Mafic dikes displacing Witwatersrand gold reefs: Evidence against metamorphic-hydrothermal ore formation

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ABSTRACT

The process responsible for the gold mineralization in the Witwatersrand Basin, South Africa, remains controversial; the debate is between a detrital placer enrichment in laterally extensive conglomerate layers, and hydrothermal introduction by metamorphic fluids long after sedimentation. While textural and geochronological data may be ambiguous, a first-order geological observation severely delimits the mechanism and timing of gold emplacement. The individual gold reefs are cut and displaced by numerous mafic dikes, which, based on geochemical data presented here, are feeders to flood basalts immediately overlying the Witwatersrand. The displacements preclude fracture-controlled fluid focusing over tens of kilometers along a single conglomerate horizon during or after regional metamorphism. Instead, basin-scale gold enrichment occurred during sedimentation or early diagenesis, well before local redistribution by metamorphic fluids.

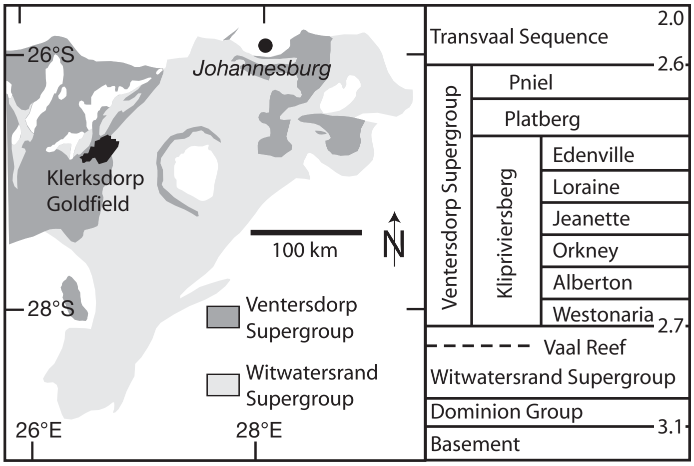

Figure 1. Location map (after Frimmel et al., 2005) and stratigraphic column with subdivisions based on Winter (1976). Numbers to the right are approximate ages in Ga.

INTRODUCTION

The Witwatersrand basin in South Africa is the world's largest gold province and best-preserved succession of Archean continental sediments. Despite a long mining history, the process of gold emplacement in these huge orebodies remains controversial, some favoring primarily placer enrichment followed by later small-scale metal redistribution and recrystallization, and others proposing introduction of gold by hydrothermal fluids.

The primary evidence for the modified paleoplacer model is the close correlation of gold grade with laterally extensive conglomerate beds, and higher enrichment in local paleochannels (Frimmel et al., 2005). Other evidence includes pebble-shaped pyrite grains (England et al., 2002) and clastic heavy minerals, including uraninite, occurring together with the gold (England et al., 2001; Vollbrecht et al., 2002). Similarities to modern wind-ablated land surfaces indicate that eolian processes may have contributed to concentrating the gold (Minter, 1999). Attempts to date the gold directly yielded a Re-Os isochron corresponding to ca. 3 Ga old, slightly older than the youngest detrital zircons in the same rocks (Kirk et al., 2001, 2002; Ruiz et al., 2006). Greenschist facies regional metamorphism overprinted the Witwatersrand sediments between 2.4 Ga and ca. 2.0 Ga ago, after deep burial by later volcanic and sedimentary rock (Fig. 1). Much of the gold in the Witwatersrand occurs as euhedral or interlocked grains in secondary textures among greenschist facies metamorphic minerals, showing that synmetamorphic to postmetamorphic hydrothermal activity modified the ore at least on a grain to hand-specimen scale (Frimmel et al., 2005; Meyer et al., 1994). Hydrothermal activity causing this remobilization may have occurred at 2.045 Ga ago (Rasmussen et al. 2007; U-Pb on monazite, xenotime).

For the hydrothermal model there are two end-member variants with regard to the timing of metal introduction. Large-scale fluid flow may have occurred shortly after sedimentation of the host rock, focused by primary permeability of the conglomerate beds (Safonov and Prokof'ev, 2006). The second, more commonly propagated metamorphic-hydrothermal model assumes the generation of secondary fracture permeability under metamorphic conditions, well after deposition and consolidation of the host sediments (Barnicoat et al., 1997; Hobbs et al., 2004; Jolley et al., 2004; Law and Phillips, 2005; Wall et al., 2004). Law and Phillips (2005) took a somewhat intermediary position, citing structural evidence for mineralization prior to the major Transvaal overburden, but emphasizing textural observations in support of hydrothermal gold introduction during peak metamorphism. Fluid focusing along the thin reefs is explained by clast-to-clast contacts in the conglomerates, leading to cracks through the pebbles that form a continuous permeability through the conglomerates, to allow stratigraphically focused gold introduction by basin-wide fluid flow during regional metamorphism. This model is supported by large-scale pyrophyllite alteration, textural observations, and chemical modeling (Barnicoat et al., 1997; Hobbs et al., 2004; Jolley et al., 2004; Law and Phillips, 2005; Wall et al., 2004). High-grade gold is commonly associated with thin hydrocarbon seams, which follow the stratigraphic reef horizons over kilometers (carbon leaders) but locally crosscut sedimentary structures on the outcrop to thin-section scale (Gray et al., 1998; England et al., 2001). The latter observation is taken to support the interpretation of the reefs being large bedding-controlled cracks, in which the carbon possibly acted as an agent for chemical gold precipitation (e.g., Barnicoat et al., 1997).

In this paper, we discuss the important observation, documented by extensive mine development maps, that the orebodies are in reality not flat sheets extending over kilometers, but rather are disrupted into numerous fragments that are commonly bounded by dikes (Fig. 2). McCarthy et al. (1990) used the orientation of these dikes to determine the paleostress field in the East Rand, but did not address the significance of this observation for ore genesis. Harris and Watkins (1990) showed that the dikes are metamorphosed and likely to be of Venterdorp age (ca. 2.7 Ga), but their attempt to quantify synmetamorphic fluid flow from oxygen isotopes remained ambiguous. We show the structural significance of these displacements for ore genesis, and support the premetamorphic timing of the dikes with new geochemical data confirming that they are feeders to flood basalts immediately overlying the Witwatersrand Basin.

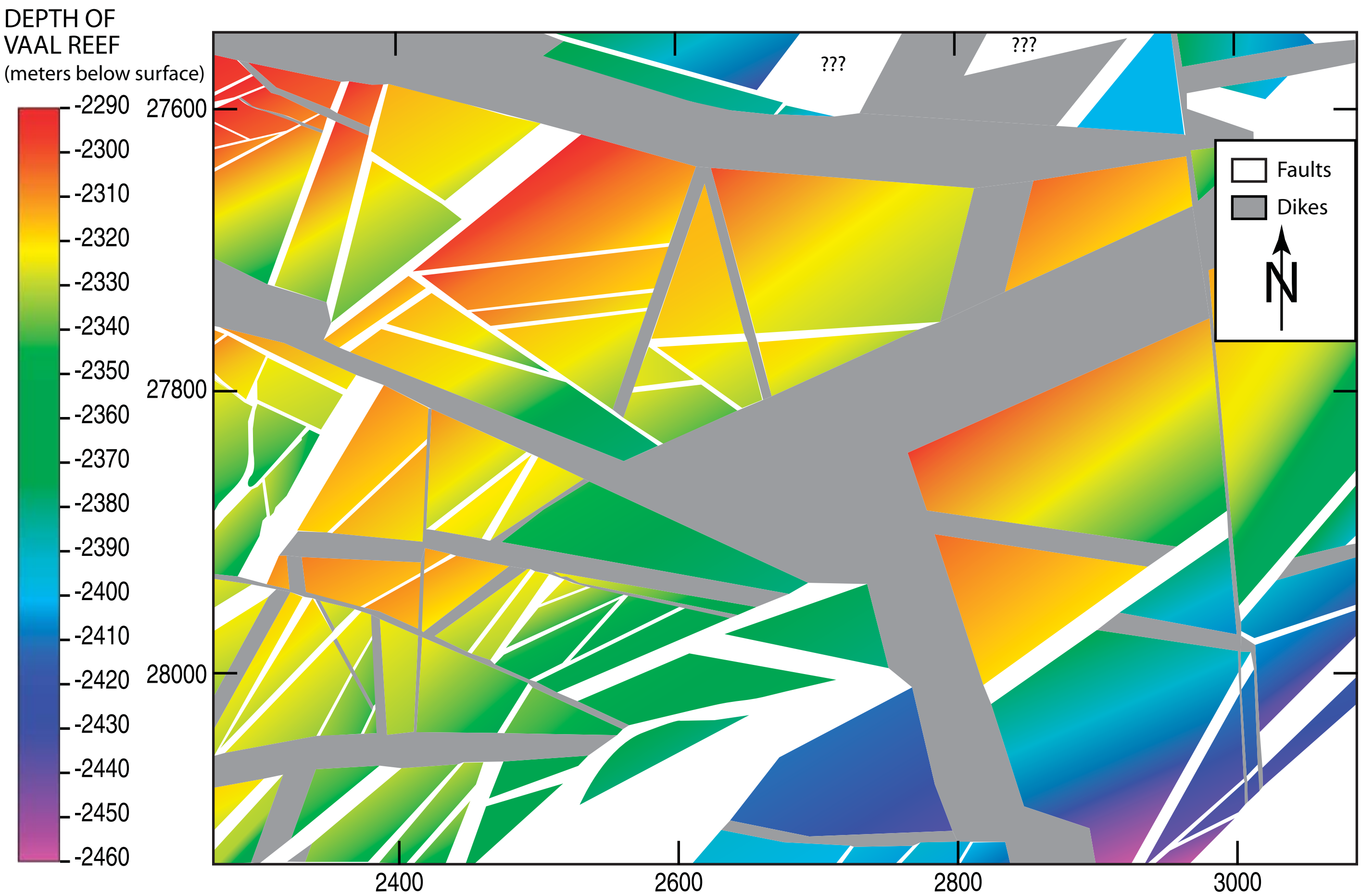

Figure 2. Horizontal map of small part of Kopanang mine, emphasizing depth variations of Vaal Reef below surface by variable colors. Breaks in color gradients show that originally planar reef horizon is cut into numerous blocks that are rotated and vertically displaced by as much as 100 m. Many of the extensional faults are filled by mafic dikes (shown in gray).

GEOLOGICAL OBSERVATIONS

The sedimentary rocks of the Witwatersrand Supergroup reach a maximum thickness of ~5 km, and are unconformably overlain by a suite of flood basalts (Klipriviersberg Group; Fig. 1), which cover in excess of 30,000 km^2 (Myers et al., 1990). The Klipriviersberg Group has been dated as 2714 ± 8 Ma old using SHRIMP (sensitive high-resolution ion microprobe) U/Pb on zircons (Armstrong et al., 1991). Together with the following Platberg and Pniel Groups, they form the Ventersdorp Supergroup, consisting mainly of volcanics with smaller amounts of sediments and exceeding a thickness of 3700 m. Including the overlying Transvaal Supergroup, a total overburden of ~10 km covered the Witwatersrand rocks prior to the emplacement of the Bushveld igneous complex ca. 2 Ga ago. The conglomerates have reached regional greenschist facies metamorphic conditions with peak temperatures of 300–350 °C at pressures of ~3 kbar, rising to amphibolite facies grade in the vicinity of the Bushveld intrusion along the northeast edge of the basin (Frimmel et al., 2005).

Vaal Reef is the main orebody mined in the Kopanang mine of the Klerksdorp goldfield (Fig. 1). Continuous, stratigraphically controlled mineralization is developed over a lateral dimension in excess of 7 km × 12 km, with an average dip of ~14°SSE. The economic horizon consists of a single bed of coarse-grained quartzite or clast-supported conglomerate, which is typically <20 cm thick and may occur as a single line of pebbles. Much of the gold is concentrated in a thin (2 mm to a few centimeters) carbonaceous layer that intermittently follows this well-defined stratigraphic horizon on the mine scale, but locally transgresses through the conglomerate, indicating that the carbonaceous material was mobile. The Vaal Reef is crosscut by numerous dikes of fine-grained dolerite occupying ~5% of the mine area. Dikes and faults displace the reef into thousands of blocks, which measure between tens to a few hundred meters along the bedding plane (Fig. 2). They are mapped in great detail for mine development, and several types and generations of dikes are distinguished in the Kopanang mine. Displacements along dikes are commonly a few meters to several tens of meters; dike thickness is typically between 1 and 10 m. Well-exposed contacts show that magma emplacement occurred during or after displacement of the reef fragments, as dike contacts are commonly unsheared and knife sharp, with chilled margins still visible despite subsequent alteration and metamorphic recrystallization. Other faults are not intruded by any magma, but map patterns such as those shown in Figure 2 demonstrate that many of these small faults predate dike emplacement, in contrast to a smaller number of later reverse and normal faults outside the map area. The mineralogy of the dikes is typical for variably altered greenschist facies mafic rocks, including quartz, albite, chlorite, white mica, pyrophyllite, and carbonates. Some samples are almost totally replaced by carbonates. At some intrusive contacts, sigmoidal veins containing fibrous quartz and chlorite are observed, documenting partly ductile deformation at metamorphic conditions and confirming a premetamorphic emplacement of the dikes. In some veins, minor sulfides (pyrite, galena, sphalerite) were precipitated. Despite clear evidence for synmetamorphic fluid activity, the metamorphosed and locally altered dikes are barren of economic gold grade and show no conspicuous structural or mineralogical difference at sites where they cross the high-grade Vaal Reef. The reef usually shows no difference in gold tenor in the vicinity of dike intersections.

GEOCHEMICAL DATA

To further test the interpretation that the reef-displacing dikes predate metamorphism and related fluid-rock interaction, we compared the chemical compositions of a suite of dike samples with those of extrusive flood basalts in the overlying Klipriviersberg Group (Fig. 1). Published geochemical data of the lavas show little lateral variation in the volcanic stratigraphy, but characteristic compositional differences among successive units (Winter, 1976; Myers et al., 1990). For comparison with our dike analyses, the most complete published data pertaining to samples located closest to the Klerksdorp South area are used (Bowen et al., 1986; Marsh et al., 1992; Myers et al., 1990; see the GSA Data Repository[1]). For this study, 11 samples from different types of dikes with different degrees of alteration were collected. Veins and other visible alteration features were removed during sample preparation. Bulk rock analysis was performed by X-ray fluorescence (XRF) for major and some trace elements, and by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) for trace elements, including rare earth elements (REEs), on XRF tetraborate tablets.

Comparison of immobile elements (Si, Ti, Al, Fe, Mn, Mg, P, Nb, Y, Ni, Cr, V, Sc, Hf, Ta, Th; e.g., Figs. 3A–3D) and REEs (Fig. 4) shows that all dikes are on a single fractionation trend overlapping the geochemically indistinguishable Jeanette, Loraine, or Edenville units of the Klipriviersberg Group (Myers et al., 1990; Fig. 1). Zr is used as a fluid-immobile fractionation indicator, resulting in either positive (Figs. 3A, and 3B) or negative (Fig. 3C) correlation or Zr-independent scatter (Fig. 3D). Younger magmatic rocks in the Witwatersrand basin (not plotted) show distinct geochemical differences from Klipriviersberg dikes and lavas, e.g., higher Zr in the Platberg Group (Bowen et al., 1986). Younger ilmenite diabase and epidiorite dikes (McCarthy et al., 1990) can be excluded based on their mineralogy and Ti, Al, Mg, Ni, Co, Cr, and V ratios. The Bushveld complex is >200 km away from the study area, and primitive Bushveld magmas differ from the analyzed dikes and Klipriviersberg lavas in element ratios among Ti, Al, Mn, P, Ni, Cr, and Zr (cf. Cawthorn, 2007). Textural distinctions between dike types mapped by mine geologists are not recognizable in their composition. Typically fluid-mobile elements, including Na, K, Ca, Rb, Sr, Zn, Cu, Co, Ba, and Pb (e.g., Figs. 3E and 3F), and variable loss on ignition (as much as 25 wt% in one sample) indicate significant hydration, carbonation, and hydrothermal alteration of the dikes during or after regional metamorphism, consistent with mineralogical observations (feldspar destruction) and local veining.

DISCUSSION AND CONCLUSION

Mine-scale mapping, subsurface outcrops, thin-section scale observations, and our reconnaissance study of bulk-rock geochemical characteristics indicate that numerous mafic dikes cutting the Vaal Reef in the Kopenang mine were emplaced into active or preexisting faults during the early stages of stratigraphic covering of the Witwatersrand Basin, as feeders to the overlying flood basalts of the Klipriviersberg Group. The dikes subsequently underwent the same postdepositional processes as the sedimentary rocks hosting the reefs, i.e., greenschist metamorphism and variable degrees of hydrothermal alteration.

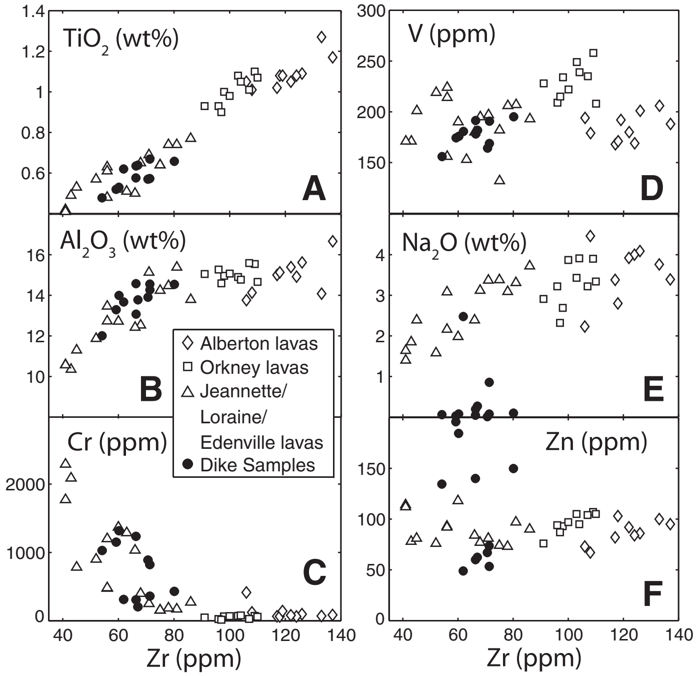

Figure 3. Comparison of dike and lava geochemistry for selected elements, plotted against Zr. Published analyses for Klipriviersberg lavas (Bowen et al., 1986; Marsh et al., 1992; Myers et al., 1990) are compared with dike samples analyzed in this study, demonstrating close overlap of all fluid-immobile elements, including Zr, TiO_2, Al_2O_3, Cr, and V, but random depletion or enrichment in highly soluble elements such as Na_2O and Zn.

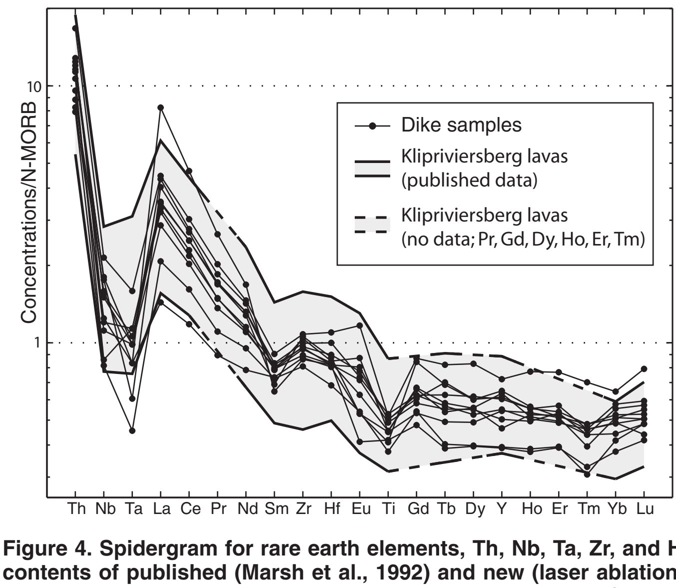

Figure 4. Spidergram for rare earth elements, Th, Nb, Ta, Zr, and Hf contents of published (Marsh et al., 1992) and new (laser ablation–inductively coupled plasma–mass spectrometry; this study) analyses, showing almost complete overlap of Klipriviersberg lavas and Kopanang dikes (normalized to normal mid-oceanic ridge basalt, N-MORB; Sun and McDonough, 1989).

This result may not seem geologically surprising, but it severely limits possible mechanisms that have been put forward to reconcile one of the first-order features of Witwatersrand gold reefs, i.e., their tight lithostratigraphic control bound to single, thin, and laterally continuous horizons, with supposed evidence for large-scale introduction of gold by synmeta-

[1]GSA Data Repository item 2009142, analyses of samples and geochemical data used for comparison, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

morphic to late metamorphic fluids. Generating the two-dimensional lateral continuity of Vaal Reef by large-scale hydrothermal gold introduction, over an area in excess of 7 × 12 km along a single stratigraphic horizon, needs a perfect mechanism of fluid focusing. Hydrothermal gold introduction would require that mineralizing fractures not only followed the clast-supported conglomerate horizon (which conceivably might have acted as a stress guide on the scale of one ore block; Barnicoat et al., 1997; Hobbs et al., 2004; Jolley et al., 2004; Wall et al., 2004), but had to jump across hundreds of dike and fault displacements without ever losing the reef horizon, and without ever missing a piece of favorable host rock. If such a process had happened during or after peak metamorphism, we would expect that the feeder dikes were selectively altered (and probably gold mineralized) and showed distinct fluid passageways (veins or breccias) at intersections linking the numerous reef segments. This is not the case. We therefore conclude that Vaal Reef formed prior to the magmatism of the Klipriviersberg Group (2714 ± 8 Ma ago; Armstrong et al., 1991), well before Platberg Group magmatism (Law and Phillips, 2005) and the deposition of the thick cover of the Transvaal Supergroup that gave rise to the regional metamorphism. Bushveld-like ages of xenotime and monazite obtained by Rasmussen et al. (2007), although recording a likely event of late metamorphic fluid flow, cannot represent the time of basin-scale emplacement of gold into the reefs. The dike displacements thus add a simple but strong argument to the conclusion that basin-scale gold enrichment occurred either during or shortly after Witwatersrand sedimentation.

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