main Bird series, thus impacting on palaeotopography, and hence strata thickness, of the entire series. Local folding is associated with lower amplitudes and only impacts on the palaeotopography of one or two stratigraphic horizons (*e.g.* Main Reef and Main Reef Leader only), thus having less of an impact on the total Bird Series isopach.

A fault and dyke distribution plan of the Central Rand Goldfield is illustrated in Figure 12. The two most prominent dyke directions are northeast/southwest and north-northeast/south-southwest, whilst the major faults strike northwest/southeast and east-northeast/west-southwest. A plot of the fault and dyke orientations (where dip orientations could be determined from plans) indicates that six different fault and dyke groups can be recognised (Figure 13). These groups have similar orientations to those identified by Grohmann (1988) (Table 2), who proposed that they could be correlated with structures associated with left-lateral wrenching (Figure 14). A comparison between the orientation of the dyke and fault groups recognised and those identified by Grohmann (1988) is indicated in Table 2, and then compared to theoretical orientations (Figure 14) of structural features associated with left-lateral wrenching. The fault and dyke groups recognised generally correlate well with the structures associated with a left-lateral wrench system, where wrenching was oriented at approximately 110°.

This study has investigated brittle deformation phases by comparing faults and dykes to channels and channel orientations. Where channels coincided with faults and dykes, these orientations were measured and plotted on a rose diagram (Figure 15). Channels can be correlated with structural discontinuities that are generally oriented north-northeast/south-southwest, northeast/southwest, east/west and northwest/southeast, coinciding with the Riedel conjugate shears, normal faulting, Riedel shears and principal shear orientations, respectively. Furthermore, these orientations conform to the general northeast/southwest,

Table 2. Classification and orientations of identified fault and dyke groups (Figure 13) and a comparison between the measured fault and dyke group orientations with those observed by Grohmann (1988) and to the theoretical orientations of a left-lateral wrench system where wrenching is oriented at 110°.

Fault and dyke groups (Figure 13)	Fault and dyke group classification	Orientation of faults and dykes in this study	Orientation of faults and dykes measured by Grohmann (1988)	Theoretical orientation (east/west wrenching)	Theoretical orientation (wrenching oriented at 110°)
1	Riedel conjugate shears	031°/88° northeast	030°	010°	030°
2	Normal Faulting	053°/85° northwest	055°-070°	040°	060°
3	Riedel shears	081°/80° south-southeast	084°	064°	084°
4	Principal shears	103°/87° southwest	112°	090°	110°
5	P shears	136°/86° southwest	132°	110°	130°
6	Thrust faults	154°/86° northeast	145°	120°	140°

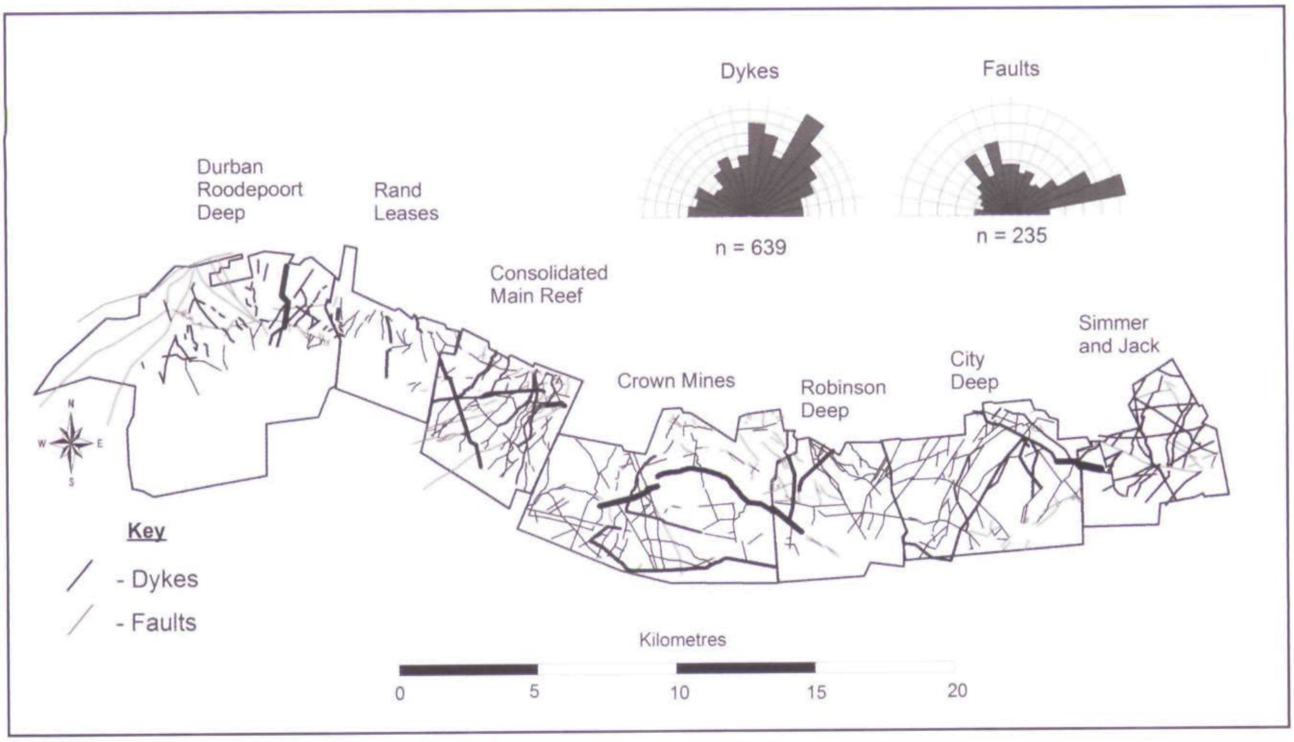

Figure 12 Fault and dyke distribution in the Central Rand Goldfield. Rose diagrams indicate directional trends (n = number of data).

cross-cutting channels first observed by Wethmar (1957) and the east/west cross-cutting channels observed by Pretorius (1974). It is, thus, proposed that brittle deformation in the form of the above-mentioned shears and faults was initiated during, or prior to, Main Conglomerate Formation times, impacting on channel development and forming discontinuity pathways for Ventersdorp dyke emplacement.

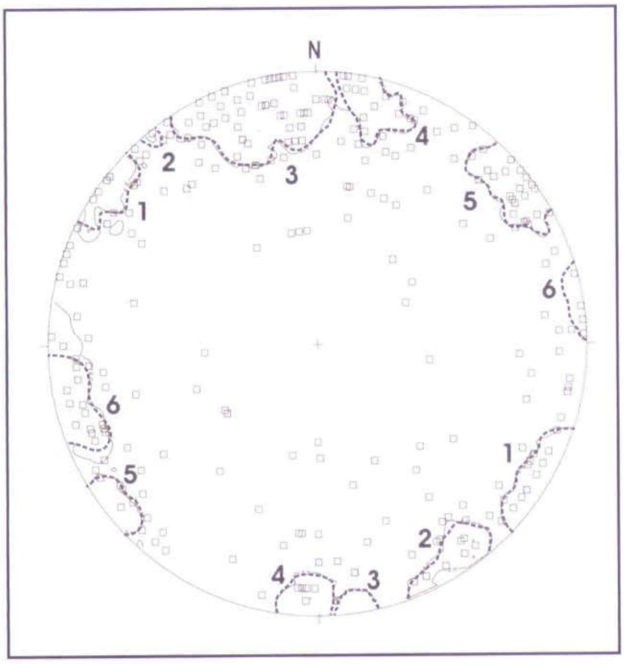

Figure 13 Stereonet plot of the faults and dykes in the Central Rand Goldfield. Based on 2% density contours, six fault and dyke groups are recognised (Schmidt projection, lower hemisphere).

Tectonosedimentary Model for the Central Rand Goldfield

Structural Model

Throughout Central Rand Group times, the Rietfontein and West Rand faults (Myers *et al.*, 1990) controlled sediment distribution in the West, Central, and East Rand areas (Figure 16). During this period, the Witwatersrand Basin was under northeast/southwest compression (Myers *et al.*, 1990). The Rietfontein Fault underwent oblique reverse movement, associated with left-lateral strike-slip (Charlesworth and McCarthy, 1990). Also in response to this compression, the West Rand Block overrode the Central Rand Block. This resulted in the Central Rand Block being down-tilted in the area of the West Rand Syncline (Figure 16), which is associated with significant thickening of the Central Rand Group (Myers *et al.*, 1990). The East Rand Block (Figure 16) rose relative to the Central Rand Block along the Springs Monocline (Myers et al., 1990).

In the study area, the northwest/southeast oriented Springs Monocline and DRD Anticline (Figure 11), define the limits of Main Reef Leader deposition. Both of these anticlines are associated with thinning of the North and South Reef packages (Figure 11). Similarly, the DRD Syncline had a pronounced influence on deposit characteristics. The Main Reef is significantly thicker along this synclinal axis. It is, thus, deduced that the West Rand and DRD synclines (Figures 11 and 16) are the same feature.

Left-lateral wrenching, associated with the Rietfontein Fault, resulted in northwest/southeast oriented fold axes. This folding accentuated the regional fold axes (Figure 11) that were formed in response to basin compression (Myers *et al.*, 1990), and also resulted

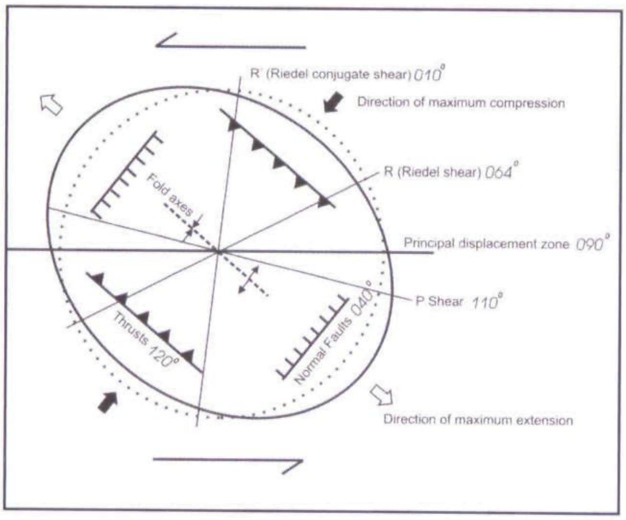

Figure 14 Strain ellipse indicating the structures associated with left-lateral wrenching (modified after Wilcox *et al.*, 1973). Also indicated are the theoretical orientations of these structures where wrenching is oriented east/west.

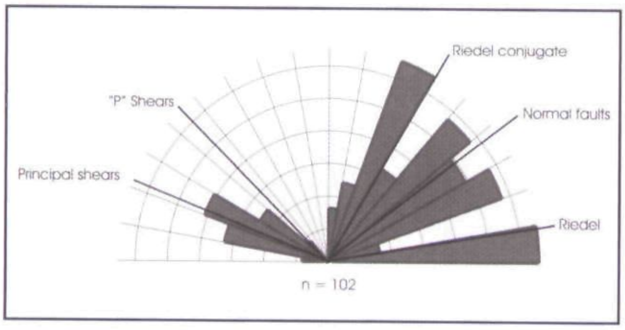

Figure 15 Rose diagram indicating the orientations of channels that are influenced by dykes and faults throughout the Goldfield. These orientations coincide with the Riedel shears, Riedel conjugate shears, principal shears and normal faulting orientations (Table 2) (n = number of samples).

in the development of local folds (Figure 11). Local folds only impact on stratigraphic thickness of one or two horizons (*e.g.* the Robinson Deep Syncline that only affects the Main Reef Leader and – to a lesser extent, the Main Reef conglomerate thicknesses). It is, therefore, deduced that the regional synclinal and anticlinal axes formed in response to basin-wide tectonic activity and were accentuated by left-lateral displacement associated with the Rietfontein Fault. The local fold axes were superimposed upon the regional folds in direct response to left-lateral wrenching associated with the Rietfontein Fault.

The timing of the brittle deformation in the Central Rand Goldfield has been debated. Camden-Smith and Stear (1986) proposed that brittle deformation was probably initiated during Turffontein Subgroup times, and Grohmann (1988) suggested that brittle deformation began during Witwatersrand deposition with the formation of east to west trending normal faults. Grohmann (1988) also proposed that brittle deformation associated with left-lateral wrenching in the form of Riedel, Riedel conjugate, principal and P-shears, as well as normal and thrust faulting, was only initiated during Ventersdorp times. Utilising a comparison between faults and dykes and channel orientations, this study has deduced that brittle deformation was initiated during Central Rand Group times in the form of Riedel shears, Riedel conjugate shears, principal shears and normal faults, associated with left-lateral wrenching. This finding conforms to that of McCarthy *et al.* (1990) and Jeffery (1975), who proposed that early Ventersdorp dykes utilised brittle discontinuity features.

The structural model proposed for the Central Rand Goldfield is, thus, a left-lateral wrench model, conforming to findings of previous investigators (*e.g.* Stanistreet *et al.*, 1986; Camden-Smith *et al.*, 1989; Pretorius, 1992; Stear, 1986; McCarthy *et al.*, 1990; Grohmann 1988), which resulted in local fold structures being superimposed on basin-wide folding and brittle deformation that impacted on depositional trends.

Depositional Model

The Main Reef and Main Reef Leader conglomerates can be classified as channelised reef horizons. Previous interpretations of Witwatersrand conglomerates emphasised braided river systems (*e.g.* Pretorius, 1974; Hiller and Mason, 1982) as the principal agents for sediment transportation, which is applicable to channelised deposits such as the Main Conglomerate Formation. During deposition, channels accommodated the majority of the river flow. This channelisation process resulted in a thick reef package, characterised by a relatively high percentage of internal quartzite and robust, clast-supported conglomerates. Upward-fining sequences are recognized within the reef package, with conglomerate at the base, carried as bedload during flooding times, capped by quartzites that were deposited during normal stream flow. Each upward-fining sequence is associated with an erosional surface at its base and represents a flooding event (degradational system), followed by normal stream flow (a gradational system).

On a regional scale, large channel complexes occur in tectonically down-warped areas (Facies 1, Figure 6) that are separated by thinner, less channelised conglomerate (Facies 2 and 3) associated with upwarped areas. Within the channel complexes, depositional "pulses" resulted in a complex pattern of depressed channels separated by sporadically elevated interchannel areas formed by gravel and sand bars. Facies 2 and 3 areas separating the channel complexes display sporadic channel development. In these facies, channels are less confined and accommodated less of the stream flow relative to the Facies 1 channels within the channel complex areas. These interchannel complex areas are more commonly associated with a sheet type, thinner reef package that would have only received sedimentation during maximum flooding and is generally devoid of any major channel development.

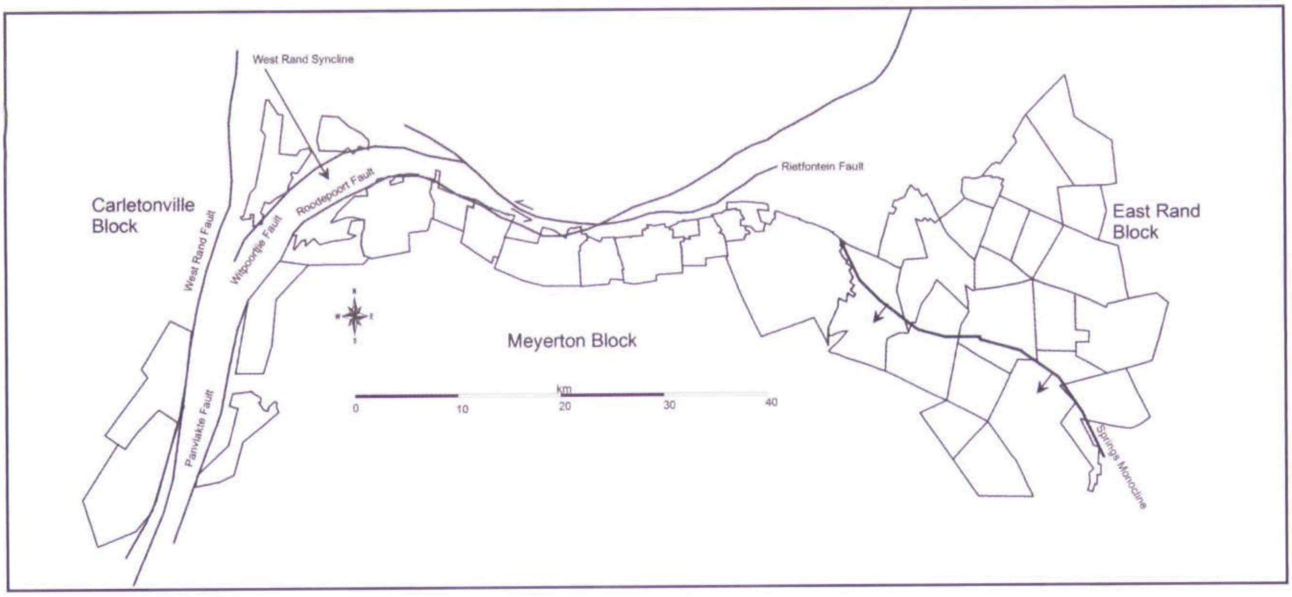

Figure 16 Regional structural setting of the East Rand, Central Rand and eastern portions of the West Rand (modified after Myers *et al.*, 1990).

Discussion

A localised model for the deposition of the Composite Reef observed at Far East Vertical Shaft, ERPM, can be broadly applied to the deposition of the Main Conglomerate Formation throughout the Central Rand Goldfield.

Prior to the deposition of the Main Reef, southerly oriented tilting, associated with uplift of the hinterland, created a broad palaeosurface and east/west oriented normal faults. A compressional environment resulted in the West Rand Block overriding the Central Rand Block along the West Rand Fault, causing down-warping of the Central Rand Block and the formation of the West Rand Syncline (Figure 16) bounded in the east by the DRD Anticline (Figure 11). Simultaneously, the Springs Monocline formed the eastern boundary of the Central Rand Block (Figure 16). Left-lateral wrenching resulted in warping along northwest/southeast trending axes and the formation of a corrugated landscape overprinted on the regional warping (Figure 17). Sedimentation of the Main Reef conglomerate in the form of elongated channel complex deposits occurred in down-warped areas (Figure 17), with a large channel complex occurring in the DRD area associated with the West Rand Syncline (Figure 17). Braided river systems resulted in local (100s of metres) deviations in channel direction from the pervasive southeast palaeoflow direction. During Main Reef deposition, brittle deformation in the form of Riedel conjugate shears, normal faulting, Riedel shears and principal shears, associated with left-lateral wrenching on the Rietfontein Fault, were established and influenced Main Reef channel orientations on scales from 100s of metres to 5km. This influence on channel orientation, however, was not strong enough to allow individual channels to cross-cut regional anticlines.

Immediately prior to the deposition of the Black Bar, large-scale erosion channels formed in the Central Rand Goldfield in the vicinity of City Deep and Village Main Reef mines (Figure 7). These channels are oriented in a northeast/southwest direction, perpendicular to the tectonic fold axis and parallel to the normal faults associated with left-lateral wrenching (Figure 15). The occurrence of the erosion channel in a surface exploration borehole (KRB 4, Figure 1), combined with evidence from the down-dip workings in City Deep Mine (Wethmar, 1957), indicates that the erosion channel changed direction by 90° to a southeasterly direction in the southern portion of City Deep Mine (Figure 7). It is proposed that the erosion channel was initiated on topographically elevated ground associated with the City Deep Anticline. The orientation of the erosion channel was controlled by northeast/southwest down-faulting. The channel continued into the topographically depressed Robinson Deep Syncline, where it changed to a southeasterly direction, parallel to this syncline.

Main Reef conglomerate deposition and erosion channel formation were terminated by the onset of a marine transgression. This transgression had a smoothing effect on the topography of the Central Rand Goldfield by depositing Black Bar material (now silt, shales and fine grained quartzites) into topographically lower lying areas (Figure 17). The palaeotopography prior to Main Reef Leader deposition was, thus, smoothed relative to Main Reef palaeotopography and consisted of a single down-warped area centred in the City Deep Syncline that was bounded by the DRD Anticline and Springs Monocline (Figure 17).

The Main Reef Leader was deposited in an elongated channel complex (Figures 8, 9 and 17), similar to the deposition of the Main Reef. The position of the channel complex indicates a shift in the depositional axis from the DRD Syncline during Main Reef deposition to the City Deep Syncline during Main Reef Leader deposition. The Main Reef Leader is typically a thinner reef package and associated with less internal quartzite, relative to the Main Reef, indicating a higher level of degradational

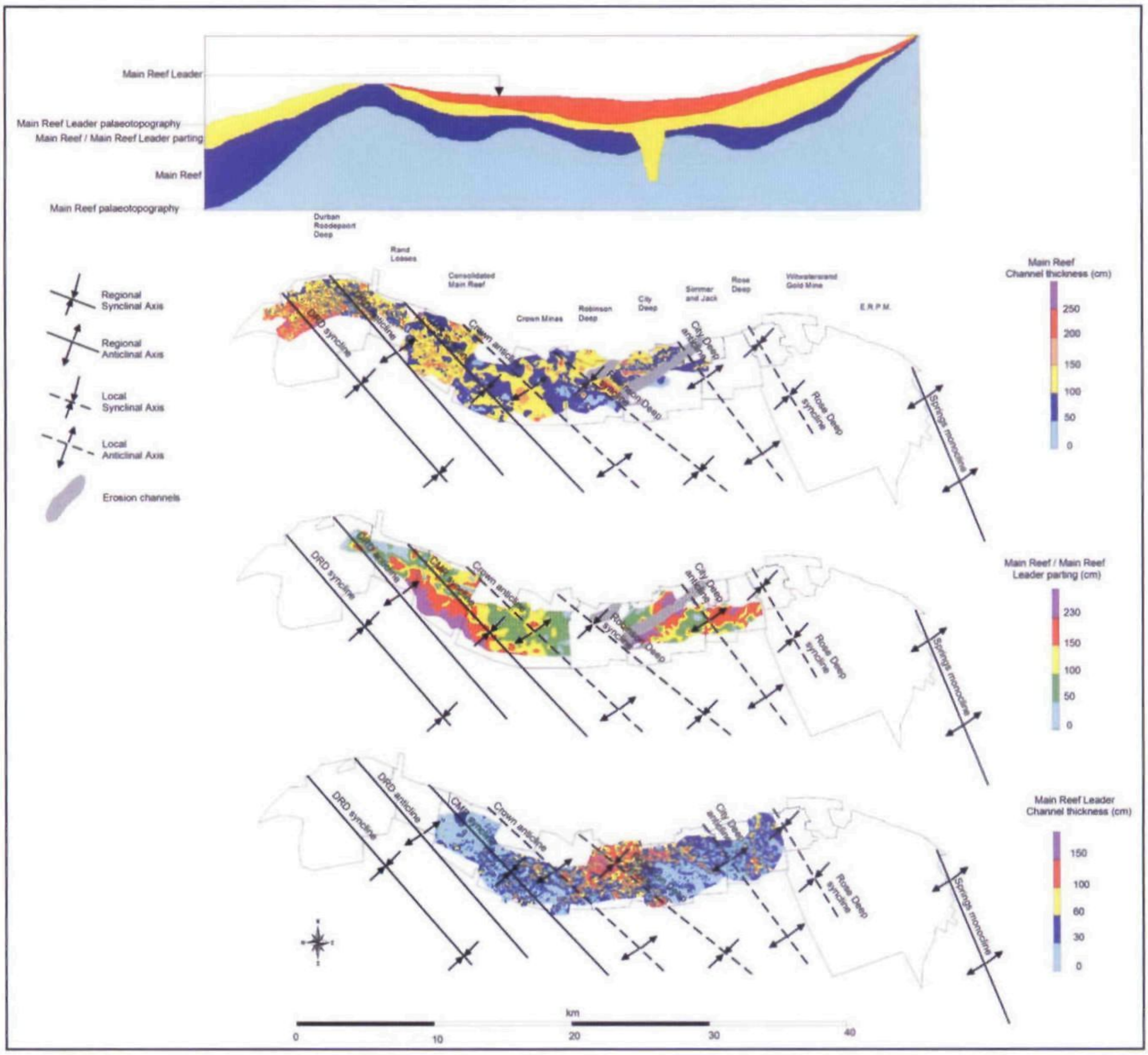

Figure 17 Schematic cross-section indicating the palaeotopographic variations prior to Main Reef deposition through the Main Reef Leader palaeotopography. The isopach plans of the Main Reef, Main Reef/Main Reef Leader parting (after Wethmar, 1957) and Main Reef Leader illustrate that thickest reef packages occur in topographically low areas, illustrating the timing of these fold structures.

activity, possibly associated with more intensive and prolonged flooding periods. During Main Reef Leader deposition, brittle deformation associated with left-lateral wrenching continued and influenced Main Reef Leader channel orientations resulting in northeast/southwest and east/west cross-cutting channels.

Conclusions

This investigation of the Central Rand Goldfield has illustrated that sedimentation and structural features are not mutually exclusive and that structural controls influenced the observed sedimentation patterns. A tectonosedimentary model is proposed for the Composite Reef at Far East Vertical Shaft, ERPM. Contrary to Jones' (1936) proposal and Hiller and Mason's (1982) interpretation, our model suggests that the Composite Reef at Far East Vertical Shaft consists of the Main Reef and Main Reef Leader, and the South Reef sporadically occurs in the hangingwall. The model recognizes underlying tectonic controls that persisted throughout the deposition of the Composite Reef, controlling the distribution of the numerous conglomerate units. Utilising the tectonosedimentary model for the Composite Reef, combined with structural and sedimentological modelling of the Main Reef and Main Reef Leader throughout the Central Rand Goldfield, a tectonosedimentary model is proposed for the Central Rand Goldfield as a whole.

The hypothesis by Camden-Smith and Stear (1986) that a left-lateral wrench model is applicable to the Central Rand Goldfield is confirmed in this study. However, pre- and syn-depositional folding was not only a function of left-lateral wrenching, but was also affected by regional compression during Central Rand Group deposition. The regional compression resulted in the formation of the Springs Monocline, the West Rand

Syncline and associated DRD Anticline. This was overprinted by northwest/southeast oriented folding associated with left-lateral wrenching on the Rietfontein Fault, resulting in a corrugated palaeosurface prior to Main Reef deposition that controlled the palaeoflow direction. The most significant depositional area of the Main Reef was associated with the West Rand or DRD Syncline, with alternating thinner and thicker reef development throughout the rest of the goldfield.

Brittle deformation was initiated during Witwatersrand times in the form of Riedel and Riedel conjugate shears, normal faults, principal shears and P-shears associated with left-lateral wrenching. This study proposes that it is these brittle deformation features that caused the northeast/southwest and east/west cross-cutting channel orientations observed by previous investigators, and the northeast/southwest oriented erosion channels. A marine transgression followed Main Reef deposition and the associated Black Bar material accumulated in topographically lower lying areas. This smoothed the pre-Main Reef Leader palaeotopography. This smoothing effect, combined with syn-depositional folding, resulted in a single Main Reef Leader channel complex associated with the Robinson Deep Syncline and restricted Main Reef Leader deposition within an area bounded by the Springs Monocline in the east and the DRD Anticline in the west.

Acknowledgements

Durban Roodepoort Deep and, in particular, Mr. Danie van den Berg are thanked for providing the sampling databases and structural maps, and Mr. Thys Heyns for facilitating and allowing access to the surface exploration borehole core. Thanks to Mr. Dave Rolfe for his support and input with regards to the organisation of the underground visits at ERPM. Dr Willo Stear is thanked for his valuable input. The DEEPMINE collaborative research programme and CSIR Miningtek are thanked for sponsoring this work, which forms part of RS' Ph D project. Hartwig Frimmel and Hielke Jelsma are thanked for their valuable reviews. This is the University of the Witswatersrand Import Cratering Research Group Contribution No. 83.

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Editorial handling: J.M. Barton