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DEWATERING OF THE FAR WEST RAND DOLOMITIC AREA BY GOLD MINING ACTIVITIES AND SUBSEQUENT GROUND INSTABILITY

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ABSTRACT

In the 1960s, the Malmani dolomite landscape of the Transvaal Sequence on the Far West Rand experienced ground subsidence in the form of sudden catastrophic sinkhole formations and extensive development of dolines by gradual subsidence. The management of the gold mines had decided to dewater some of the dolomitic compartments to allow their workers to extract the gold-bearing ore of the underlying Witwatersrand Supergroup economically and safely.

Several of the gold mines on the Far West Rand have now reached the end of their life span and are due to be decommissioned. Dewatering will be discontinued. Some of the dykes that form the boundaries of the individual dolomitic compartments have been breached by mining activities so that flooding of one compartment will eventually impact on the other compartments. The eventual static level of the water-table in this new 'super-compartment', as well as the points of decant of the dolomitic water, are uncertain. Flooding of the 'super-compartment' will cause the original dolomitic eyes feeding the Wonderfontein Spruit to start flowing again, which will impact on groundwater quality and ground instability. Of particular concern is the occurrence of millions of tonnes of mine tailings within the catchment area.

The most important problem in the catchment area is that the sedimentary phase of the Wonderfontein Spruit and its impoundments is continually being enriched with heavy metals and radio nuclides originating at the mining works. These could be remobilized and released into the downstream water, causing deterioration of water quality for downstream users.

KEY WORDS: gold mining; dolomite; dewatering; sinkhole; doline; ground instability; land degradation; South Africa

INTRODUCTION

The Far West Rand, also known as the West Wits line among the mining fraternity, extends over an area of approximately 600 km^2 south west of Randfontein, South Africa (Figure 1).

Dolomite, and the associated karst development in this area, harbours rich water resources, which have been used by local people since time immemorial (Wolmarans, 1984). Valuable hominid remains from the 'Cradle of Humankind World Heritage Site' in Gauteng Province, South Africa, have been preserved as a result of the existence of these dolomites. These fossil remains assisted in piecing together the history of the evolution of mankind (Brink, 1979). De Kock (1964) described how these fossils were also found by the early settlers at the strong flowing, natural springs called the Bank and Oberholzer Eyes (Figure 2).

Gold was discovered by the Pullinger Brothers in the 1890s at Venterspost (Figure 2). In 1910, shortly after the Anglo-Boer War, they tried to sink a shaft on the Far West Rand to locate the 'lost' gold reef beneath the dolomite. They discontinued their efforts at a depth of only 29·5 m in 1912 due to the inflow of huge, unstoppable volumes of dolomitic groundwater into the shaft. It was the same phenomenon that was responsible for catastrophic ground

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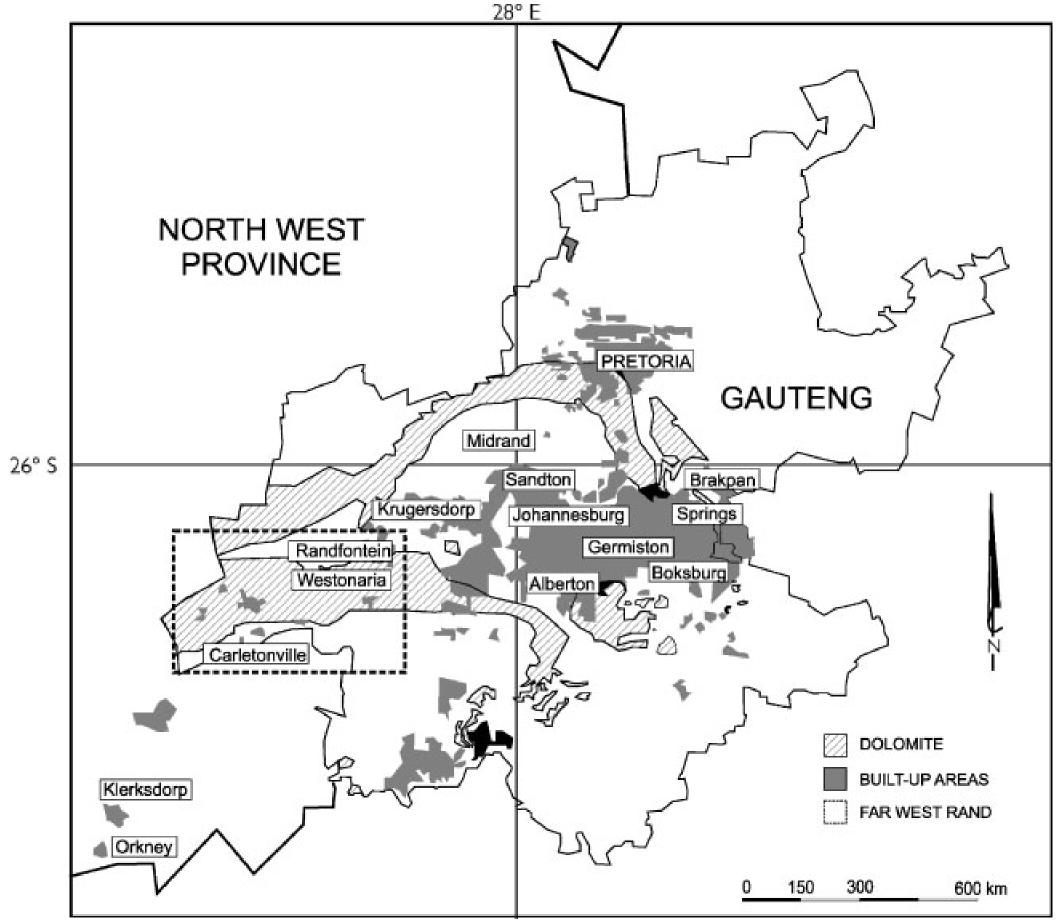

Figure 1. Location of dolomite on the Far West Rand. Adapted from Council for Geoscience (2003).

subsidence in the area some 40 years later, when gold-mine managers dewatered some of the overlying dolomitic compartments of the Malmani Subgroup (Table I) of the Transvaal Sequence (Truter, 1963), in order to work the gold-bearing ore of the Witwatersrand Supergroup economically and safely (Wolmarans, 1984). Not all the mine managers agreed that dewatering was the correct approach (E. J. Stoch, Personal communication, Welverdiend, South Africa, 15 September 2005).

Commercial gold mining started in 1934, after Dr Rudolph Krahman confirmed the existence of the West Wits Line (the Far West Rand) in 1930, by using his, then revolutionary, magnetometer to follow the magnetic layers from Johannesburg to this area. Currently 12 mines are actively extracting gold on the Far West Rand.

Dolomite in general and particularly the Transvaal dolomite has a notorious reputation for causing instability. Although dolomite-related instability may occur in any karstic terrain, most instability features in the Far West Rand in South Africa have been noted in the Malmani Subgroup (Table I). Since the mid-1950s, mining activities on the Far West Rand have resulted in extensive sinkhole formations as well as other subsidence landforms. Sensational media coverage of these incidences caused serious concern among the local communities and negatively influenced potential investments by entrepreneurs (Wolmarans, 1984). During the past 55 years, some 38 people have lost their lives as a result of sudden sinkhole collapse, and the damage to buildings and other structures constructed on the dolomites has been more severe than on any other geological formation in South Africa (Brink, 1979). Not only did sudden catastrophic sinkholes appear, but dolines developed as a result of

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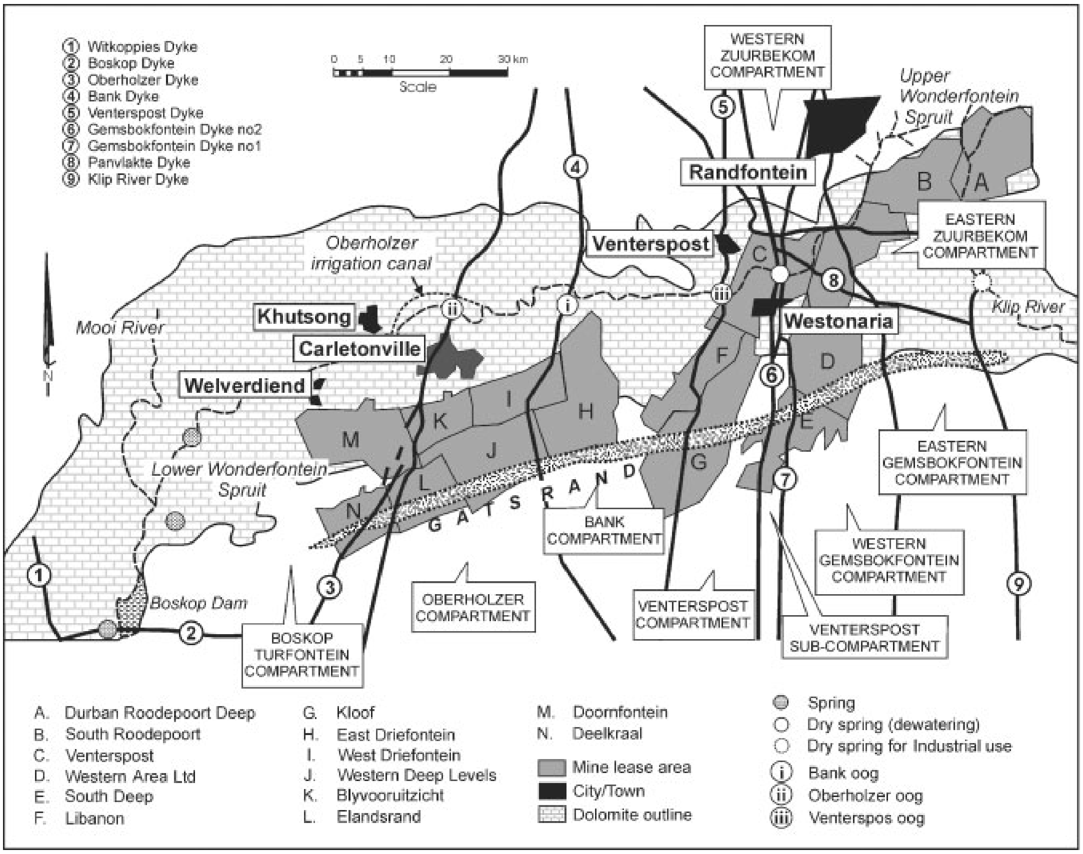

Figure 2. Dolomitic compartments of the Far West Rand. Adapted from Swart *et al*. (2003, p. 635), by kind permission of Springer Science and Business Media.

Table I. Lithostratigraphic nomenclature within the Transvaal Sequence as located in the Western Transvaal

Supergroup	Sequence	Group	Subgroup	Formation	Thickness
Witwatersrand	Transvaal	Pretoria			
		Chuniespoort		Penge	
			Malmani	Frisco	30 m
				Eccles	490 m
				Lyttleton	290 m
				Monte Christo	740 m
				Oaktree	330 m
				Black Reef Quartzite	
		Buffelsfontein			

Adapted from Eriksson (1971a p. 8).

gradual subsidence. The highly compressible ‘wad’ often associated with dolomite, also caused major problems for foundation structures. Wad is an insoluble and highly compressible material that develops during the weathering of dolomite. It consists of a mixture of manganese and iron oxides that contains minor impurities.

Based on an extensive study of the literature, the purpose of this article is to put the dewatering by gold mining activities and the resultant ground instability into historical perspective and to explore future possibilities of renewed ground instability and other forms of land degradation on the Far West Rand area. The article highlights

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lessons that should be learnt from the past and identifies areas of uncertainty regarding future instability and degradation of the area that require ongoing monitoring and further research.

This article deals first with the regional geology of the Far West Rand, followed by a discussion of the weathering and erosion of the Malmani dolomite. It then discusses the impact of mining on the ground water levels, ground instability associated with the dolomite landscape and some aspects of doline and sinkhole formation on the Far West Rand as recorded since the pre-mining phase. Finally, some comments are made on the way forward in terms of instability and degradation of the Far West Rand area.

GENERAL GEOLOGY OF THE AREA

Most of the gold-mining districts on the Far West Rand are underlain by ancient carbonate rocks. On the 1:250 000 and 1:50 000 Geological Map Series of South Africa prepared by the Geological Survey of South Africa (now known as the Council for Geoscience; CGS), the southern areas of Transvaal (Gauteng), which include the Far West Rand, show an arrangement of dolomitic rocks in the form of a half circle. This half circle reaches from the Natal Spruit through Westonaria and Carletonville to Orkney (see Figure 1).

Looking at the broad picture, this dolomitic outcrop represents the southern leg of the asymmetric Hartebeesfontein Anticline. The layers of the Transvaal Sequence dip at approximately 6 degrees at the southern leg of the anticline. In the Gauteng Province, the Malmani Subgroup is the carbonate formation of the Chuniespoort Group (see Table I) of the Transvaal Sequence ($\sim$2600–2400 Ma). The Chuniespoort Group is divided into seven formations. The Malmani Subgroup consists of the lower five dolomite- and chert-rich layers of the Chuniespoort Group, which, together with a basal layer of Black Reef Quartzite sediments, cover the Witwatersrand layers (South African Committee for Stratigraphy, 1980).

On the Far West Rand, the Malmani Subgroup is between 1200 and 1450 m thick. In places, the dolomitic formations are overlain by younger rocks of the Pretoria Group (2350–2100 Ma), the Transvaal Sequence and the Karoo Sequence (300–200 Ma). The basal Archaean granite is covered by the Witwatersrand Supergroup. It is in the upper layers of this succession that the gold-bearing conglomerates are found between layers of quartzite (Wolmarans, 1984).

Walraven and Martini (1995) estimated the onset of limestone deposition at 2550 Ma. The precursor mineral to dolomite was aragonite. After precipitation, the limestone underwent a process of dolomitization in an environment where meteoric and marine water mixed, the brine becoming supersaturated with magnesium and silica, and undersaturated with calcite. This increased the potential for dolomitization and chertification (Trollip, 2002).

THE DOLOMITE OF THE FAR WEST RAND

Dolomite, limstone and dolomitic limestone have been defined and characterized by Sweeting (1972), Snyman (1981) and Warren (2000). The dolomite in Gauteng formed as part of a 500 000 km^2 shallow, inland sea. Algae, which is considered to be one of the sources of carbonate sediments (through algal photosynthesis), populated this inland sea. Photosynthesis promoted the removal of CO_2 from the solution and thereby encouraged the dissociation of soluble calcium bicarbonates ($Ca(HCO_3)_2$) to form insoluble calcium carbonate ($CaCO_3$). Inorganic precipitation is another source of carbonate sediment. Over a period of millions of years, the calcium carbonate accumulated to form thick sequences of limestone. Seawater rich in magnesium, iron and manganese percolated through the limestone and altered the original material to dolomite (Council for Geoscience, 2003).

Recent research on the Malmani dolomites indicates that the carbonate rocks in the Malmani Subgroup are essentially dolomitic limestone (a limestone that has been incompletely dolomitized), with a few limestone bands (Trollip, 2002). In South Africa the term 'dolomite', where it denotes the rock type, has substituted the term 'dolomitic limestone'. Dolomitic limestone, as a natural rock, consists of the mineral dolomite ($CaMg(CO_3)_2$), the mineral calcite (calcium carbonate, $CaCO_3$) and the mineral magnesite (magnesium carbonate, $MgCO_3$). Certain portions of the rock may be richer or poorer in either of the latter minerals (Council for Geoscience, 2003).

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The post-Transvaal plutonic activity of igneous rocks of the Bushveld Igneous Complex manifested in this area as diabase sills, which intruded into the sediments of the Transvaal Sequence.

The geological event that had the biggest influence on the hydrology of the Far West Rand was the deformative tectonic force culminating in the Vredefort Impact Crater. This caused movement along the sedimentary and interbedded discontinuities. Proof of the bedding plane faults can be seen in the underground mine diggings and although it does not influence the erosion patterns of the dolomite, it has a major influence on the water flow in the gold mines and groundwater levels.

Much of the foregoing applies to the Far West Rand, which is characterized by the formation of the Pilanesberg alkaline (syenite and diabase) dykes, a geological episode that had a major influence on the hydrology of this area. The dykes are mainly north–south inclined and subdivide the aquifers of the Wonderfontein Spruit valley into separate groundwater compartments. The width of the dykes varies from 6 to 60 m, and they are the main structural features causing a succession of springs along the Wonderfontein Spruit and Mooi River (see Figure 2). A pattern of fractures that coincide with the strike of the Pilanesberg intrusions is well documented on the underground structure maps of the gold mines. Many quartz veins with the same strike have also been mapped on the surface of this area (De Kock, 1964). This phenomenon can also be seen in the passages of the caves in the area, notably the Apocalypse and Wonderfontein caves, which have the longest surveyed tunnels (> 10 km) of any cave structure in the Republic of South Africa (E. J. Stoch, Personal communication, Welverdiend, South Africa, 15 September 2005).

WEATHERING AND EROSION OF THE DOLOMITE

Weathering of dolomite starts even before its exposure to the atmosphere and has been well described by Germishuys (1987), amongst others. Most of the dolomite in solution leaves the West Rand area as the total dissolved solids (TDS) load of the water. This causes the formation of the conduits and cavities in the dolomite, which forms the aquifer where the water is found (E. J. Stoch, Personal communication, Welverdiend, South Africa, 15 September 2005). When the dolomite in solution is deposited again, it will slowly crystalize as calcite crystals (Germishuys, 1987). In the slightly acidic groundwater in the vadose as well as the phreatic zones the processes of solution progress very slowly. Water rich in bicarbonates (90 per cent) and silica (10 per cent) results from this and emerges at the many springs in the area (Figure 3). The silica content is an indication that partial solution of the chert also takes place. Above the water-table, in the vadose zone, the process of solution widens joints and fractures. Between adjacent openings formed in this way, pillars of rock stand as pinnacles rounded off by solution. Insoluble layers of chert are squeezed together when the intervening dolomitic layer dissolves and the residuum sags between the rock pinnacles (Brink, 1979). In geologic time the water level changed several times so that one now finds cave structures both above and below the pre-dewatering water level (E. J. Stoch, Personal communication, Welverdiend, South Africa, 15 September 2005).

Small quantities of wad can be seen in all the caves, chert rubble and contact zones between the dolomite and other rock types, such as dykes and sills, in this area. The weathering and erosion of dolomite cause a natural instability of dolomitic rocks, with sinkholes and dolines being formed continuously. According to Jennings (1985) rockfalls, block slides and rock slides are more significant in karst than in any other morphogenetic system. Solution acts freely both laterally and vertically to form cliffs and caves where the roofs as well as the walls are subject to collapse.

EFFECT OF THE GROUNDWATER LEVEL

Given sufficient time and the correct triggering mechanisms, ground instability in dolomite land occurs naturally, but it is expedited by many orders of magnitude by human actions. The most important triggering mechanisms caused by people are:

- the ingress of water from leaking water-bearing services;
- poorly managed surface drainage (usually at urban structures); and
- groundwater draw-down (Trollip, 2002).

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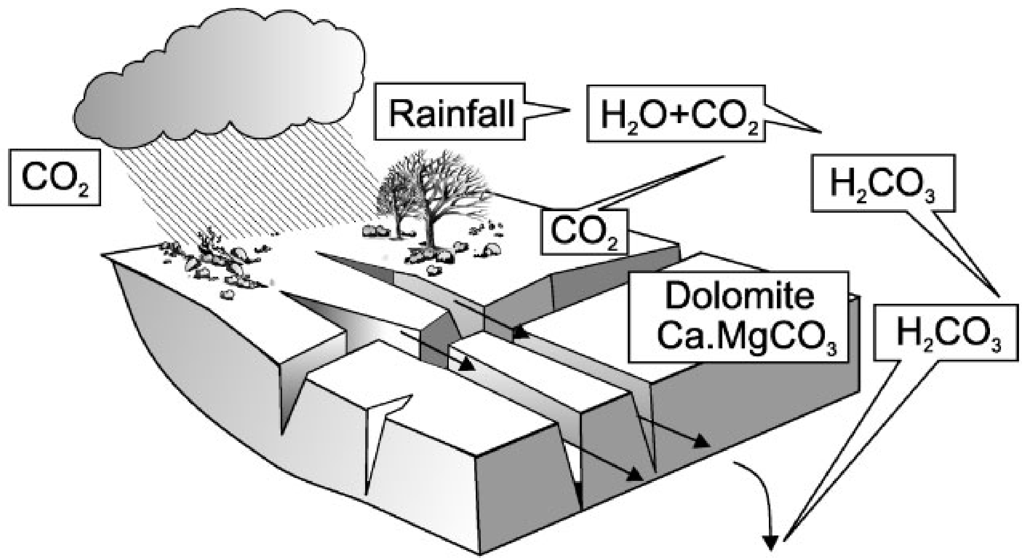

$$3CaCO_3 + 2MgCO_3 + 5H_2CO_3 = 3Ca(HCO_3)_2 + 2Mg(HCO_3)_2$$

Figure 3. Weathering of dolomite.

Phreatic groundwater (below the water-table) is not static. It continuously removes bicarbonates by slow migration of the solution along the joints. The flow obeys the ordinary flow-net theory for seepage through a jointed rock mass. This flow-net tends to flatten out as the solution enlarges the flow paths near the phreatic surface as can be seen in Figure 4.

The horizontal component of flow soon exceeds the vertical component of flow and solution takes place mainly along the horizontal flow direction. Lateral leaching therefore mainly takes place directly beneath the water-table where the hydraulic pressure gradient is greatest. The flow of the carbon dioxide-charged water from the overlying

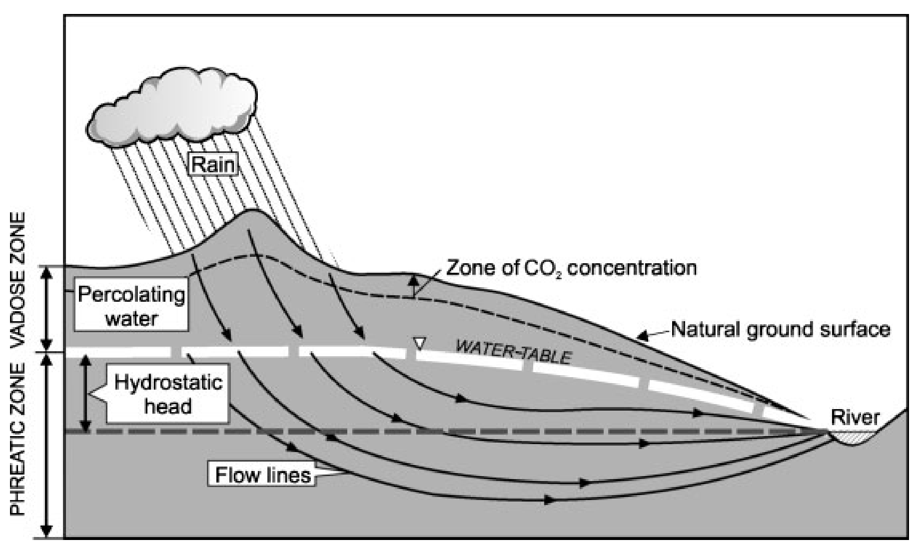

Figure 4. Phreatic groundwater flow. Adapted from Brink (1979, p. 202).

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vadose zone results in the development of a network of interconnected caverns in the phreatic zone. Lateral leaching below the water table shows a sharp decline with depth (Enslin, 1967).

Apart from the daily tidal effect and the seasonal flux of the groundwater (E. J. Stoch, Personal communication, Welverdiend, South Africa, 15 September 2005), cycles of erosion and planation result in long periods of a relatively static water-table. This leads to the concentration of solution cavities at particular subsurface elevations. Subsequent lowering of the water-table leads to the exposure of such cavities in the vadose zone above the newly created water-table. The drop in the water level may lead to local ground instability features such as sinkholes and dolines in sensitive areas. Additional solution cavities below the new relatively static water-table will start to develop (Brink, 1979). Changes in the depth of the water-table will continually influence ground instability.

GROUND INSTABILITY ASSOCIATED WITH DOLOMITE LAND

The specific term 'dolomite land' has been defined by Trollip (2002:2) as follows:

> In South Africa, the term *dolomite land* is used for areas underlain directly or at shallow depth (<100 m) by dolomitic rock of the Chuniespoort Group of the Transvaal Sequence (Proterozoic age). It therefore includes areas where dolomite is covered by younger deposits (Pretoria Group) of the Transvaal Sequence, the Karoo Sequence (Palaeozoic age) or unconsolidated deposits of Cenozoic age.

This definition was established because research had shown that these are the areas that will have an influence on ground instability. The areas of ground instability are related to the depth of the dolomite relative to the surface and the presence or absence of chert. While the characteristics of the soil mantle can influence the permeability of water, soil can mask the danger lurking or developing below (E. J. Stoch, Personal communication, Welverdiend, South Africa, 15 Septembre 2005).

The process of dissolution of the dolomitic rocks has resulted in a vertical succession of residual products on the Far West Rand. Hard, unweathered dolomitic bedrock is overlain by slightly weathered, jointed bedrock, which, through a sudden transition, is overlain by totally weathered, low-strength, insoluble residual material, mainly consisting of manganese oxide (wad), chert and iron oxides. This very low strength, porous and permeable horizon is generally less than 10 m thick. In certain locations it may be up to several tens of metres thick, depending on the local subsurface conditions. With the downward progression of the weathering of the dolomite and the slow passage of geological time, compaction by the huge mass of the overlying materials causes these low-strength materials to show a progressive densification. The vertical succession of the residual products of weathered dolomite therefore shows a downward decrease in strength and a downward increase in porosity and permeability. This means that there will be a decrease in overburden quality with depth, leading to an increased possibility that infiltrating water from leaking services or any other surface accumulations may result in a serious loss of support through slumping or subsurface erosion (Trollip, 2002). Enslin (1967) has provided a vivid description of the nature of the dolomite as witnessed by the shaft sinkers and recorded in their logs.

According to Irving (1958), the factors that influence the risk of subsidence actually taking place are:

- topography;
- drainage;
- the natural thickness and origin of the transported spoils and residuum;
- the nature and topography of the underlying strata;
- the depth to, and expected fluctuations of, the water-table; and
- the presence of structural features such as dykes, faults and fractures (Enslin *et al*., 1976).

Brink (1979:179) has defined a sinkhole as 'a subsidence which appears suddenly, and sometimes with catastrophic consequences, as a cylindrical and steep-sided hole in the ground. It is usually, but not always, circular in plan, and may be up to 125 m wide and 50 m deep'. In contrast, a doline (or compaction subsidence) is 'a surface depression which appears slowly over a period of years. It may be circular, oval or linear in plan. Where circular or oval it may be up to two or three hundred meters in diameter; where linear, up to 1 km long. It may attain

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a depth of up to about 12 m. The periphery of a doline is characterised by the presence of tension cracks within a zone of shear' (Brink, 1979).

Jennings (1971; 1985) and Brink (1979) have described the mechanism of sinkhole formation in detail. This mechanism can be summarized as follows:

- Cavities exist within bedrock or the overburden, which may be in a state of equilibrium.
- Active subsurface erosion caused by concentrated ingress water will result in transportation (mobilization) of materials downwards into the nearest cavity (receptacle).
- Headward erosion leads to successive arch collapse. The last arch may be stable for a considerable length of time and is sometimes supported by a near-surface layer of hardpan ferricrete.
- A triggering mechanism leads to the breaching of the last arch. Particularly in the case of small sinkholes, the cross-section resembles a bottleneck (narrow opening at surface), a shape that may be maintained for some time.

Five independent conditions are therefore necessary before a sinkhole can form:

(1) There must be adjacent rigid material to form abutments for the roof of the void.
(2) A condition of arching must develop in the residuum.
(3) A void must develop below the arch in the residuum.
(4) A receptacle must exist below the arch to accept mobilized material.
(5) Some disturbing agency must arise to cause the roof to collapse.

Figure 5 shows sinkhole and doline formation due to dewatering of the groundwater compartment. Diagram (a) shows the equilibrium situation before lowering of the water-table. Diagram (b) shows the position after lowering of the water-table, when active subsurface erosion occurs due to subsurface crevices being flushed out by a process of headward erosion. Diagram (c) shows the complete collapse of the last arch to produce a sinkhole surrounded by concentric tension cracks (Brink, 1979).

A dewatering-type doline occurs gradually and typically manifests itself as a large enclosed depression. The mechanism of doline formation is briefly summarized as follows (Figure 5):

- A deeply weathered zone within the dolomite rock is filled with potentially highly compressible material, part of which is submerged below the groundwater level.
- Rapid draw-down of the groundwater level results in exposure of the previously submerged and unconsolidated debris.
- Compression may be excessive and the rate of surface settlement is rapid if a thick succession of wad is exposed by this draw-down.
- The settlement manifests as a depression at the surface.
- Surface tension cracks occur in the peripheral areas of differential movement (Trollip, 2002).

HISTORY OF DOLINE AND SINKHOLE FORMATION ON THE FAR WEST RAND

Surface instability as a manifestation of the influence of dewatering of the groundwater compartments was initially ignored by the mining companies because they were illegally dewatering the compartments. The first Permit that allowed the dewatering of a dolomitic compartment was issued as recently as November 1964. The Venterspost Eye ran dry in 1947, the Obelholzer Eye dried up in 1959 and sinkholes occurred in the Oberholzer Irrigation Board Canal (E. J. Stoch, Personal communication, Welverdiend, South Africa, 15 Septembre 2005). By the end of 1960 the West Driefontein Mine recognized the first signs of surface depressions at the Number 2 shaft. Distortion of buildings and the reduction plant caused great concern. A shaft was sunk next to the plant to investigate the cause of the instability. Most of the mines conducted their own investigations and no coordination of these investigations took place.

Some houses and streets in the town of Carletonville also started to slump. Soil movement and damage to property were investigated by the Council for Geoscience (CGS). Only after the CGS had come to the conclusion

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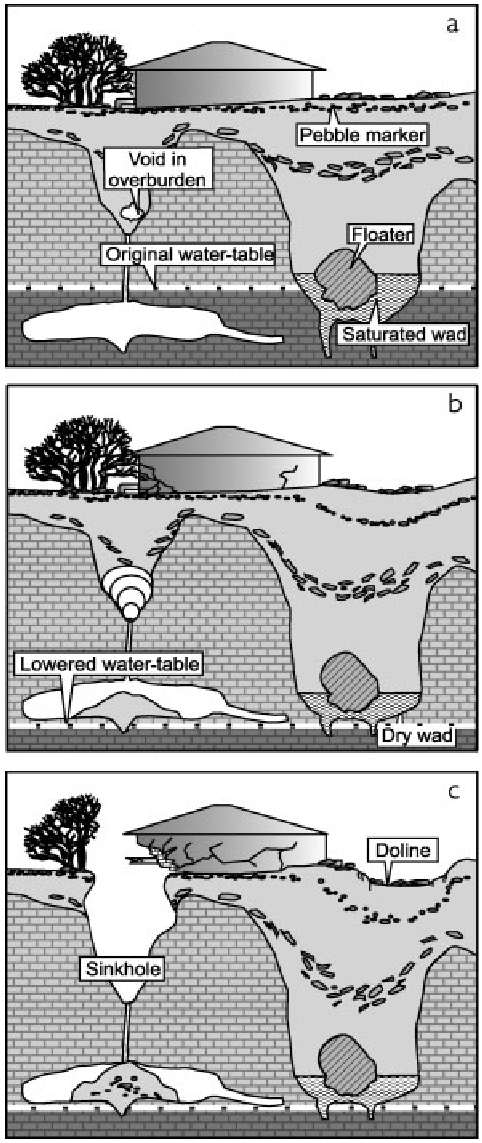

Figure 5. Sinkhole and doline formation by dewatering. Adapted from Council for Geoscience (2003).

that the lowering of the water-table was possibly the dominant cause of the differential subsidence and some of the sinkholes that formed in the Venterspost and Oberholzer Compartments in 1960, did coordinated efforts begin. This research programme was still in progress when a huge sinkhole engulfed a three-storey crusher plant at the West Driefontein Mine on 12 December 1962, killing 29 people. The sinkhole was 55 m in diameter and at least 30 m deep. A serious survey of the ground stability situation of the Township of Carletonville was undertaken by the West Driefontein Mine in 1962 and updated in 1966.

The West Driefontein disaster came as a huge shock to the mining industry, the community and the government, even though investigations had been underway for more than two years by the time of the occurrence. Before dewatering north of the Gatsrand (see Figure 2) and south of the Wonderfontein Spruit in the Oberholzer, Venterspost and Bank compartments started, only a few, isolated sinkholes had occasionally formed in the

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irrigation canal and the streambed of Wonderfontein Spruit (Wolmarans, 1984). According to Nel (1935), the general acceptance is that in the pre-mining situation, the dolomite, water and sinkholes are closely related but confined to specific areas. One can therefore conclude that the sinkhole risk in these areas was low before dewatering commenced. Industrial and township development between 1934 and 1960 did not cause instability. Historical information shows a completely different scenario north of the Wonderfontein Spruit. After the establishment of the township of Khutsong in 1959, nine sinkholes formed in the close vicinity of the township, all of which had a direct connection with one or other form of soil saturation (Wolmarans, 1984). Khutsong is situated on the non-dewatered Boskop Turffontein compartment (see Figure 2).

The oldest mine on the Gatsrand, Blyvooruitzicht Mine, recorded a series of reliable statistics dating from 1948, i.e. before the onset of dewatering caused the formation of sinkholes and dolines. These data, combined with the notes on sinkhole formation collected by Doornfontein Mine, where dewatering did not cause sinkhole incidents, helped to classify the reasons for sinkhole formation before the onset of dewatering. Sinkholes at the Doornfontein Mine were caused by surface water ingress due to industrial development, leading to soil saturation. No reliable statistical information exists of the paleo-sinkholes on the Far West Rand. Yet there is enough information to conclude that the rate of sinkhole formation before the onset of industrial development in the area was extremely low. At Blyvooruitzicht Gold Mine, five paleo-sinkholes were identified prior to the mine's inception in 1948, compared to the more than 39 sinkholes that occurred in the first nine years of gold production and dewatering. This same tendency can be seen at Doornfontein Mine. When the history of sinkhole formation in these two mining areas is considered together, it becomes apparent that the surface locations of tailings dams were responsible for 95 per cent of the sinkhole incidences since gold production commenced, but before the dolomitic compartments were dewatered (Wolmarans, 1984).

Since dewatering started, sinkhole incidences increased dramatically and 90 per cent of these could be linked directly to the dewatering of the groundwater compartments (Wolmarans, 1984).

THE FUTURE

Several of the gold mines on the Far West Rand are reaching the end of their life span and the dewatering of the dolomitic compartments is due to be reduced and eventually discontinued completely as the mines are decommissioned. Some of the dykes that form the boundaries of the individual dolomitic compartments have been breached by mining activities so that flooding of one compartment will eventually impact on most other compartments. The eventual static level of the water-table in this new 'super-compartment', as well as points of decant are therefore uncertain.

After pumping has been discontinued, flooding of compartments will take from 10 to 40 years, depending on precipitation, as well as the volume of the actual mine void and the effective porosity of the different zones (De Roer, 2004). After the compartments have been flooded, the original dolomitic eyes feeding Wonderfontein Spruit will start flowing again. However, due to the possibility of the reactivation of sinkhole formation when allowing the water to return to the original level, it may become policy to permanently keep the water between 6 and 10 m below the original water level. Because of typical karstic landforms, the mines have diverted the flow of the Wonderfontein Spruit since 1978 via a one-metre-diameter pipeline to prevent surface water in the Wonderfontein Spruit recharging the underground workings. It is uncertain whether the capacity of this pipe will be able to accommodate the increased flow expected when decanting commences after flooding. If the capacity is insufficient, the effect of the freely flowing Wonderfontein Spruit on groundwater quality and ground stability will have to be investigated.

Another point to consider is that the compartments have been dewatered for about half a century and have probably reached equilibrium conditions. Once rewatering starts, this equilibrium will be disturbed, which could lead to the reactivation of sinkholes. Studies have been done to identify areas of concern, and as a result the complete township of Khutsong (about 200 000 people) will be shifted to a stable area within the next three years at an estimated cost of ZAR 1·5 billion (ZAR 500 million per year for three years ($80 million)). An environmental impact assessment of the area to which these people have to be moved is currently being undertaken and is at the

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public participation stage of the process. The social dimension of this disruption will be immense to the inhabitants of Khutsong.

The expected quality of the decanting water after rewatering of the dolomitic compartments will also need to be investigated as mining activities have an adverse effect on water quality. The city of Potchefstroom (with approximately 250 000 citizens) is currently reliant on the Mooi River as its sole source of raw water for the supply of potable water to its citizens. However, the water quality in the Mooi River is impacted upon by water from its Wonderfontein Spruit tributary, which is contaminated by gold-mining industries and associated abandoned infrastructures and deposits in the Wonderfontein Spruit catchment area (Wade *et al*., 2000; Riedel, 2003). Data from the Department of Water Affairs and Forestry (gauging station C2H048) indicate that the TDS concentration of water in the Lower Wonderfontein Spruit just upstream of the confluence with the Mooi River has continuously been in the range of 400–600 $mg\,l^{-1}$ since 1998. These elevated TDS values can be partially attributed to high sulphate concentrations, which have been fluctuating in a narrow range around 200 $mg\,l^{-1}$ between 1998 and 2004. Although this water quality is still acceptable for potable purposes, the values are on the upper limit as prescribed by the South African Water Quality Guidelines (DWAF, 1996a).

In terms of agricultural use, certain crops are very sensitive to elevated TDS levels, and water from the Lower Wonderfontein Spruit is only marginally acceptable for irrigation purposes. Only a 90 per cent relative yield of moderately salt-tolerant crops can be maintained by using low-frequency applications of this water, and a leaching fraction (the fraction of the total water application that needs to leach to below the root zone to prevent the accumulation of salinity to levels at which plants cannot extract water) of up to 0·15 may be required. Wetting of the foliage of sensitive crops should be avoided (DWAF, 1996b)

Of particular concern for future scenarios are the millions of tonnes of mine tailings within the catchment area. Sinkholes forming beneath some of these tailings dams are a common occurrence, and there is a real possibility of tailings previously used to fill sinkholes liquefying after rewatering, thereby becoming mobile. Further salinization of the surface and ground water (particularly by sulphates) has been a problem for many years (Riedel, 2003; Personal communication, Potchefstroom, South Africa, 3 October 2003).

An important concern in the catchment area is the fact that the sedimentary phase of the Wonderfontein Spruit, its dams and impoundments are continually being enriched with heavy metals and radio nuclides originating at the mining works. These contaminants could be remobilized and released into the downstream water under certain conditions (Wade *et al*., 2000; Coetzee *et al*., 2002), resulting in a significant deterioration in the water quality for all downstream users, including the city of Potchefstroom (Riedel, 2003).

CONCLUSION

Since the inception of gold mining on the Far West Rand in 1934, dewatering of the dolomitic ground water compartments was undertaken for economic reasons and to supply the mine workers with a safe working environment. This resulted in ground instability in the form of catastrophic sinkhole collapses and doline formation, causing loss of life and severe damage to building structures.

The first occurrence of instability features on the Far West Rand was recognized in the 1960s and since then intensive research has been carried out by the Council for Geoscience, the Chamber of Mines and other independent researchers. The CGS released the following statement regarding sinkhole and doline formation on 28 March 2002:

> For the past 60 years, the Council for Geoscience has played a major role in attempting to ensure that development on dolomite areas has been properly planned so that the integrity of the subsurface materials are not negatively affected and that its condition is maintained in perpetuity. Over the years, a large amount of research has been undertaken and attention given by members of the CGS to the evaluation of risk on dolomitic land. A number of documents have been produced in this regard, which have included recommendations and measures for appropriate development (Council for Geoscience, 2003).

This indicates the role this organization has attempted to play in avoiding disasters.

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Today, more than 70 years after the inception of gold mining on the Far West Rand, some of the gold mines are reaching the end of their economic viability and will close down. Dewatering of the dolomitic water compartments will cease and the water table is expected to rise over the next few years. Several types of land degradation are expected to occur, such as renewed ground instability and acid mine drainage. Research on these aspects needs to be undertaken as a matter of urgency, hazards should be identified and development projects carefully planned. More importantly, monitoring and maintenance schemes to minimize and mitigate the risks of damage to property, loss of life, and future land degradation should be implemented before further disastrous events occur.

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