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SINKHOLE AND SUBSIDENCE RECORD IN THE CHUNIESPOORT GROUP DOLOMITE, GAUTENG, SOUTH AFRICA

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ABSTRACT

Karst related sinkholes and subsidence's occur on areas underlain by Chuniespoort Group dolomite bedrock in the Gauteng Province. Dolomite land occurs across several South African provinces; however sinkhole and subsidence formation in Gauteng is more well-known than in of the other provinces. Thousands of sinkhole and subsidence events have occurred in the past 60 years.

In the past, data on sinkhole and subsidence occurrence has been amassed separately by various consultants, companies and state authorities. There is currently no legal requirement for sinkhole and subsidence events to be reported to a central authority, yet this data is crucial for future assessment of sinkhole hazards and decision making.

This study focuses on the dolomitic land areas within four Gauteng municipalities, vulnerable to karst related sinkhole and subsidence formation. Historical as well as current information regarding the sinkhole record for Gauteng was compiled from various sources to develop as comprehensive an inventory of the study area as possible. The importance of sinkhole inventories are reviewed as well as the expediency and efficiency of Geographic Information Systems in data capturing and viewing.

Data originates from numerous sources and compiling a comprehensive database presented many challenges, most importantly the large percentage of missing data that could not be retrieved and that the format and quality varies. Only karst related sinkhole, subsidences and crack events prior to 31 December 2011 were considered in this study. The data compiled is only an estimation of the number of events that has occurred in Gauteng. Once all the available sinkhole and subsidence data was collected and compiled, it was organized into multiwave frequency tables and various aspects were analyzed. The data collected, although limited in some cases, is used in statistical analysis to investigate the relationship between the formation of sinkholes and subsidences and underlying geology, size distributions, frequency of events and external influences.

Results indicate that to date just over 3000 events (sinkholes, subsidences and ground cracks) are recorded within the study areas, and:

- *Sinkholes and subsidences are still regularly occurring in areas underlain by dolomite in Gauteng, however based on available data, events in the West Rand and Tshwane appear to show decreasing trend over the last decade.*
- *More events occur in high rainfall months or years (due to increased ingress water entering the ground profile).*
- *The most dominant type of event recorded is sinkholes.*
- *Overall the largest percentage of events has occurred on the chert-rich Monte Christo Formation and Eccles Formation.*
- *Triggering mechanisms were considered for the different areas: on the West Rand most occurrences before 1984 were due to dewatering while after 1984, most are attributed to ingress. The largest percentage of events on the West Rand has occurred in the Oberholzer*

Groundwater Compartment. In Tshwane almost all occurrences can be attributed to ingress, while in Ekurhuleni, just under a quarter of events were identified as due to dewatering.

- *When considering sinkhole and subsidence size and depth distributions; the largest percentage of sinkholes in the West Rand (>60%) are large to very large (i.e. from greater than 5m to greater than 15m diameter), the largest percentage of sinkholes in Tshwane (>60%) are medium to large (i.e. from greater than 2m to less than or equal to 15m diameter) and the largest percentage of events in Ekurhuleni (>70%) are small to medium (i.e. less than or equal to 5m diameter).*
- *When considering size distribution on the different formations, it was not possible to determine if certain sizes were more prevalent for specific formations.*

ACKNOWLEDGEMENTS

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The opinions expressed are those of the author and do not necessarily represent the views of any of the bodies that supplied data.

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TERMINOLOGY

Karst: *a landscape that is distinguished by its underground drainage, so that its landforms evolve in response to rainfall and surface water flowing into the ground (Waltham et al., 2005). Development of karst topography (sinkholes, subsidences, caves, caverns or valleys) requires the subsurface dissolution of some soluble rock, usually limestone or dolomite (Collins Dictionary Geology, 2003).*

Dolomite (dolomitic) land: *land underlain by dolomite or limestone rock directly or at a shallow depth, typically no more than (SANS 1936[1]):*

- *60 m in areas where no de-watering has taken place and the local authority has jurisdiction, is monitoring and has control over the groundwater levels; or*
- *100 m in areas where de-watering has taken place or where the local authority has no jurisdiction or control over groundwater levels.*

Sinkhole*: a feature that occurs suddenly and manifests itself as a hole in the ground (SANS 1936). It is usually, but not always, circular in plan (Foose 1967).*

- *In South African literature these types of events in dolomite ground are broadly termed a sinkhole, internationally they may be further classified with respect to the mechanism of ground failure and the nature of the material which fails, i.e. dissolution sinkholes, collapse sinkholes, caprock sinkholes, dropout sinkholes or suffusion sinkholes as classified by Waltham and Fookes (2003).*

Subsidence (dolomite ground): *shallow, enclosed depression (SANS 1936). A feature that appears slowly over time and may be circular, oval or linear in plan, and may attain a diameter/ length of hundreds of meters to a kilometer and depths up to 12m. The periphery of a subsidence is usually characterized by the presence of tension cracks (Brink 1979).*

- *Subsidence in dolomite ground was previously termed 'doline' in South African literature.*

Event: *occurrence referring to a sinkhole or subsidence on dolomite ground (SANS 1936).*

- *In the context of this study 'event' also includes cracks. The term 'event' may be used interchangeably with the term 'occurrence'.*

[1] SANS 1936-2 is a South African National Standard.

Hazard: *a potential source of harm. Hazard is the function of magnitude (of the events), area, and frequency (SANS 1936).*

Residuum: *a portion that remains after the weathering of dolomite rock (SANS 1936).*

Chert: *A dense extremely hard microcrystalline siliceous sedimentary rock, typically white, black or grey. Chert occurs mainly as aggregations in limestone and dolomite (Collins Dictionary Geology, 2003).*

Wad*: an insoluble and highly compressible material that consists of a porous mixture of Mn and Fe oxides left behind after dissolution of dolomite and has a cellular structure inherited from the texture of the rock. Wad forms a favorable horizon for cave or cavity formation. It has a high mobilization potential and groundwater seepage causes subsurface erosion. The highly compressible nature also supports the development of shallow but wide subsidences (Martini, 2006).*

Gryke*: Dissolution fissure within the bare rock of a limestone (dolomite) pavement (Waltham et al, 2005).*

Pinnacles or pinnacled rockhead*: extremely irregular rockhead with soil-filled fissures and buried sinkholes between remnant rock pinnacles (Waltham et al, 2005).*

Dewatering: *occurs when abstraction of groundwater out of an aquifer exceeds natural replenishment, resulting in the progressive lowering of the water table (Wolmarans, 1984).*

CHAPTER 1 – INTRODUCTION

1.1 BACKGROUND

According to Ford and Williams (in Angel, *et al*. 2004), sinkholes are the most diagnostic surface expression of karst landscapes and can be found extensively throughout the world (approximately 7-10% of the earth surface has been classified as karst terrain). Karst related sinkholes and subsidences occur in areas underlain by dolomite ground. Dolomite land occurs across several South African provinces including Gauteng, Mpumalanga, Limpopo, North West and Northern Cape; however sinkhole formation in Gauteng is more well-known than in any of the other provinces.

Thousands of sinkhole, subsidence and crack events have occurred in the past 60 years within the Gauteng Province. According to Buttrick *et al*., (2011), four to five million people currently work or reside on dolomite land. These instability events are a serious problem that have resulted in loss of life and/or damage to property when they coincide with human development. Damage to buildings and other infrastructure has been more severe on dolomite than any other rock type in South Africa (Brink, 1979; Wagener, 1985) and thus far 39 people have lost their lives (Buttrick and Roux, 1993).

In the past, data on sinkhole and subsidence occurrence has been amassed separately in papers, research theses and databases held by various consultants, companies and state authorities. There is currently no legal requirement for sinkhole and subsidence events to be reported to a central authority (Heath & Oosthuizen, 2008). Sinkhole statistics have not been available since the work by Wolmarans (1984) and Schőning (1990), although Heath and Oosthuizen (2008) have indicated in excess of 2400 instability events in a preliminary overview of the sinkhole record for South Africa. Sinkhole and subsidence data is crucial for future assessment of sinkhole hazards and decision making.

1.2 STUDY AREA

Gauteng is situated in the interior of South Africa (Figure 1) having a surface area of 16547.8 km^2. It was originally part of the former Transvaal Province, and known as the Pretoria-Witwatersrand-Vereeniging (PWV) area, but was rezoned and renamed ‘Gauteng’ in 1994. Gauteng houses the two major cities of Johannesburg and Pretoria. This study will focus on the dolomite land areas within Gauteng, as they are vulnerable to karst related sinkhole and subsidence formation.

In Gauteng the Malmani Subgroup (Chuniespoort Group, Transvaal Supergroup) dolomites occupy a surface area of approximately 2 576 km^2 (14% of Gauteng's surface area, 1:250 000 Scale geological map series; 2528 Pretoria, 2626 West Rand & 2628 East Rand.) and form two broad arches (northern and southern) around the Halfway House Granite. However the area considered as "*dolomitic land*" (Bosch, 2003), includes areas covered by younger non-dolomitic formations but still underlain by dolomite at depth. This covers an area of approximately 4005 km^2 (24% of Gauteng's surface area).

Sinkholes and subsidences have historically been considered in only two separate dolomitic areas (the Far West Rand and the area south of Pretoria). This study will focus on all past and current information on each of these areas, plus the remaining municipal areas of Ekurhuleni and City of Johannesburg, prior to combining the records in a provincial overview. Gauteng is divided into three metropolitan municipalities, and two district municipalities, which are further divided into local municipalities. The areas are listed below and shown in Figure 1;

- West Rand District Municipality (total area: 2456.87 km^2): Study area of approximately 1827.62 km^2 of dolomitic land, from Oaktree in the north to Welverdiend in the west to Bekkersdaal in the east. This District Municipality also encompasses the areas of Carletonville and Westonaria, historically known as the Far West Rand;
- Tshwane Metropolitan Municipality (total area: 6344.29 km^2) : Study area of approximately 497.24 km^2 of dolomitic land, from Atteridgville in the north west to Pierre van Ryneveld in the east and parts of Grootfontein and Sterkfontein, to Irene Agricultural Research Institute in the south. This area was also historically known as 'southern Pretoria';
- Ekurhuleni Metropolitan Municipality (total area: 1924.34 km^2): Study area of approximately 988.79 km^2 from Clayville in the north-west to Etwatwa in the east to Selcourt in the south and from Dawn Park to Tokoza.
- City of Johannesburg Metropolitan Municipality (total area: 1645 km^2): dolomitic area of approximately 218.47 km^2 containing parts of Soweto and Lenasia;
- Sedibeng District Municipality (total area: 4177.3 km^2): dolomitic area of approximately 473.05 km^2 from Bronkhorstfontein in the north to Vereeniging in the south and parts of Lochvaal and Seekoefontein.

1.3 OBJECTIVES

This study has the following main objectives:

- To undertake a literature study on karst related instability events within Gauteng Province.
- To compile historical and current event data for Gauteng and develop an inventory of the study area.
- To use the available data in statistical analysis to investigate the relationship between the formation of sinkholes and subsidences and underlying geology, size distributions, frequency of events and external influences such as rainfall.
- To add to the current body of knowledge on sinkholes and subsidences with regard to occurrence within Gauteng Province.

1.4 METHODOLOGY AND SCOPE

Past studies, papers, maps and reports held at the Council for Geoscience (CGS) were examined for information on occurrences of sinkholes and subsidences on the Chuniespoort dolomite within Gauteng; a summary is given in the literature review Chapter 2. The compilation of the database is detailed in the methodology Chapter 3. Historical as well as current information gathered from literature and supplied databases, is made use of in the analysis (Chapter 4).

For convenience, 'sinkholes, subsidences and cracks' will be referred to collectively, where necessary, as 'events' or 'occurrences'. Only karst related events prior to 31 December 2011 were considered in this study. Organization of data was undertaken with the aid of the Department of Statistics of the University of Pretoria.

1.5 CHALLENGES

Challenges in many cases are due to the following:

- Events that have occurred on undeveloped areas such as in open fields or on private farms are often not reported.
- Much of the historical data is contained in reports or research files that are difficult to find.
- Data has been compiled over the decades by different people and the format and quality varies, and large portions of data are missing.
- As reporting of events by the public is voluntary, it is assumed that many events may not have been reported and may have been repaired by land owners themselves.

- Many occurrences are no longer visible in the field, making field verification difficult, and the data accuracy of the reported event must be relied on.

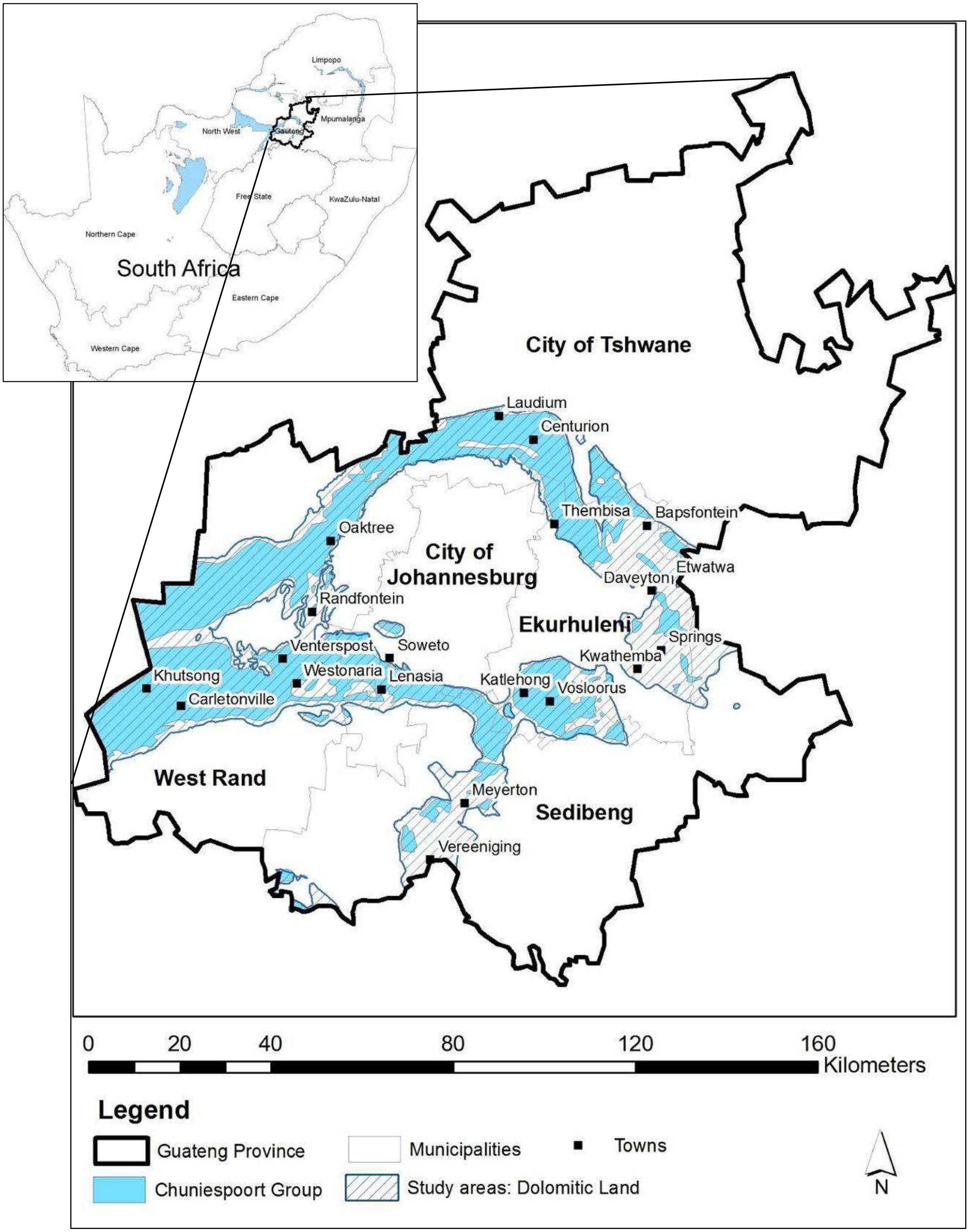


Figure 1: Locality Map: occurrence of dolomitic land in each of the municipal areas of Gauteng Province.

CHAPTER 2 – LITERATURE STUDY

2.1 REGIONAL GEOLOGY

The oldest rock formation in Gauteng is the Archaean Granite and Gneiss of the Johannesburg Dome (~ 3100 Ma), situated between Pretoria and Johannesburg. The Johannesburg Dome is surrounded by younger sediments of the Witwatersrand Supergroup (~ 2800 Ma) and Transvaal Supergroup (~ 2600 - 2400 Ma). The Ventersdorp Supergroup (~2650 Ma) volcanic lavas are found to the south, southeast and east of Johannesburg. The mafic layered intrusions of the Bushveld complex (~ 2060 Ma) occur in the north of the province, as well as the Mokolian Waterberg Group (~2000-1700Ma). The younger Karoo Supergroup (300-200 Ma) sediments cover southern, eastern and northern portions of the Province and sometimes form outliers in the west (Johnson *et al.*, 2006). Numerous syenite and diabase intrusions are also present. This study will focus on the dolomitic rocks (light blue arches shown in Figure 2), of the Chuniespoort Group, Transvaal Supergroup and these formations will be further discussed below.

2.2 GEOLOGY OF THE STUDY AREAS

2.2.1 Deposition of Carbonates

A major period of erosion in post-Ventersdorp times resulted in the development of the Transvaal Basin. The water occupying the basin was rich in bicarbonates and silica which had been leached from the decomposed rocks of the basement complex (Brink 1979). The Transvaal Supergroup sediments were deposited in this vast eperic sea 2,300 -2,600 million years ago (Button, 1973, Eriksson *et al*, 2001).

Limestone accumulated in the eperic sea, from the carbonate rich waters present (Eriksson *et al.*, 1975). According to Ford & Williams (2007), limestone deposits begin as unconsolidated muddy sediments with porosity 40% to 80%. Diagenesis led to their alteration to consolidated rocks with a porosity of 5% to 15%. As dolomitization of limestone proceeded there was a progressive reduction in porosity due to infilling. Eriksson *et al.*, (1975) suggested dolomitization of the primary limestone took place shortly after deposition and was probably related to meteoric waters which lowered the pH. According to Brink (1979) the carbonates were deposited in alkaline waters, but when transition towards an acidic environment developed, the carbonates were no longer stable; began to absorb significantly more Mg and recrystallized to form dolomite. Silica, present in solution (from transported quartz or from

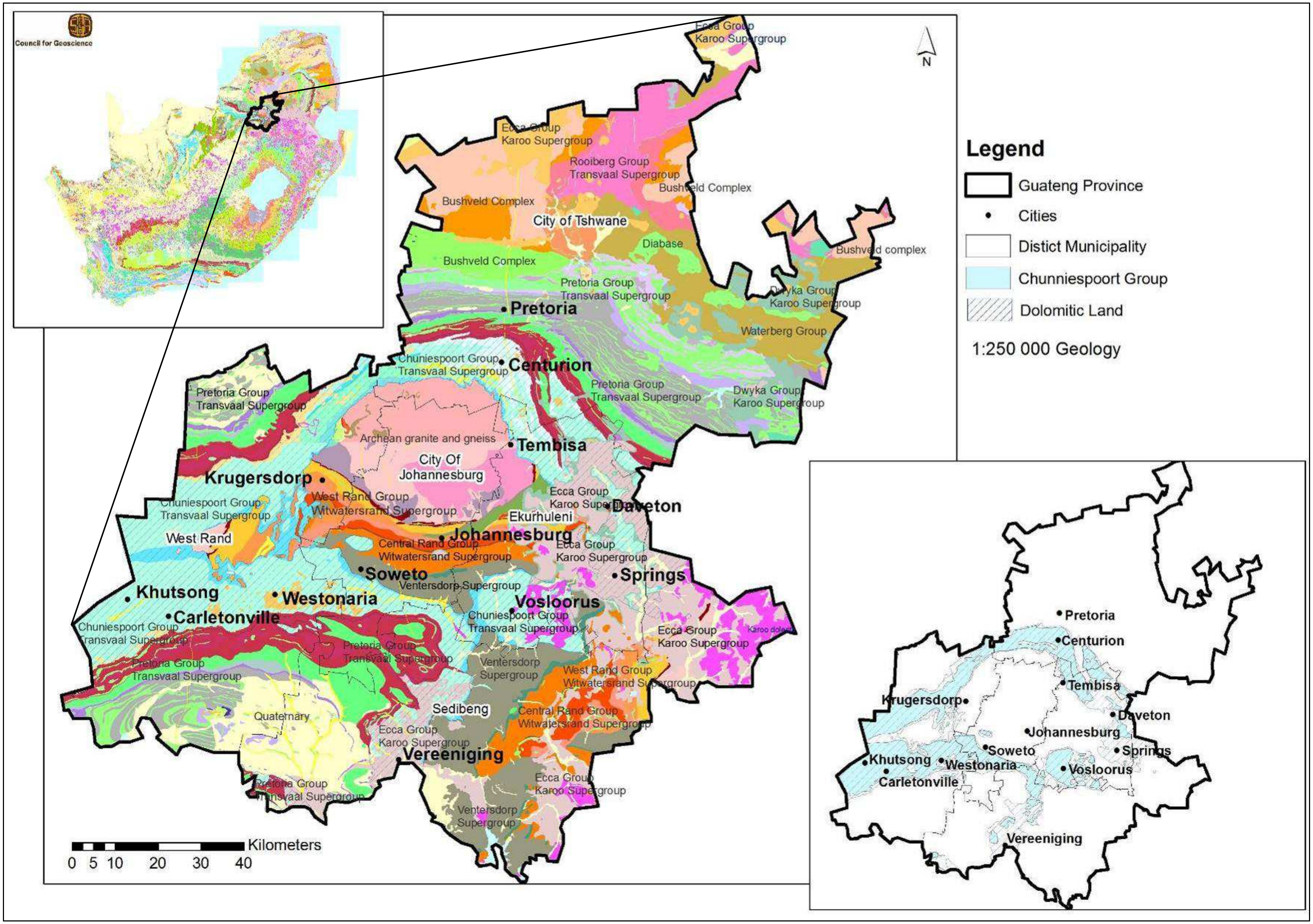


Figure 2. Regional Geology of Gauteng Province.

siliceous sponges, radiolarian and diatoms (Ford & Williams, 2007)), in the highly saline marine water, while stable under alkaline conditions does not deposit until the pH is reduced by the addition of meteoric water to 8 or less (Brink, 1979). From there it is immediately precipitated and even replaced carbonate to form accretionary nodules or chert bands/lenses commonly interlayered with the dolomite. These nodules or chert bands usually accumulate along bedding planes where they may coalesce to form continuous sheets. Chert tends to be more abundant in older dolomites (Ford & Williams, 2007).

2.2.1.1 Environment of deposition

Eriksson & Truswell (1974) and Eriksson *et al.,* (1975) suggested a tidal flat paleoenvironmental model for the Malmani Subgroup with a range of environments extending from an intertidal zone, through a high energy agitated regime and out into a shallow subtidal environment (Eriksson *et al., in* Johnson *et al.,* 2006).

Clendenin (1989) later subdivided the Malmani sediments into 'packages' of genetically related strata, which are separated by low angle unconformities and proposed a south-westerly inclined carbonate ramp (shallow siliciclastic, peritidal, subtidal periplatform, shallow basin) depositional model for the Malmani Subgroup (Eriksson *et al., in* Johnson *et al.,* 2006). These 'packages' or formations have a sheetlike nature across the basin, showing little variation in thickness (Eriksson and Reczko, 1995) and represent a shallow (<40-80m deep) marine depositional system, produced by alternating transgression and regression.

Clendenin (1989) notes that while related these deposits are dominated by particular sub-facies or depositional character. In brief, the deposition facies or subfacies proposed for the Transvaal Basin by Clendenin (1989) (Figure 3) follows:

- Fluvial sub-facies (shallow siliciclastic) when the Black Reef quartzite accumulated in the Transvaal basin.
- The Oaktree Formation was deposited in a submerged shelf sub-facies (periplatformal facies).
- The Lower Monte Christo was deposited in a shoaled flats sub-facies (periplatformal facies). Carbonate sedimentation was disrupted at the end of the lower Monte Christo depositional system and a regional unconformity was formed. Rapid deepening associated with north – north - eastward transgressions reintroduced carbonate

sedimentation during the upper Monte Christo depositional system. The depositional character of this system is shoaled flats sub-facies (periplatformal facies). A sub-regional unconformity was produced above the upper Monte Christo.

- After a hiatus, the Lyttelton – Eccles depositional systems were deposited. The lower Lyttelton is indicated as shoaled flats subfacies, while the upper Lyttelton and Eccles have a submerged shelf sub-facies depositional character. A second sub-regional unconformity was produced after a second retreat of marine facies into the Northern Cape.
- The Frisco-Penge depositional systems were then deposited.
- Rapid regression occurred soon after the deposition of the Frisco –Penge Formations and a third sub-regional unconformity was produced by this retreat.

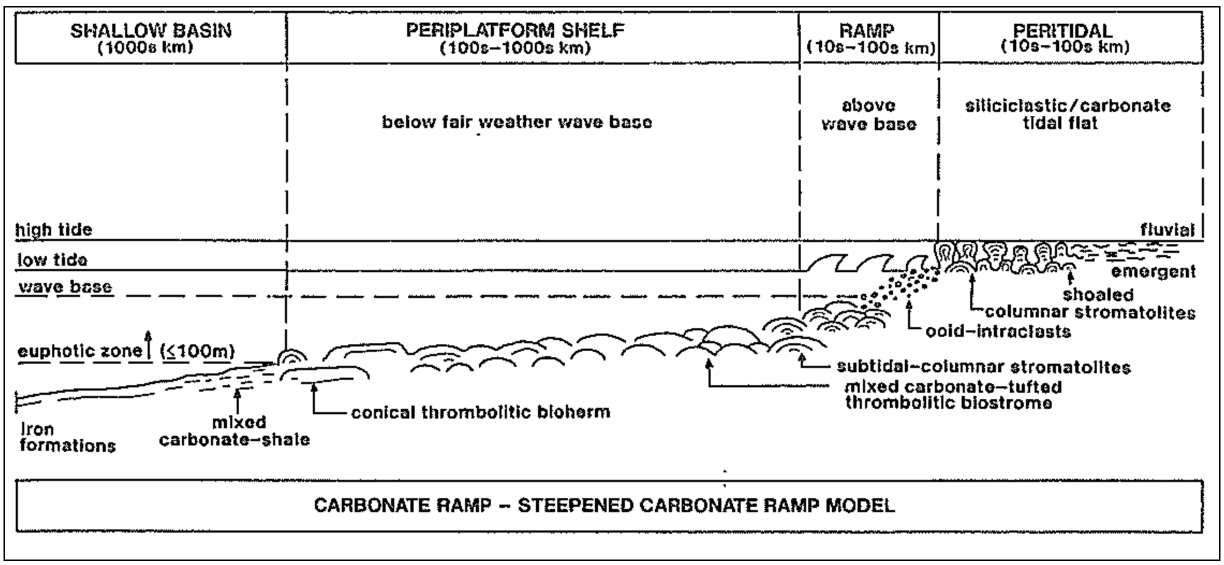


Figure 3: Carbonate ramp model after Clendenin 1989 (taken from Eriksson *et al.,* 1993).

2.2.2 Dolomite formations of the Transvaal Supergroup

According to Beukes, Altermann and Wotherspoon, (Eriksson *et al., in* Johnson *et al.,* 2006), the Transvaal Supergroup (late Archean to early Proterozoic) is one of the world's earliest carbonate platform successions. The Transvaal Supergroup rocks were intruded by the ~2060Ma Bushveld Complex. In most areas Transvaal Supergroup strata dip towards the Bushveld lithologies.

Carbonate rocks are found in the basal Black Reef Formation and the Chuniespoort Group; the Black Reef Formation (approximately 30m thick) consists predominantly of quartz arenites with lesser conglomerates and subordinate mudrocks. A basal conglomerate is succeeded by thicker sandstones and thin shale with a gradual transition from carbonaceous shale to carbonate, the whole forming an upward- fining sequence (Eriksson *et al., in* Johnson *et al.,* 2006). Arising from a weathering product from the carbonate, wad is also encountered in the Black Reef Formation (Brink, 1979).

The Chuniespoort Group overlies the Black Reef Formation and comprises the Malmani Subgroup, followed by the Penge Formation which in turn is unconformably overlain by the Duitschland Formation (Eriksson *et al., in* Johnson *et al.,* 2006) (Figure 4). The Malmani Subgroup is dated between ~2600 - 2500 Ma and is of particular concern in this study as it contains the dolomite formations that are vulnerable to sinkhole and subsidence formation.

According to Button, Eriksson and Truswell, (Eriksson *et al., in* Johnson *et al.,* 2006), the Malmani Subgroup in the Transvaal basin is up to 2 000 m thick and divided into five formations based on chert content, stromatolite morphology, intercalated shale and erosion surfaces.

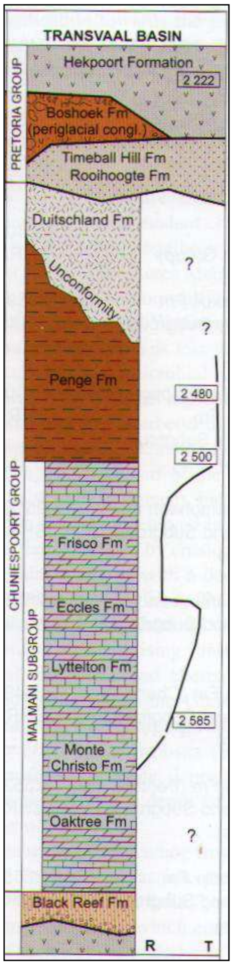
The Malmani Subgroup starts above the Black Reef Formation with the basal chert- poor Oaktree Formation. This Formation is transitional from siliciclastic sedimentation to platformal carbonates and consists of 10 m -200 m thick carbonaceous shales, stromatolitic dolomites and locally developed quartzites following Martini *et al*., 2006 (Eriksson *et al., in* Johnson *et al.,* 2006). The higher percentage (>1%) of manganese in the dolomites of the Oaktree Formation is responsible for the presence of large quantities of wad and manganocrete (Roux, 1984). The wad at the base of the Oaktree Formation is surprisingly stiff with an elastic modulus of 20 MPa and samples show no disintegration in water (Day, 1981).

The 300-500 m thick chert-rich Monte Christo Formation follows, beginning with an erosive breccia and continues with stromatolitic and oolitic platformal dolomites according to Tyler and Tyler (Eriksson *et al., in* Johnson *et al.,* 2006).

The Lyttelton Formation overlies the Monte Christo Formation, with 100-200 m of shales, quartzites and stromatolitic dolomites (Eriksson *et al.,* in Johnson *et al.,* 2006). The chert-poor Lyttelton Formation, like the Oaktree Formation, has a higher concentration of Fe and Mn (1.5%) which gives rise to wad formation (Roux, 1984).

The Lyttelton Formation is in turn overlain by the chert-rich dolomites of the Eccles Formation, which are up to 600 m thick, and includes a series of erosion breccias (Eriksson *et al.,* in

Johnson *et al.,* 2006). Weathering to a depth of 90 m is known to have occurred in the Eccles Formation (Roux, 1984).



An erosion breccia separates the Eccles from the overlying Frisco Formation (up to 400 m thick), comprising mainly stromatolitic dolomites according to Tyler and Tyler (Eriksson *et al., in* Johnson *et al.,* 2006). The Frisco Formation is not present in the study area.

The overlying banded iron formation of the Penge Formation and unconformably succeeding Duitschland Formation (approximately 700m thick, which consists of carbonaceous mudrocks, limestones and dolomites, with subordinate conglomerates, diamictites and lavas) are not present in the study area.

A number of breccias, consisting of mainly chert, are developed in the Malmani dolomites. Obbes (2000) refers to a chert breccia at the top of the Eccles Formation, called the Leeuwenkloof Member.

The Rooihoogte Formation (10-150m) at the base of the Pretoria Group overlies the Chuniespoort Group in the study area. A basal chert breccia is known as the Bevets member. Thick mudrocks and sandstones form the upper part of the Rooihoogte Formation (Eriksson *et al., in* Johnson *et al.,* 2006).

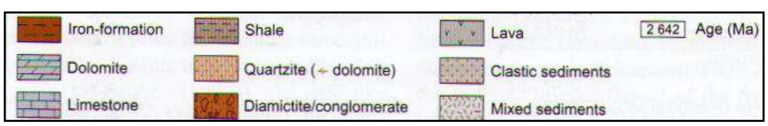


Figure 4: The Chuniespoort Group (*taken from Johnson et al., 2006*).

2.3 REGIONAL GEOHYDROLOGY

According to Martini (Martini, *in* Johnson *et al.,* 2006), the karst areas in South Africa have been extensively studied due to their relevance to groundwater resources and the artificial acceleration of sinkhole development in recent times. Many, groundwater compartments and sub compartments (approximately 43 in all) exist within the dolomite of the Chuniespoort Group within Gauteng.

Drawing from Davis (*in* Brink and Partridge, 1965), cave or cavity development occurs through the activity of the groundwater in two zones separated by the water table; the phreatic zone below the water table and the vadose zone above the water table. Water in the phreatic zone moves in non-turbulent laminar flow from areas of higher to lower hydrostatic pressure, and flow concentrated in the zone just below the water table. In dolomite rock the water table generally becomes flatter than in other areas, since there is an extensive network of interconnecting cavities. The water table may be considered as a surface of free standing water. Water movement in the vadose zone is controlled by relative permeability and capillary action and may be slow or free flowing.

2.3.1 Dewatering in the Far West Rand

Groundwater compartments divided by dykes exist in the dolomite. On the Far West Rand (area from Westonaria to Carletonville, within the West Rand District Municipality) the width of the generally north - south trending syenite dykes (Pilansberg age 1290±180 Ma) varies from about 6 m to 60 m (Kleywegt & Pike, 1982). These dykes form watertight compartments (bounded to the north by Archaean granite of the Hartebeesfontein anticline and by the dip of the Pretoria Group rocks in the south) where the groundwater tables were nearly horizontal and the level was controlled by a spring or "eye" at the point of intersection of the Wonderfontein stream with the western dyke of each individual compartment (Brink, 1979). Post-Transvaal faults and fractures have promoted leaching of the dolomite. Most of the groundwater is stored in the overburden and in the leached zones along the faults and fractures (Kleywegt and Pike, 1982).

According to Brink (1979), dewatering starts when the quantity of water pumped from the underground exceeds the natural rate of replenishment. Brink and Partridge (1965) note that one of the most important factors in the formation of sinkholes and subsidences, is that the frequency of the occurrence is closely related to the lowering of the water table in the compartment concerned. Roux (1984) indicates that a water table that undergoes less than 3m of seasonal variation does not create a risk, but there should be no possibility that a water table can be drawn down by more than 6m, or else instability may arise.

Several of the groundwater compartments in the dolomite formations on the Far West Rand were dewatered from the late 1950's -70's to allow mining operations on the gold bearing reefs which underlie the dolomite to continue safely (Bezuidenhout & Enslin, 1969). The areas affected by dewatering on the Far West Rand fall within the West Witwatersrand Goldfield and are restricted to approximately 770 km^2 in the valley of the Wonderfonteinspruit, which includes mines and the towns of Carletonville, Westonaria and Venterspost (Brink 1979). As a result of dewatering by the mines in the compartments, the water table has been locally drawn down into cones of depression (Figure 5) at the pumping points and the springs have ceased to flow (Jennings *et al*., 1965). Groundwater levels dropped from about 100m below surface to more than 550m in July 1966 (Foose 1967).

The first compartment to be dewatered was the Venterspost Groundwater Compartment commencing in 1935/6, followed by the Oberholzer compartment in the early 1960's. Dewatering of the Bank Compartment began in 1960's (Brink, 1979). The dewatering of these compartments was followed by accelerated sinkhole and subsidence formation on the Far West Rand. The water table is the baseline for subsurface erosion. Lowering of the water table results in a new baseline within a short period of time and the drained overburden and cavernous bedrock cannot reach a state of natural equilibrium without the occurrence of significant instability (Partridge *et al.*, 1981). The dewatered compartments are shown on Figure 6.

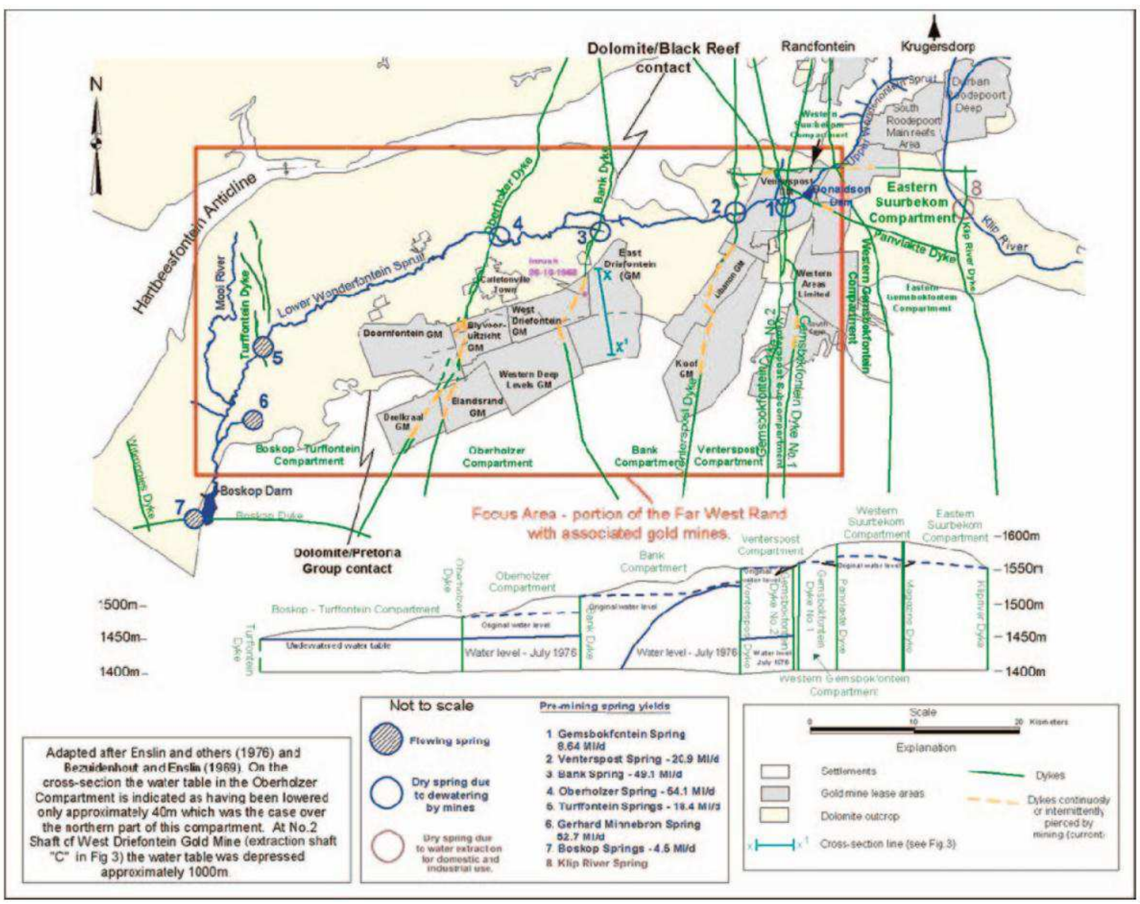


Figure 5: Groundwater section along the Wonderfonteinspruit on the Far West Rand (*taken from Swart et al., 2003*).

2.3.2 Dewatering in Ekurhuleni

More recently (from 1999) dewatering has occurred due to agricultural abstraction in Ekurhuleni in the Bapsfontein Groundwater Compartment (Wagener, 2008) and the adjacent Elandsfontein Groundwater Compartment has experienced several occurrences recently (Figure 6).

2.4 WEATHERING OF DOLOMITE

Dolomite is a carbonate mineral, common in ancient platform carbonates. Dolomite, the rock, contains a large proportion of dolomite the mineral. The mineral dolomite has a crystal lattice consisting of alternating Ca and Mg, separated by layers of carbonate (CO_3) and is typically represented by a stoichiometric chemical composition of $CaMg(CO_3)_2$ where calcium and magnesium are present in equal proportions (Warren, 2000).

The dolomite rock which occurs in the Transvaal Supergroup comprises of a series of alternating bands of insoluble chert and dolomite. Small amounts of iron and manganese carbonates are also commonly present (Brink and Partridge, 1965).

Dolomite rock possesses a system of discontinuities (fractures, joints and faults), which act as preferential solution passages. Although dolomite rock is relatively impervious (porosity less than 0.3%) and insoluble in pure water, rainwater which has become charged with carbon dioxide in its passage through the atmosphere and the soil flows along these discontinuity passages and slowly acts to dissolve this rock type (Brink, 1979). The process may be represented as follows;

$$CaMg\ (CO_3)_2 + 2\ H_2CO_3 \rightarrow Ca\ (HCO_3)_2 + Mg\ (HCO_3)_2$$

Above the water table (vadose zone), solution results in the widening of joins and fractures into grykes or slots. These slots may continue to below the water table (phreatic zone) where the flow of CO_2 charged water results in the development of a network of cavities or caverns. Eventually steep valleys are corroded within the shear zones of faults, with dolomite rock standing as pinnacles (Plate 1). Some of the subsurface valleys become very deep (up to 200m) (Brink, 1981). The hard rock dolomite is usually followed by an upward succession of residual products (weathered dolomite, wad, chert and residual chert) that is overlain by younger formations or is intruded (Brink, 1979).

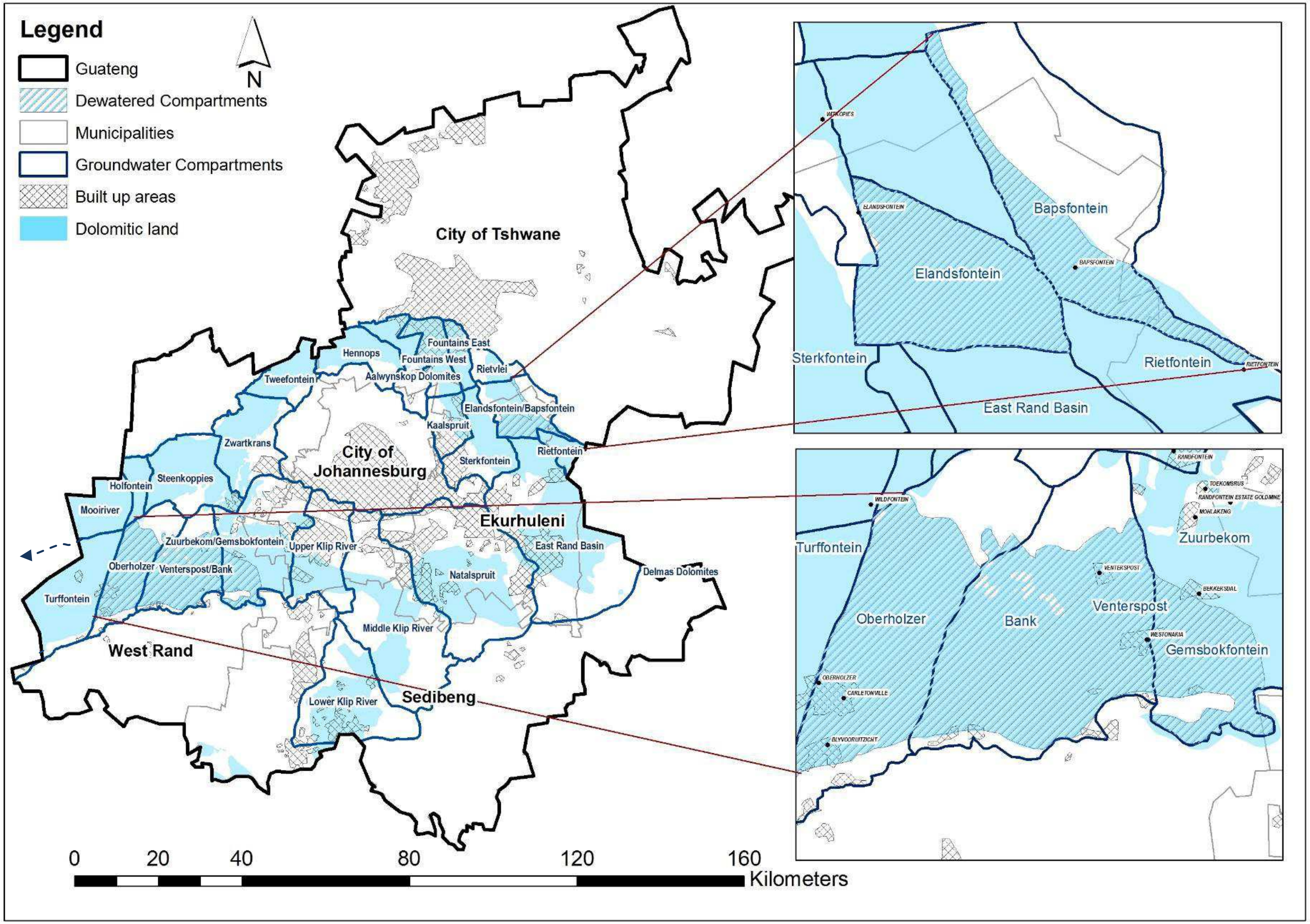


Figure 6. Regional Geohydrology (Groundwater Compartments from Department of Water Affairs)

The residual mantle can be extremely irregular (Martini *in* Johnson *et al.*, 2006). A residual product such as wad has, in most cases, low strength and is highly compressible and may be tens of meters thick. The vertical succession of these residual products therefore normally reflects an increase in compressibility with depth. Voids may also be present in the wad (De Bruyn and Bell, 2001). A typical profile is show in Figure 7**.**

The thickness and type of overburden is an important characteristic to consider when analyzing the stability of an area, whether it is dewatered or not. The properties of the residual dolomite (wad) especially, as it's such an erodible and compressible material. Areas with outcrop and relatively shallow dolomite (<15 m depth) can be subject to sinkhole formation if small grykes are present. Where deep weathering occurs over large areas, subsidences form when the water table is lowered or a leaking service causes saturation (Roux, 1984).

Plate 1. A small scale example of pinnacled bedrock.

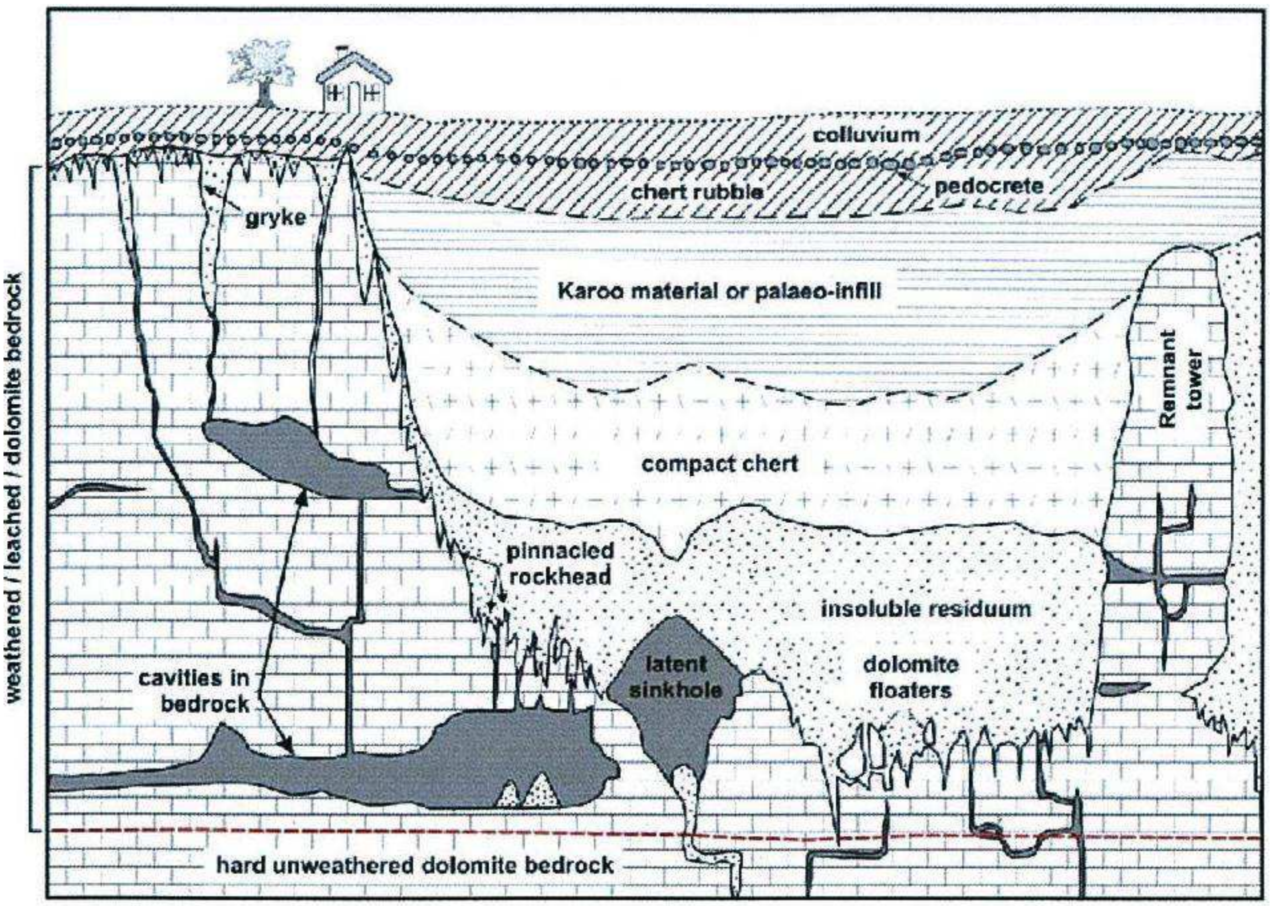


Figure 7. Conceptual diagram of a typical dolomite profile, as historically seen in South Africa (*taken from Trollip, 2006).*

2.5 MECHANISM OF SINKHOLE AND SUBSIDENCE FORMATION

Jennings *et al.,* (1965) describes ground subsidence in dolomitic formations as taking place in one of two ways: as a gradual or caving *subsidence* or a rapid and catastrophic subsidence defined as a *sinkhole*. Sinkholes and subsidences in Gauteng are due to either concentrated ingress of water or dewatering. Further Jennings *et al*., (1965), states "*the frequency and severity of the problem is much increased in areas where the water table is lowered*" and both types of ground subsidence (sinkholes and subsidences) "*are serious economically, but sinkholes are also dangerous because of the possible consequences to life*".

2.5.1 Formation of sinkholes

2.5.1.1 Ingress scenario

Sinkholes occur by the collapse of an arch or dome which spans an air filled void according to Jennings *et al.*, (1965).

- Cavities exist in the bedrock or overburden, which may be in a state of equilibrium.
- Concentrated ingress water from leaking service (Plate 2) or poorly managed surface water will result in active subsurface erosion, transporting materials downwards through slots into the cavity.
- An arch forms in the residual material above the cavity and headward erosion results in successive arch collapses until the surface is breached and a sinkhole manifests. (Figure 8) (Council for Geoscience /South African Institute of Engineering and Environmental Geologist (CGS/SAIEG), 2003).

In cross section the sinkhole may look like a bottle neck. Small sinkholes may retain this shape for a considerable period of time. Larger sinkholes tend to rapidly develop concentric tension cracks in the soil around the collapse crown and further collapse takes place within a short period of time. In most cases sinkholes are circular in plan (Brink, 1979).

In more detail, Jennings *et al.,* (1965) prescribed five concurrent conditions that must exist for sinkhole formation:

1. There has to be adjacent rigid matter to form abutments of an arched roof. These abutments are provided by dolomite pinnacles or the sides of a steep sided subsurface canyon. The span has to be appropriate to the strength of the bridging material, since with a span which is too large or with a material which is too weak, the arch cannot form.
2. A condition of arching has to develop in the residuum, i.e. all of the vertically acting forces due to self-weight have to be carried by arching thrusts to the abutments.
3. A void must develop in the residuum below the arch. This void can be quite small.
4. A reservoir has to exist below the arch to accept the material removed in the enlarging void. Some means of transportation, such as flowing water is also essential.
5. When a void of appropriate size has been established in the residuum, some disturbing agency has to arise to cause the roof to collapse. The void will move progressively upwards towards the surface.

Buttrick (1985) notes that; *"the factors listed by Jennings et al., (1965) are but a few of many conditions potentially contributing to sinkhole formation*". The nature of the material between the abutments as well as the overlying material will also contribute to the susceptibility to sinkhole formation.

Plate 2. Leaking pipeline in Alaric Road, Valhalla (1996). (Photo from CGS archives, referenced by Waltham et al., 2005 as taken by/from F. Bell).

2.5.1.2 Dewatering Scenario

The water table represents the base level of subsurface erosion; therefore the lowering of the water table initiates an accelerated cycle of subsurface erosion which results in sinkholes and subsidences (Brink 1996). Sinkholes due to dewatering on the Far West Rand have reached diameters of 125 m and 50 m in depth (Brink, 1979). The general process follows (Council for Geoscience /South African Institute of Engineering and Environmental Geologist, 2003):

- Cavities exist within bedrock or the overburden, which may be in a state of equilibrium. The cavities are occupied by groundwater.
- Lowering of the water table leads to the exposure of poor residual material (wad) and these cavities.
- The equilibrium is disturbed and the corrosive effect of groundwater percolating along joint and fracture planes, serve to weaken (removing buoyant support) the overlying material (Jennings *et al.*, 1965, Wagener, 1985)
- Headward erosion finally results in collapse (Figure 8).

Buttrick (1987) suggests sinkholes in dewatered areas may also be associated with the process of liquefaction, as the low density, highly compressible weathering product (wad), has the potential to liquefy given externally induced dynamic loading.

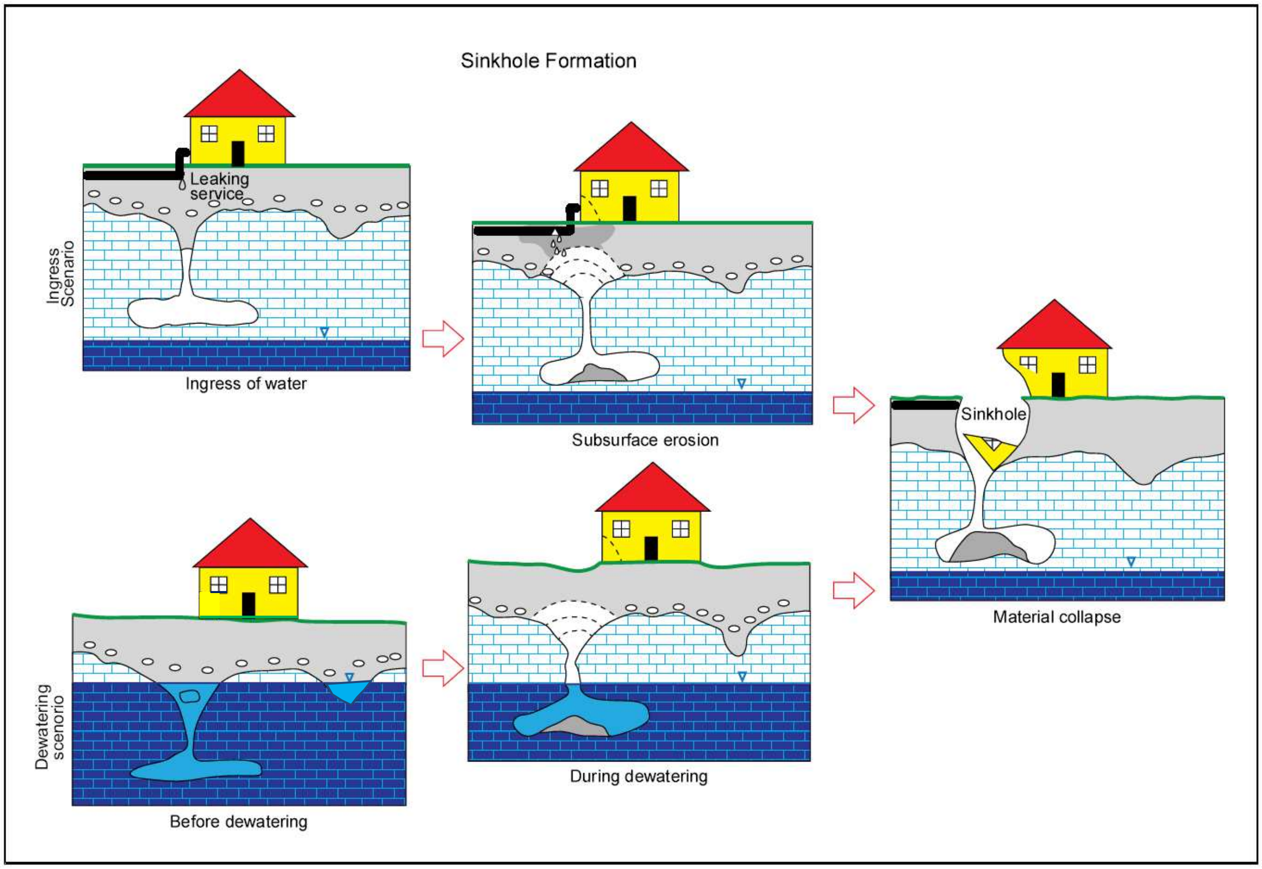


Figure 8: Diagram depicting the mechanism of sinkhole formation in ingress and dewatering scenarios (Drawn by B. Oosthuizen, CGS).

Some examples of sinkholes that have occurred due to ingress and dewatering over the years in Gauteng are shown in Plates 3 - 18.

Plate 3: Sinkhole in Finus Road, Valhalla, Tshwane (1973) due to a leaking service (*Photo from CGS achieves*).

Plate 4: Sinkhole on Cantonments Road, Lyttelton, Tshwane (1995), due to a leaking service (*Photo from CGS archives*).

Plate 5. A house in Centurion (military area) destroyed by a sinkhole (1995). (*Photo from CGS archives, referenced by Waltham et al., 2005 as by/from F. Bell*).

Plate 6: Sinkhole on Waterkloof Airforce Base, Tshwane (1996), due to poor surface drainage. (*Photo from CGS achieves*).

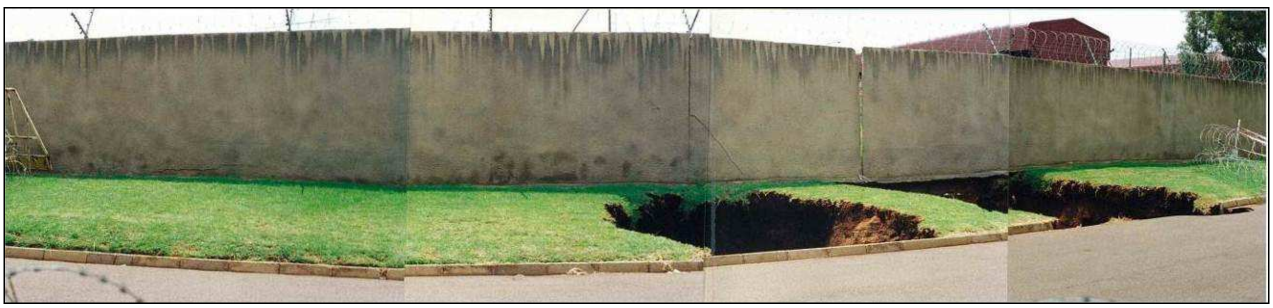


Plate 7: Sinkholes outside boundary wall of Waterkloof Airforce Base, Tshwane (1996), due to poor surface drainage (stormwater damming up behind wall). (*Photo from CGS achieves*).

Plate 8a & b (view towards house): Sinkhole at house in Centurion, due to a leaking service (*Photos from CGS archives, referenced by Waltham et al., 2005 as taken by/from F. Bell*).

Plate 9: Sinkhole at house in Cornwall Hill (2006). Due to a leaking swimming pool (*Photo by A.C. Oosthuizen, CGS*).

Plate 10: Sinkhole In Laudium (2007), due to a leaking service. *(Photo by A.C. Oosthuizen, CGS).*

Plate 11: Sinkhole in Valhalla, Tshwane (2008), Due to a leaking service. *(Photo by S Richardson).*

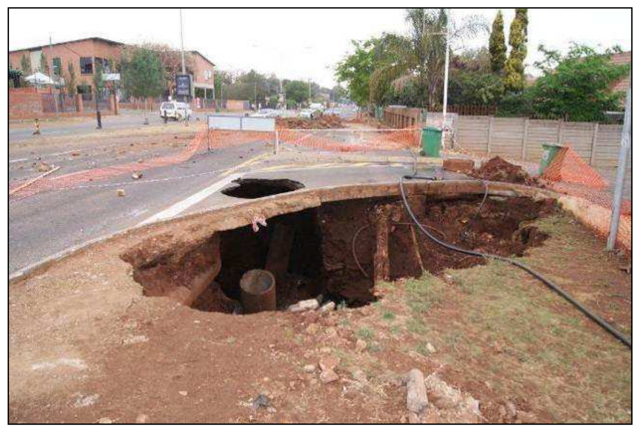


Plate 12. Sinkhole in Jean Avenue (2011), due to a leaking service. (*Photo by I.J.Breytenbach,SoilKraft*).

Plate 13. Sinkhole on Venterspost Golf Course, West Rand (1960's) approximately 50m deep, as a result of dewatering. *(Photo from CGS achieves).*

Plate 14. Sinkhole on Venterspost-Westonaria Road, West Rand (1960's) as a result of dewatering (*Photo from Oberholzer Ground Stability Group).*

Plate 15. Sinkhole in Bapsfontein, Ekurhuleni (2004), as a result of dewatering. *(Photo by A.C. Oosthuizen, CGS).*

Plate 16. Sinkhole in Elandsfontein, Ekurhuleni (2007) as a result of dewatering *(Photo by G.J Heath, CGS)*

Plate 17. Sinkhole near Carletonville, West Rand (2010), due to a leaking and overflowing canal. *(Photo by S.Richardson)*

Plate 18. Sinkhole just south of Venterspost Town, West Rand (2011), approximately 9m diameter and 69 m deep. *(Photo by S.Richardson)*

2.5.2 Formation of subsidences

2.5.2.1 Ingress scenario

Subsidences occur gradually and while extremely damaging to buildings, there is time to give warning (Brink and Partridge, 1965). The general process follows (Council for Geoscience /South African Institute of Engineering and Environmental Geologist, 2003):

- The corroded valleys in the dolomite surface, as discussed previously contain weathering products such as chert residuum and wad (which is highly compressible).

- When the water table is within or below this highly compressible material and the materials above become saturated owing to concentrated ingress.
- A surface depression occurs gradually due to the increased load of the overlying materials on the deeper, lower - density materials, which settle into a denser state.
- This type of subsidence is caused by *saturation.* (Figure 9).

2.5.2.2 Dewatering scenario

Lowering of the water table can also cause a subsidence to form.

- The deeply weathered zones within the dolomite are filled with highly compressible material.
- A *dewatering* subsidence forms when the progressive draw down of the groundwater level (which may be within or above the highly compressible material) results in the exposure of the highly compressible material resulting in loss of hydrostatic support and consequent compaction (Jennings, 1965; CGS/SAIEG, 2003).
- The settlement manifests as a depression at the surface (Figure 9).

The amount of settlement will depend on the compression index (Cc) of the consolidating material, and the rate of settlement on its coefficient of consolidation (Cr). Wad has a mean Cc greater than 1 and a mean Cr greater than 300 mm^2/minute. If there is a substantial thickness of wad below the water table, the extent of settlement may be extensive (Jennings, 1966). The most famous example is Schuttes depression on the West Rand (Plate 28).

Some examples of subsidences that have occurred due to ingress and dewatering in Gauteng, are shown in Plates 19- 26.

2.5.3 Partly developed sinkholes

A partly developed sinkhole occurs when the cavity in the subsurface is not large enough to accommodate the material which migrates downwards and it becomes choked. In such a situation the surface expression may be in the form of a subsidence (De Bruyn and Bell, 2001).

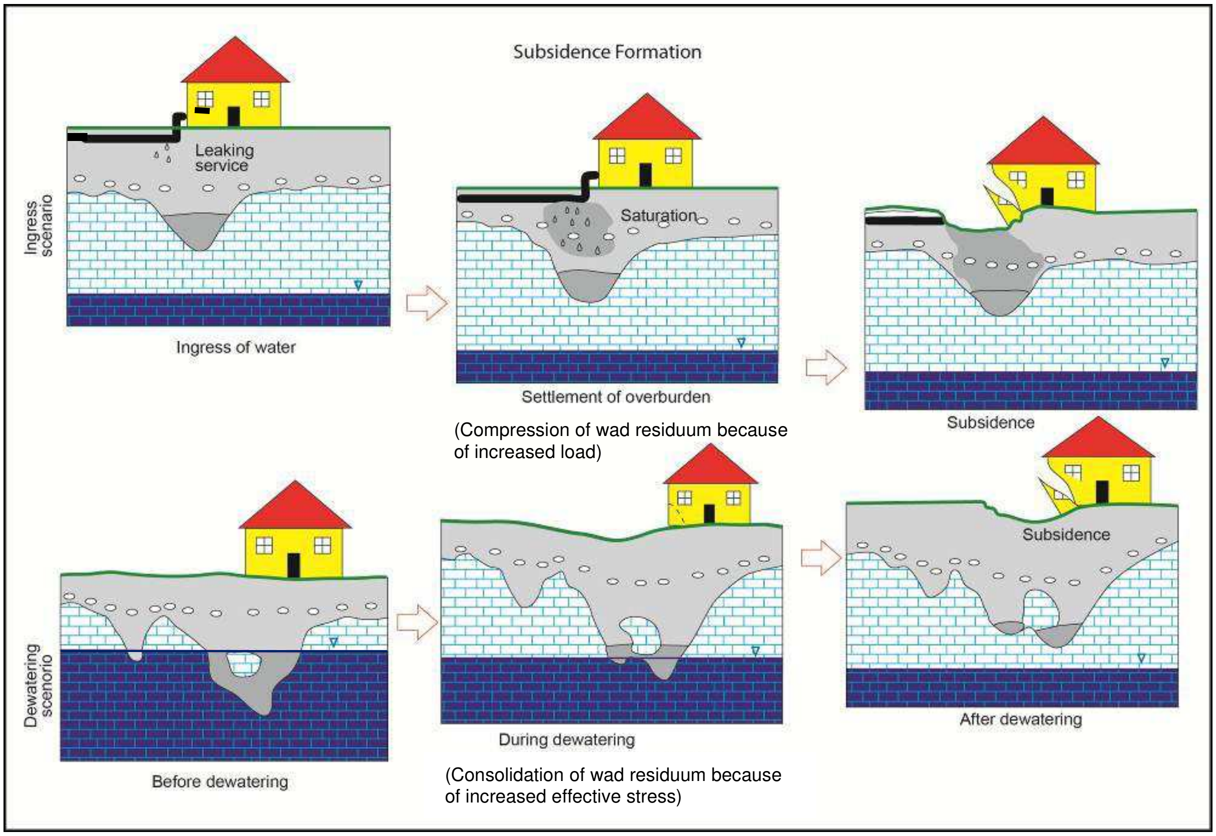


Figure 9. Diagram depicting the mechanism of subsidence formation in ingress and dewatering Scenarios (Drawn by B. Oosthuizen, CGS).

Plate 19: Subsidence in Laudium, Tshwane (1996), due to a leaking service (*Photo from CGS achieves*)

Plate 20: Subsidence at Irene Research Institute, Tshwane (1990's), due to a leaking service (*Photo from CGS archives*).

Plate 21. Subsidence in Lyttelton, Tshwane (2008), due to a leaking service (*Photo by A.C.Oosthuizen, CGS).*

Plate 22.Subsidence in Irene, Tshwane (2009), due to a leaking service (*Photo by A. C. Oosthuizen, CGS*)

Plate 23.Subsidence in Irene, Tshwane (2010), due to a leaking service (*Photo from CGS archives*).

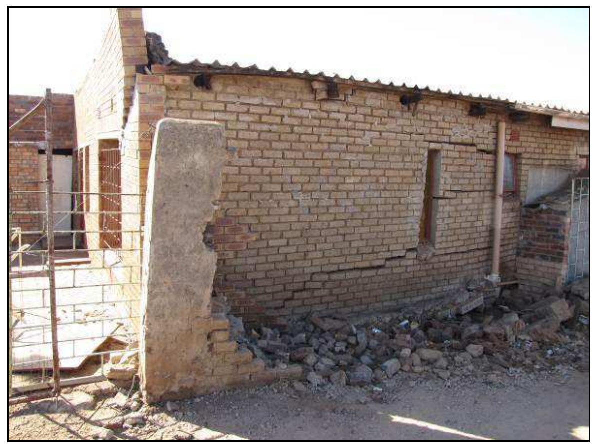


Plate 24. Subsidence in Khutsong, West Rand (2011), due to a leaking service (*Photo by S Richardson*).

Plate 25. Subsidence in Bapsfontein, Ekurhuleni (2004), due to dewatering (*Photo taken from Wagener, 2008*).

Plate 26. Dewatering subsidence, Elandsfontein, Ekurhuleni (2009), due to dewatering (*Photo by G.J. Heath, CGS*).

2.6 SINKHOLES AND SUBSIDENCES IN GAUTENG PROVINCE

Numerous papers have been published and abundant research exists on the subject of sinkholes and investigation techniques on dolomite in South Africa, and particularly Gauteng in which the bulk of the incidents have been reported. Historically the Far West Rand (area from Westonaria to Carletonville) has been the focus of many studies due to the frequent occurrence of sinkholes and subsidences in the 1960's and 1970's as a result of dewatering of several of the groundwater compartments. The area south of Pretoria (City of Tshwane) has also seen scores of sinkholes in recent history, while relatively few events have been reported in Ekurhuleni and City of Johannesburg. The following sub-sections will review previous work in the karst study areas within Gauteng

2.6.1Brief history of studies undertaken and significant events

2.6.1.1 Far West Rand

The gold reefs on the Far West Rand lie below the dolomite formations. According to Wolmarans (1984), the first attempt to sink a shaft through the dolomite was in 1912, but flooding problems were encountered as a result the first mine was only opened in June 1934 (Venterspost Mine). Production in the mines started between 1939 (Venterspost Mine) to 1974 (Elandsrand and Deelkraal Mines) and by 1982 accounted for a third of gold production in South Africa. Westonaria and Carletonville naturally became important residential nodes housing over 250 000 people on dolomite areas (Wolmarans, 1984).

Following Bezuidenhout and Enslin (1969), when mining started, no ground subsidence was apparent and the area was considered safe to develop. As a result, much of the surface structures of the mines were built on dolomite. As dewatering progressed instability started to occur more rapidly and certain areas were evacuated.

According to Brink and Partridge (1965) the Wonderfontein valley experienced some ancient occurrences of sinkholes and subsidences (post Ecca and Tertiary periods), prior to the more recent accelerated development. These were evident from surface mapping and drilling by the mines. They further note that these ancient occurrences are significantly fewer, than those which have occurred since 1958 due to dewatering. Further Partridge *et al.*, (1981), states that prior to 1960, events on the Far West Rand were very rare but increased dramatically to approximately 50 events per annum in the early 1960's. As mentioned previously, several groundwater compartments were dewatered (Figure 5 & 6) resulting in the differential subsidence of large areas and the formation of sinkholes (Bezuidenhout and Enslin, 1969).

From Brink (1979), it is gathered that the Oberholzer Compartment was the first to experience a catastrophic sinkhole. In 1962 a 55 m diameter and 30 m deep sinkhole swallowed a three storey mine crusher plant resulting in the deaths of 29 men (Plate 27). The following year Schuttes depression (180 m diameter and 8 m deep) appeared near Carletonville (Plate 28), and a large subsidence developed at Lupin Place spanning 20 houses. In August 1964 a house with a family of five was engulfed by a 55m diameter, 30m deep sinkhole (Plate 29), and in the same year a 21 m diameter sinkhole fell in a suburb of Westonaria (Plate 30). By February 1966, eight very large sinkholes (>45 m diameter and 30 m deep) had occurred (Foose, 1967). The largest sinkhole (125 m diameter and 50 m deep) appeared in a field in Carletonville Extension 8 in Feb 1966. Brink (1979) notes that by 1966, at least 122 additional, smaller sinkholes had fallen on the Far West Rand, but the frequency of sinkhole development decreased after 1966 until dewatering commenced in the Bank Compartment towards the end of 1969. The next death due to a sinkhole occurred in October 1970, when a sinkhole fell under a tennis court at Venterspost recreational center, destroying part of the club house and engulfing one spectator (Plate 31) (Brink 1979). The next year a sinkhole (9 m diameter and 26 m deep) appeared in the bowling greens at Venterspost recreation center 60 m from the tennis courts. In April 1975 a sinkhole 20 m wide and 7 m deep formed under the railway line near Bank town (Plate 32). Three coaches derailed and two passenger coaches were left suspended (Brink 1979).

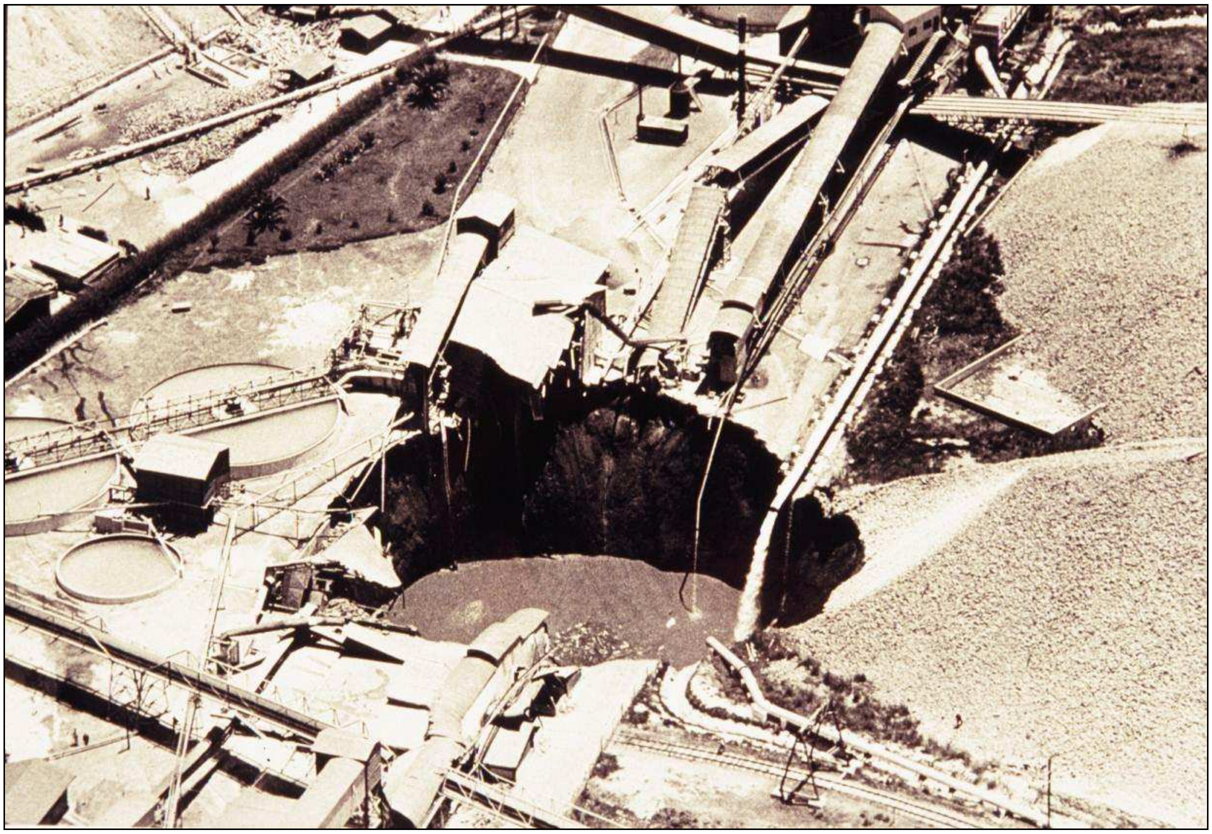
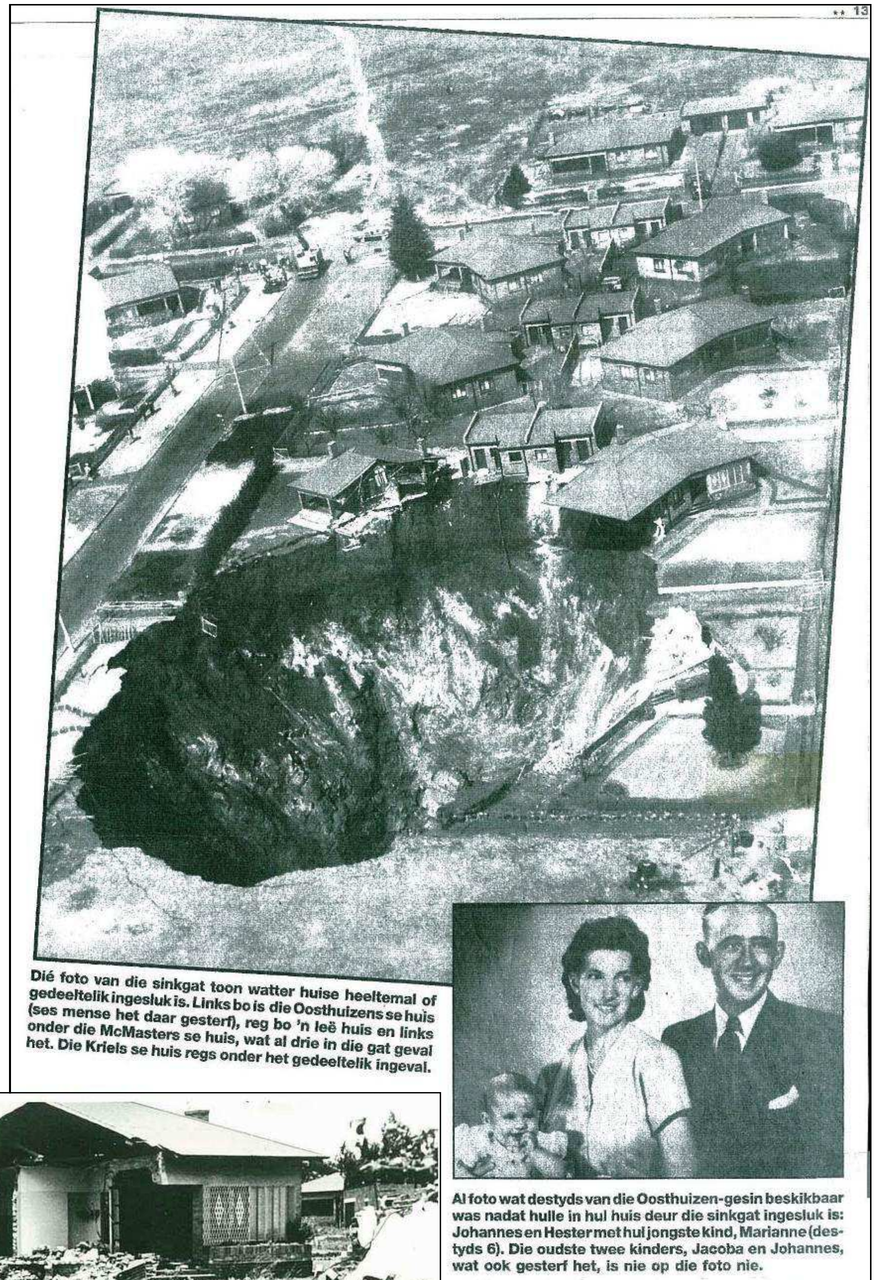


Plate 27. Very large sinkhole (55 m diameter and 30 m deep) that swallowed a 3 storey mine crusher plant and 29 men at West-Driefontein mine on 12 December 1962 (*CGS archives, also shown in Brink, 1979).*

Plate 28. Schulte's depression (180 m diameter and 8 m deep), Carletonville (*taken from Brink, 1979*).


13

Dié foto van die sinkgat toon watter huise heeltemal of gedeeltelik ingesluk is. Links bo is die Oosthuizens se huis (ses mense het daar gesterf), reg bo 'n leë huis en links onder die McMasters se huis, wat al drie in die gat geval het. Die Kriels se huis regs onder het gedeeltelik ingeval.

Al foto wat destyds van die Oosthuizen-gesin beskikbaar was nadat hulle in hul huis deur die sinkgat ingesluk is: Johannes en Hester met hul jongste kind, Marianne (destyds 6). Die oudste twee kinders, Jacoba en Johannes, wat ook gesterf het, is nie op die foto nie.

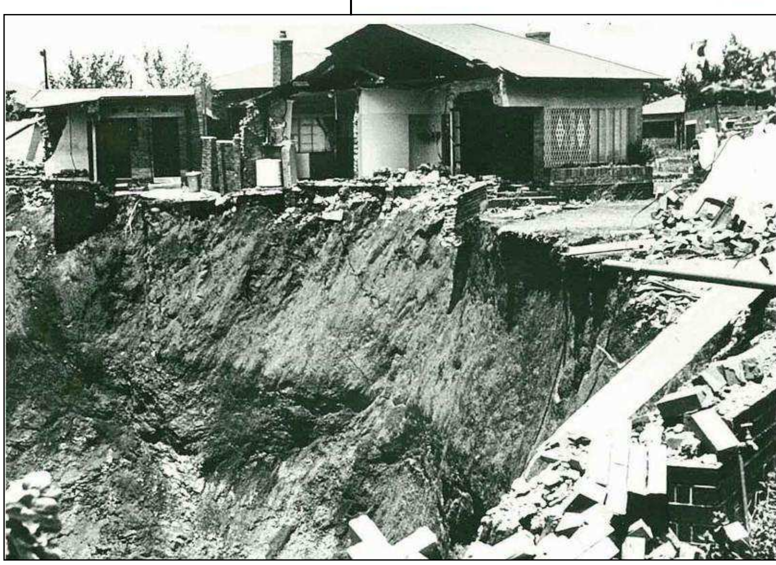


Plate 29. Blyvooruitzicht sinkhole (55m diameter, 30m deep), that resulted in the death of 5 people on 3 August 1964 (*Picture top right from Die Beeld Newspaper, bottom left from CGS files*).

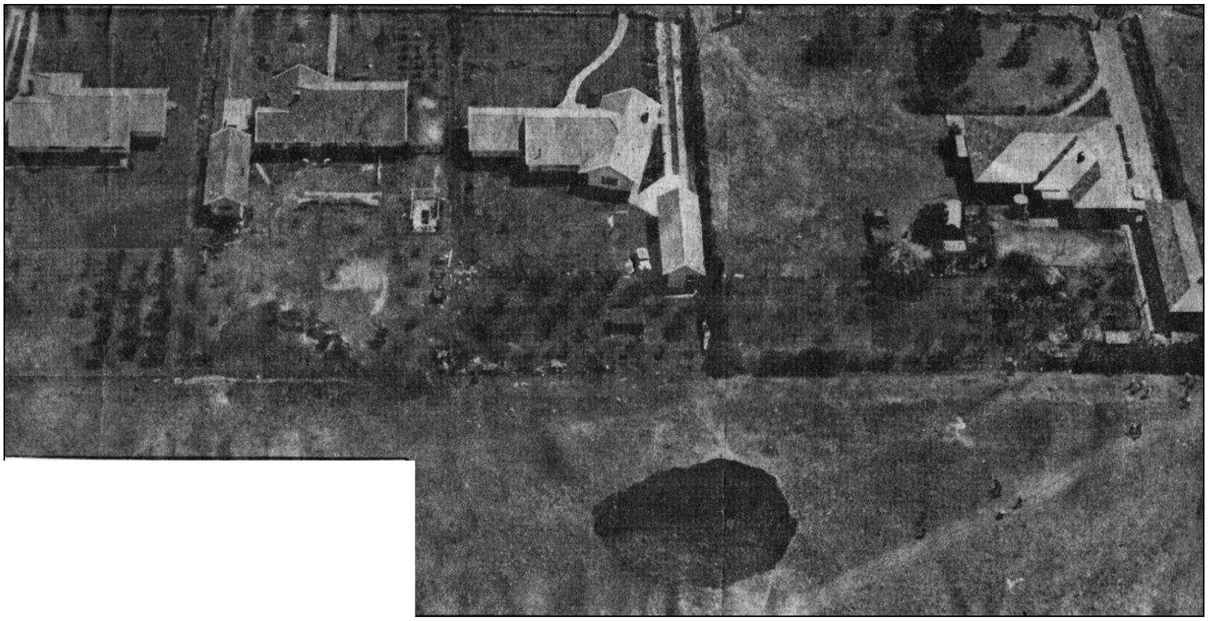


Plate 30. 1964 Westonaria sinkhole which occurred close to residences (*Picture scanned from unknown newspaper*).

Plate 31. A sinkhole at Venterspost recreational center that swallowed part of the club house and one spectator on 24 October 1970 (*Picture from CGS files*).

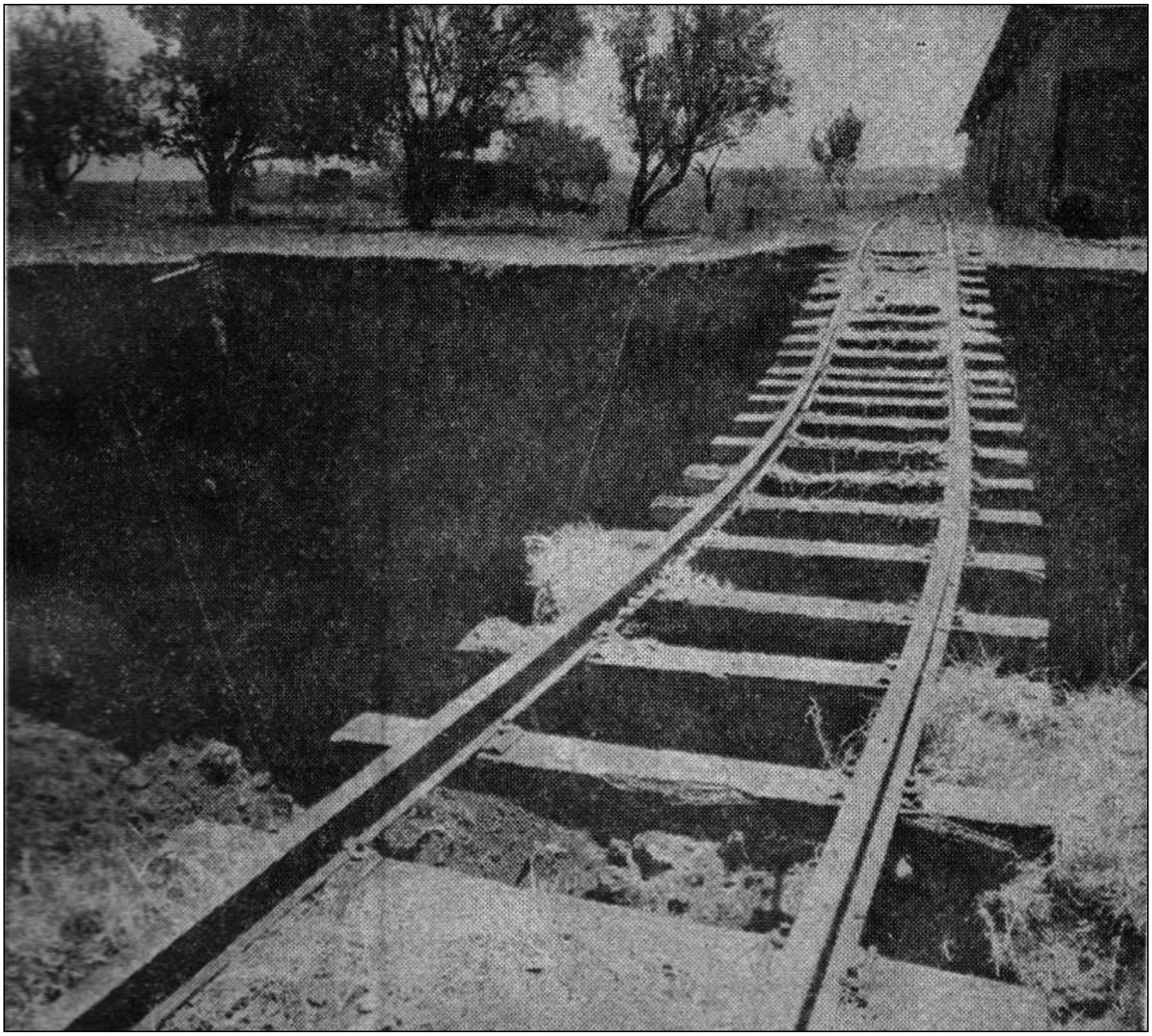


Plate 32. Bank sinkhole (20 m wide and 7 m deep) which formed under the railway line in 1975 (*Picture scanned from unknown newspaper*).

Wolmarans (1984) undertook a study on the dewatering of the dolomite area on the Far West Rand. The study area was approximately 40 km along the Wonderfonteinspruit from Westonaria in the east to Carletonville in the west. By 1984 there were 12 Gold Mines operating in the area south of Carletonville, namely; Venterspost Mine, Libanon Mine, Kloof Mine, Western Area Mine and Cooke Mine (around Westonaria) and Doornfontein Mine, Deelkraal Mine, Elandsrand Mine, Blyvooruitzcht Mine, Western Deep Levels Mine, Wes-Driefontein Mine and East Driefontein Mine. Randfontein Estate Mine was to the north of the study area, east of Randfontein (Figure 5).

Wolmarans (1984) suggests before the start of dewatering in 1957, at least 102 sinkholes and subsidences had occurred on the Far West Rand due to supersaturation, especially on slimes dams (Table 1). Wolmarans updated his data in 1996, to include events in Khutsong, which lies on shallow dolomite in the Turffontein compartment (not dewatered), and had reported more than 40 events after blasting and trenching during service upgrades in 1985. This concurs with Buttrick and Roux (1993), who reported in excess of 44 sinkholes in Khutsong after water bourne sewerage systems were installed in the late 1980's.

Table 1. Sinkholes before the start of dewatering (*after Wolmarans, 1984 & 1996*).

COMPARTMENT	NUMBER OF SINKHOLES (1984 study)	NUMBER OF SINKHOLES (1996 paper)
Turffontein (not dewatered)	76	117
Oberholzer (dewatering-early 1960's)	26	26
Bank (dewatering- June 1969)	0	0
Venterspost (dewatering- 1935)	0	1
Total	**102**	**144**

De Beer (1987) notes that 95 ground movement events (sinkholes, subsidences, cave entrances or palaeo-sinkholes) had been recorded on the Blyvooruitzicht property; 42 events are known to have occurred prior to dewatering and 53 events after dewatering. Out of the total, 45 were associated with slimes dams.

Venterspost Mine experienced serious problems with groundwater, and by September 1955 was pumping out amounts of groundwater that exceeded natural replenishment. The original groundwater level in the Venterspost Compartment was 1540,8 m a.m.s.l, but by the end of 1958 it had been drawn down by 20 m - 30 m and by the late 1960's it was down between 80 m - 100 m (Heath *et al*, 2008[2]). Many very large sinkholes occurred during this period (Figure 10).

Portions of Venterspost Town were abandoned. A sinkhole on the West Rand Garden Estates in the Venterspost Compartment in 1957 measured a diameter of 100 m with a depth of 40 m deep (Plate 33). The groundwater table did show a rise in the 1970's due to very wet periods, accompanied by noticeable increase in sinkhole and subsidence formation in some areas (Heath *et al*., 2008[2]).

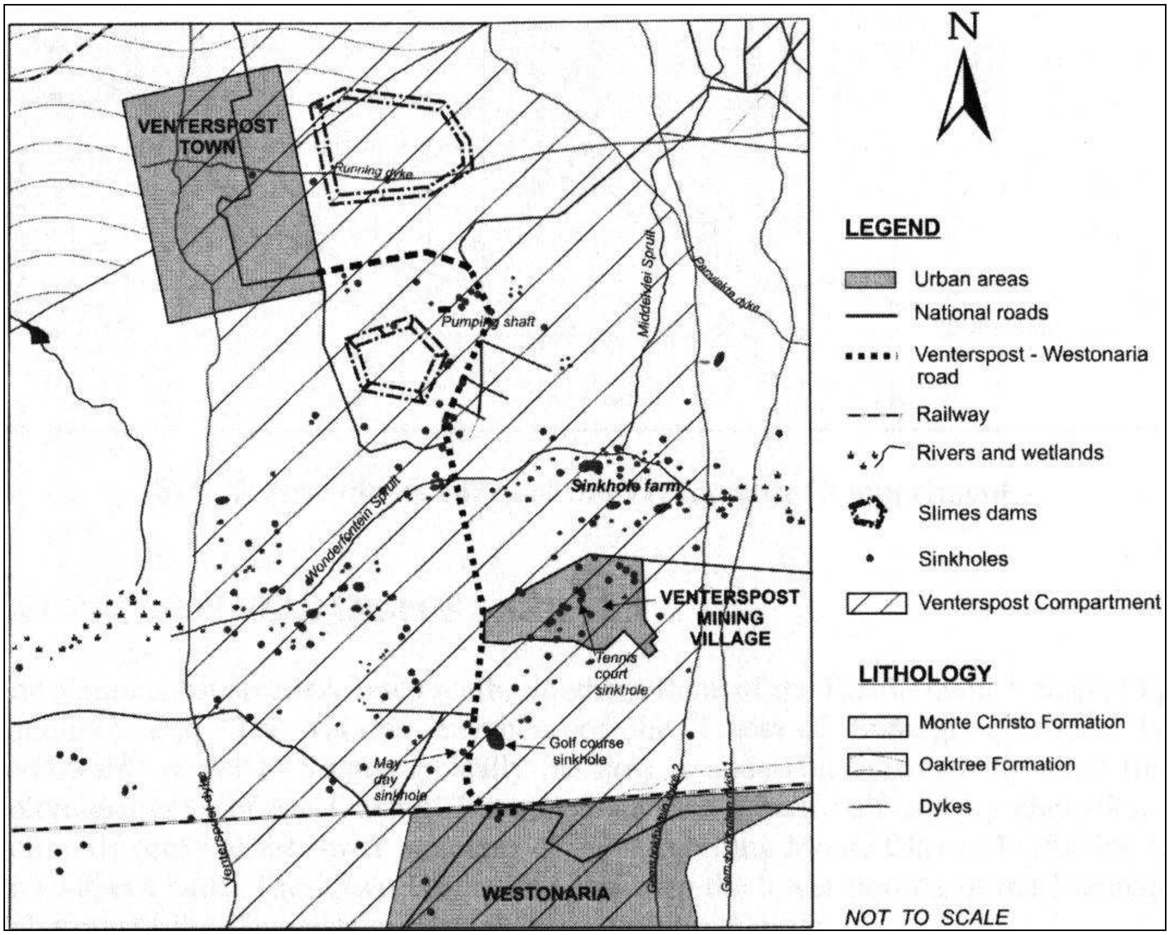


Figure 10. Sinkholes that occurred in the Venterspost Groundwater Compartment (*taken from Heath et al, 2008*[2]).

Small sinkholes occurred between 1954 and 1958 and a very large sinkhole (80 m diameter, 20m deep) occurred on 4 December 1958, 700 m west of the Gemsbokfontein eye. Signs of subsidence due to dewatering occurred in 1960 around Shaft no. 2 of the Wes-Driefontein mine and shortly after in Carletonville. In February 1966 a sinkhole measuring 125 m diameter and 50 m deep appeared in an open field in Carletonville Extension 8 (Brink 1979). Widespread sinkhole and subsidence formation (Plate 33 & Figure 11) lead to the abandonment of Bank Town; residents were vacated by January 1970 (Waltham *et al.,* 2005 and Brink 1979).

Up until 1984, a total of 691 events (589 after the start of dewatering) had been recorded in the Venterspost, Bank and Oberholzer Compartments (Wolmarans, 1984), although not all events were as a result of dewatering (Table 2 and Figure 11). According to De Bruyn and Trollip (2000), several hundred buildings were demolished in the Venterspost, Bank and Oberholzer compartments between 1960 and 1976 as a result of dewatering.

Plate 33. A house that was destroyed by a sinkhole in the abandoned Bank Town (*taken from Waltham et al 2005, photo by Wal Gamble*).

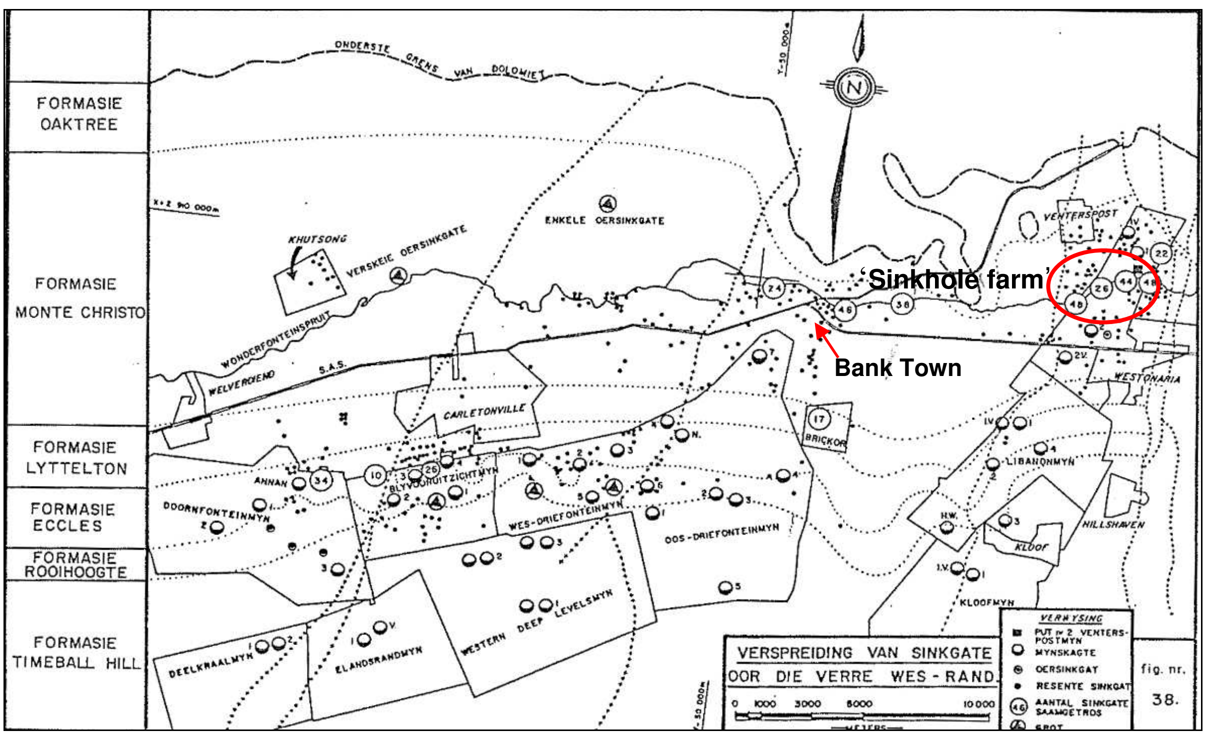


Figure 11**.** Sinkholes prior to 1984 on the Far West Rand (*taken from Wolmarans, 1984*).

Table 2. Number of sinkholes after dewatering on the Far West Rand prior to 1984 (after *Wolmarans, 1984).*

COMPARTMENTS	SINKHOLES DUE TO DEWATERING	SINKHOLES DUE TO INGRESS	TOTAL
Venterspost	262	2	**264**
Oberholzer	75	42	**117**
Bank	186	22	**208**
Total	**523**	**66**	**589**

The southern side of the Wonderfonteinspruit became known as the "sinkhole farm" (Figure 11 & Plate 34), since 166 sinkholes had occurred in a 4, 5 km^2 area. Sinkholes are not shown in such numbers around the spruit in the non-dewatered Compartment (i.e. Turffontein in the west). Sinkholes south of the spruit are more numerous than north of it (Wolmarans, 1984). Brink (1979) also noted that the vast majority of the sinkholes formed in the pediment and the flood-plain of the Wonderfonteinspruit, where the effect of the lowering of the water table has been substantial.

Gold Fields on behalf of the mines responsible for dewatering have historically kept a comprehensive record of all sinkholes in the dewatered areas. This record, since 1984, does not incorporate Wolmarans's earlier work. In Heath and Oosthuizen (2008), the number of events that had occurred on the Far West Rand prior to end of 2008 was estimated at 1200.

Plate 34. Picture of the 'sinkhole farm' (*Photo by I.S Venter, 1982*).

2.6.1.2 Area South of Pretoria- Tshwane

A subsidence due to compressible wad occurred in 1938 at the south abutment of the Fountains Viaduct in Pretoria. Later, in 1953, a swimming pool at Waterkloof Airforce base was drained as a result of a sinkhole and an ablution block at Swartkops Airforce base tilted, due to a sinkhole caused by a leaking pipe (Jennings, 1965).

The only deaths recorded in Tshwane were in 1970 when three men died while stabilizing a sinkhole caused by a leaking service (Brink 1979). The representative from the Municipality on site later reported that the sidewall of the excavation caved in and buried them (Pers comm IS Venter).

For a study, Roux (1984) focused on geotechnical investigation for township development on dolomite, sent out 10 000 questionnaires requesting information about sinkholes and subsidences in the then Verwoerdburg Municipality, now City of Tshwane. In total 2880 replies were received and were used to prepare a map of all known sinkholes and subsidences in the area south of Pretoria. This map cannot be located in the CGS archives. From this questionnaire, indications are that most subsidence movements had occurred in Doringkloof, Irene and Lyttelton, which are on the Monte Christo Formation. Lyttelton Township had the most sinkholes (30) in the 14 years prior to 1984, while Irene had three and Doringkloof had only one. Stands in Irene were over 4000 m^2, which was double that in Lyttelton (Roux, 1984). Roux (1984) further stated that the frequency of sinkholes and subsidence formation drastically lessens with the implementation of precautionary (preventative) measures.

According to Roux (1984) the first geological map produced for the Pretoria area by Hall in 1905 already indicated positions of sinkholes. Later after township development, sinkholes were frequently investigated by the Council for Geoscience (formerly the Geological Survey of South Africa). Roux estimates damages prior to 1984 to be over a million Rand and at that time at least 50 military buildings had been damaged or demolished due to sinkholes and subsidences.

Roux (1984) makes note of cases where swimming pools have caused sinkholes and subsidences, when they develop cracks and leak. Three olympic size swimming pools in military areas, a high school swimming pool and at least two private swimming pools had been damaged prior to 1984 in the area south of Pretoria. Further, french drains also caused sinkholes in the area south of Pretoria in the past (Roux, 1984). Roux also indicates that leaking services is one of the most important factors leading to sinkhole and subsidence development.

Roux's data were later compiled by Schőning (1990), to complete his study on the distribution and statistical analysis of sinkholes and subsidences in the dolomite area south of Pretoria.

Buttrick and Roux (1993) included a comparison of the number of sinkholes occurring in some township areas south of Pretoria with stand sizes, and Table 3 below gives an indication of the number of sinkholes that had occurred in four townships.

Table 3. Sinkholes in four townships south of Pretoria (*after Buttrick and Roux, 1993*).

TOWN	**NUMBER OF SINKHOLES**
Lyttelton	30
Irene	4
Erasmia	8
Valhalla	70

A report produced by VGIconsult (1999) estimates that in excess of 280 sinkholes and subsidences had occurred on the Waterkloof Airforce Base alone prior to 1999. In excess of 30 buildings were demolished on this base and many others suffered structural damage and were evacuated

De Bruyn and Trollip (2000) and De Bruyn *et al* (2000) note that more than 430 events were recorded prior to 1997 in the area south of Pretoria. Later, Trollip (2006), in a study of an area east of Irene, indicated that in excess of 800 sinkholes had occurred in southern Tshwane alone.

Buttrick *et al*. (2011), using sinkhole occurrence from 1984 to 2004 in selected areas of mixed land use (i.e. residential, commercial and industrial), south of Pretoria, indicates the number of events as 650, as a result of leaking services, poor storm water management, ponding water etc.

Venter (2008), in a paper based on Lyttelton Agricultural Holdings submits that the only way to achieve proper planning and development on dolomite is to analyse instability data and goes on to list 35 instability events having occurred from 1982 to 2008, with half occurring near municipal servitudes and the other on residential or commercial stands.

In Heath and Oosthuizen (2008), the number of sinkholes that had occurred in the area south of Pretoria prior to 2008 was estimated at 1100 events.

2.6.1.3 Ekurhuleni

De Bruyn and Trollip (2000) make note of a study of the Katorus area by Heath and Keyter, (1996), on the East Rand. Approximately 25 sinkholes and more than 50 subsidences had developed in the previous years. From Heath and Oosthuizen, (2008); 19 dolomite instability incidents were reported having occurred in Katlehong and surrounding areas and 29 events in the Vosloorus and Tokoza areas. Further, the CGS extracted 72 events from various consulting reports available in its databank. The total number of events recorded in the Katorus area is estimated by Heath & Oosthuizen, (2008) to be 120.

A total of 27 events are noted by Wagener (2008) in the Bapsfontein area of Ekurhuleni, with the CGS having recorded a further four (Heath & Oosthuizen, 2008).

Other events had been recorded near Olifantsfontein and Thembisa (4), Daveyton (2), Springs (1) and Kwa-Themba (1) (Heath and Oosthuizen, 2008).

2.6.1.4 Sinkholes in other karst areas in Gauteng

Literature for the central and southern Gauteng is non-existent/scarce. Very few occurrences were noted by and could be obtained from officials of the City of Johannesburg. No information could be obtained from Sedibeng Municipality and this Municipality is excluded from any further discussion.

2.6.1.5 Summary of record of events and deaths

The sinkhole and subsidence numbers and deaths reported in literature are summarized as follows in Table 4 & 5:

Table 4. Summary of sinkhole and subsidence numbers reported in literature.

Area	Time period	Literature source	Number of sinkholes and subsidences	Number each formation	Number in each compartment	Number of deaths
West Rand: Westonaria-Carletonville-Khutsong	Prior to dewatering (1957)	Wolmarans (1984)	102	Eccles: 135 Lyttelton: 32 Monte C: 483 Oaktree: 6 Other: 35	Turffontein: 117 Oberholtzer:26 Bank: 0 Venterspost:1	
	After dewatering prior to 1984	Wolmarans (1984)	589		Oberholtzer:117 Bank: 208 Venterspost:264	36
	1957-2008	Heath & Oosthuizen (2008)	1200			
Tswhane: Area south of Pretoria.	Prior 1984	Roux (1984)	Sent out questionnaires (at least 119 events on residential stands)			3
	Prior 1990	Schőning (1990)	375	Eccles: 201 Lyttelton: 47 Monte C: 118 Oaktree: 0 Other: 9		
	Prior 1997	De Bruyn & Trollip (2000)	>430			
	Prior 2004	Buttrick *et al* (2011)	650 *(Study areas only)*			
	Prior 2008	Heath & Oosthuizen (2008)	1100			
Ekurhuleni/East Rand:	Prior 2000	De Bruyn & Trollip (2000)	75			
	Prior to 2008	Heath & Oosthuizen (2008)	138			

Table 5. Summary of deaths due to sinkholes, as reported in literature.

Date	Location	Compartment	Deaths	% Deaths	Sinkhole Dimensions	Depth
12 December 1962	West Driefontein mine crusher plant	Oberholzer	29	74.4	55m (Brink, 1970)	30m
3 August 1964	Blyvooruitzig mining village	Oberholzer	5	12.8	55m (Brink, 1970)	30m
24 October 1970	Venterspost recreation club	Bank	1	2.6	>5m (Buttrick and Roux, 1993)	
30 April 1970	Suburb in Verwoedburg (Centurion)		3	7.6	5m (Buttrick and Roux, 1993)	
29 July 1980	Carletonville	Oberholzer	1	2.6	<5m (Buttrick and Roux, 1993)	
		Total	39	100		

2.6.2 Development of knowledge

The compilation of event data and significant events were discussed briefly in the previous subsection, this subsection will deal with the use of the event data in analysis and to develop understanding, systems and classifications.

2.6.2.1 Groundwater and Dewatering

In a study of the Bank Compartment, Kleywegt and Enslin (1973) proposed that where the original water table was approximately 30 m below surface, sinkhole formation began on a large scale once the water table had been lowered by 6 m. By the time it had been lowered by 10 m, 34 sinkholes were generated in this compartment. They further indicate that where the original water level was shallower than 30 m (<30m) and then lowered, 81 sinkholes occurred. Kleywegt and Enslin (1973) concluded that 83% of all sinkholes that formed within 18 months of the start of dewatering, formed in areas where the water table was less than ≤30 m below ground level, but there was still a noteworthy amount of sinkholes that occurred where the original water level was between 30 m and 60 m deep. Further where the original water level was deeper than 60 m, very few but very large sinkholes fell. In a dewatered area Kleywegt and Enslin (1973) suggests that important factors are the depth from the surface to the original groundwater level, the thickness and nature of the overburden overlying the dolomite bedrock and its relationship with the original groundwater level and the lowered groundwater level. Kleywegt and Enslin (1973) found that most of the sinkholes occurred in the period from 1957 to 1961.

Kleywegt and Enslin (1973), explain that subsidences tended to occur where the original water level was above or within the residual compressible material. The amount of subsidence which takes place tends to reflect the thickness and proportion of unconsolidated deposits which have consolidated.

According to Jones and Wagener, (2005), instability events in the Bapsfontein area had drastically increased in the 10 years prior, due to the artificial lowering of the groundwater level (120 m) by pumping for irrigation.

2.6.2.2 Stratigraphy

Wolmarans (1984) discussed the influence of stratigraphy in the formation of sinkholes and subsidences in the Far West Rand, as shown in Table 6 below.

Table 6. Sinkholes on geological formations on the Far West Rand (*after Wolmarans, 1984*).

COMPARTMENT	TIMEBALLHILL	ROOIHOOGTE	ECCLES	LYTTELTON	MONTE CHRISTO	OAKTREE	TOTAL
Venterspost	0	0	2	2	260	0	**76**
Bank	0	7	5	19	171	6	**264**
Oberholzer	11	12	74	3	43	0	**208**
Turffotein	1	4	54	8	9	0	**117**
Total	**12**	**23**	**135**	**32**	**483**	**6**	**691**

Wolmarans (1996) later updated the number of occurrences on the Monte Christo to 524 and suggested that the high chert content of the Eccles (>10%) Formation and Monte Christo (0-10%) Formation promotes differential leaching with associated cavity formation. Comparatively low incidence of occurrence is recorded after the start of dewatering in the Oaktree and Lyttelton Formations, which is ascribed to the absence of chert by Wolmarans, (1996).

Karoo outliers on the Far West Rand also have a history of sinkhole formation. Roux (1987) discusses the point that it was previously thought that a uniform thickness of 20 m or more would provide acceptable stability, however in the case of Davies Street in Westonaria (4 April 1967), he points out that a sinkhole (3 m diameter and 29 m deep) fell through thick (no less than 20 to 30m) Karoo sediments (albeit in a paleosinkhole), after heavy rain (150 mm) had fallen. The sinkhole was filled in with mine-slimes and formed again in 1974.

Following Beck and Sinclair (1986), the formation of sinkholes is a product of the underlying geology, and sinkholes are generally limited to areas where the dolomite is within a few tens of meters of the surface. When discussing geological formations, Roux (1984) states that at the time no known sinkholes or subsidences had occurred on the chert - poor Oaktree Formation, even though large quantities of wad are often present. This is attributed, by Roux (1984), to a combination of; the stabilizing effects of the shallow dip (between 5° and 8°), the ferricrete formation, the intercalated shale and the concordant intrusions which occur in this formation. Roux (1984) puts forward that most of the town areas south of Pretoria have been developed on the chert- rich Monte Christo Formation, with shallow intrusives occurring in this formation which cover large areas and offer a stabilizing influence, with the chert in this formation being responsible for cave formation. The chert-poor Lyttelton Formation like the Oaktree Formation has higher concentration of Fe and Mn which gives rise to wad. According to Roux (1984), many natural and man-made sinkholes are known to have occurred on the chert-rich Eccles Formation and small sinkholes (~ 3 m) are known to occur in sediments of Karoo outliers.

Roux's (1984) suggested that when investigating an area for development the stratigraphic position can already give an indication of the likelihood of sinkhole or subsidence formation and an indication of the size. Roux (1984) made the following observations:

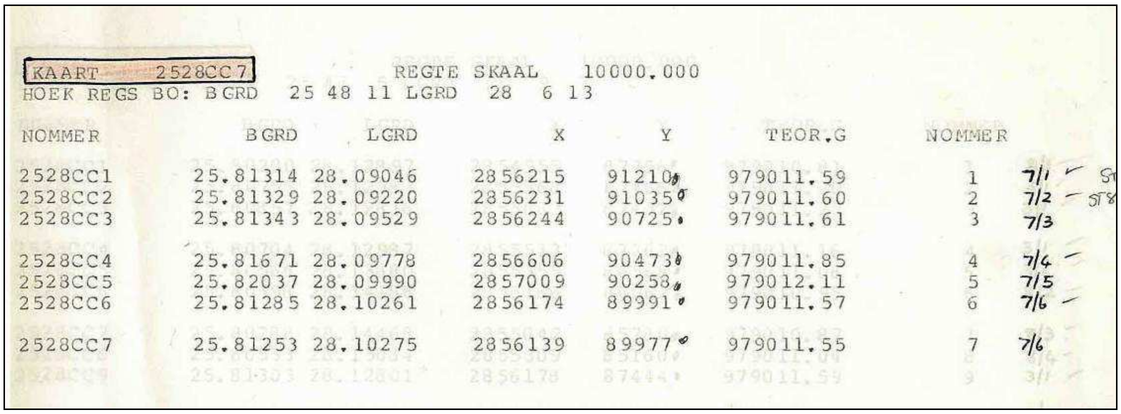
- Oaktree Formation: no known natural or man-made sinkholes
- Monte Christo Formation: sinkholes and subsidences up to 30 m diameter.
- Lyttelton Formation: small sinkholes average diameter of 3 m.
- Eccles Formation many large sinkholes, the maximum known diameter is 100 m with a depth of 20 m.

Roux (1996), later noted that very few sinkholes are known in the Oaktree Formation and sinkholes of all sizes occur in the Eccles and Monte Christo Formations.

Schőning (1990) states that, "*generally it is assumed that the various Formations in the Chuniespoort Group have different geotechnical behaviour patterns. Chert-rich formations are regarded as more susceptible to the formation of events since they allow for differential weathering which creates receptacles*". Schőning determined the number of sinkholes and subsidences that had occurred on the different dolomite formations, as shown in Table 7. The different formations have different chert contents and chert-rich formations (i.e. Eccles & Monte Christo) were regarded as more susceptible to sinkhole and subsidence formation. However, no preference, in terms of formations, could be determined according to Schőning (1996). Schőning did not include a locality plan indicating the exact positions, as this information was classified at that time, however typed sheets and index cards (Figures 12 & 13) were found and Figure 15 shows the distribution produced using original co-ordinate data compiled by Schőning (1990). The most events had occurred on the Eccles Formation and Schőning (1996) suggests that this could be due to the fact that urban development in Pretoria took place southwards, with the Eccles Formation being developed first and been subjected to longer periods of leaking services and poor storm water management.

Table 7. The occurrence of sinkholes and subsidences on the dolomite formations (*after Schőning, 1996*).

FORMATION	SINKHOLES	SUBSIDENCES
Eccles	130	71
Lyttelton	39	8
Monte Christo	94	24
Oaktree	0	0
Total	263	103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NOMMER	BGRD	LGRD	X	Y	TEOR.G	NOMMER	
2528CC1	25.81314	28.09046	2856215	91210	979011.59	1	7/1
2528CC2	25.81329	28.09220	2856231	91035	979011.60	2	7/2
2528CC3	25.81343	28.09529	2856244	90725	979011.61	3	7/3
2528CC4	25.81671	28.09778	2856606	90473	979011.85	4	7/4
2528CC5	25.82037	28.09990	2857009	90258	979012.11	5	7/5
2528CC6	25.81285	28.10261	2856174	89991	979011.57	6	7/6
2528CC7	25.81253	28.10275	2856139	89977	979011.55	7	7/6

Figure 12. Example of typed co-ordinates compiled by Schőning (1990), which relate to an index card by a number i.e. 7/4.

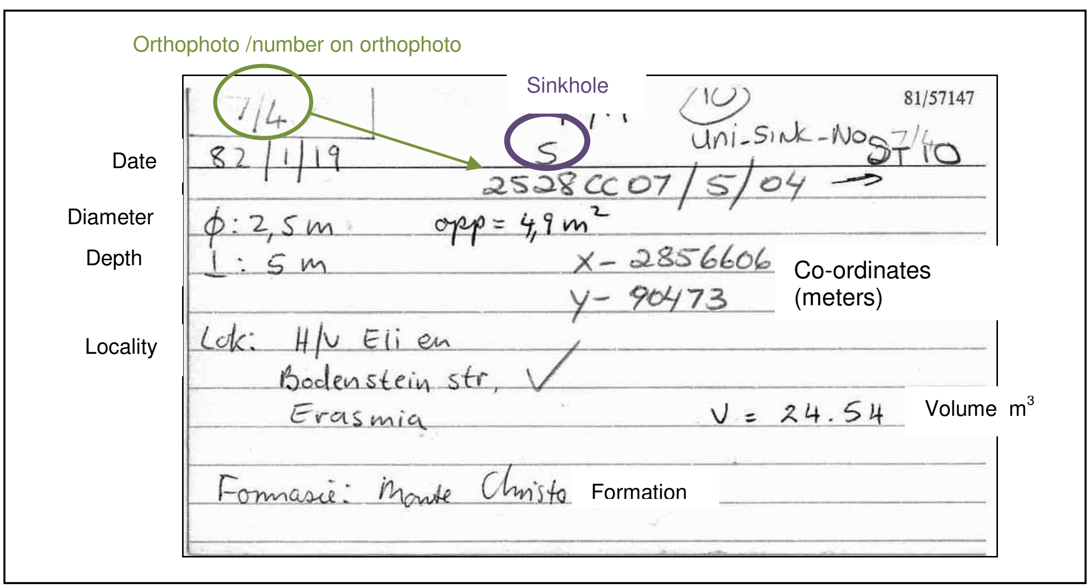

Figure 13. Example of an index card compiled from Schőning (1990) to capture sinkhole data.

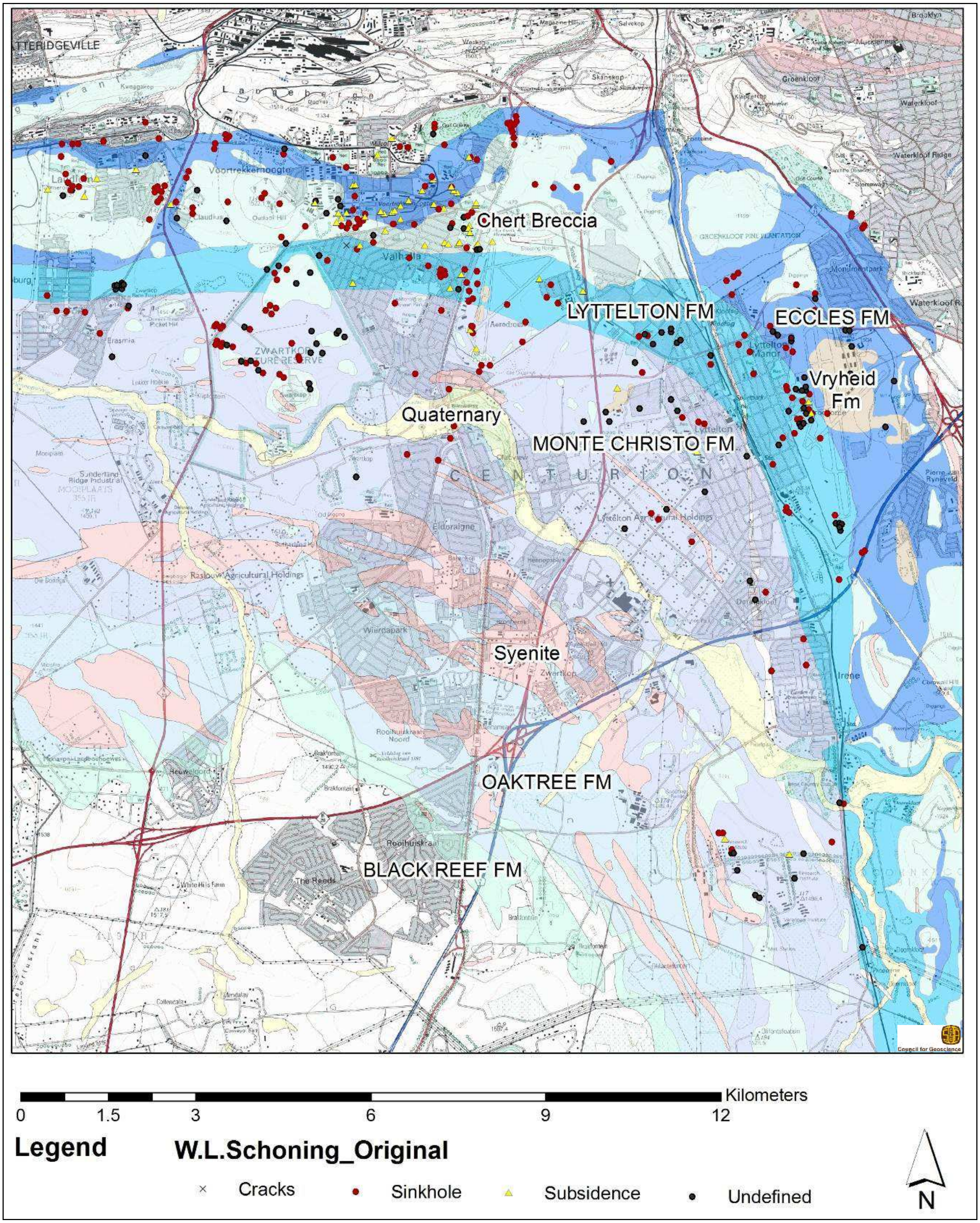

Figure 14. Sinkholes and subsidences prior to 1990 in the area south of Pretoria (map produced by S. Richardson using co-ordinate data compiled by Schőning, 1990) (Unpubl. Geology: Council for Geoscience).

Schőning (1996) also takes note of the fact that the formations have different surface areas. The Eccles Formation covers at least twice the area of the Lyttelton Formation, thus he suggests one could expect more occurrences on the Monte Christo Formation as it covers the largest surface area and some form of standardization is necessary.

In order to standardize the data Schőning assumes that "*the formations follow concordantly and the surface coverage is proportional to the thickness, and the number of recorded events is characteristic of the formation in terms of geotechnical characteristics, development type, age, density, degree of abuse".* Using the thickness of the Lyttelton Formation as a base, the formula used by Schőning to standardize the thickness, follows:

$$\frac{n}{tf} \times tf(L)$$

Where n= number of sinkholes

tf = Thickness of relevant geological formation

tf(L) = Thickness of Lyttelton Formation

Schőning's (1990) standardized values for the Eccles and Monte Christo formations are; 99 sinkholes and 28 Subsidences, and 177 sinkholes and 51 subsidences respectively. These are lower than actual values for the Eccles Formation (Table 7) and higher for the Monte Christo Formation. Schőning concludes that it could not be determined with certainty that the chert-rich formations are more prone to the formation of sinkholes or subsidences.

The 375 events recorded by Schőning (1990) were transferred to GIS and later 272 of these events were used by Honiball (1999). Honiball (1999) researched the relationship between surface features and subsidences in the dolomitic area south of Pretoria, which involved the interpretation and evaluation of events on specific land facets. Honiball (1999) concluded that "*most events occurred on the pediment land facet which is mainly confined to areas underlain by chert rich formations, however the occurrence of events on a specific land facet is independent of its occurrence on a specific geological formation and standardizing the sinkhole and subsidence data to the thickness of the Lyttelton Formation leads to the conclusion that events do not occur preferentially on the chert rich formations*".

2.6.2.3 Rainfall

External factors leading to sinkhole and subsidence formation include rainfall (Enslin, 1951). Beck and Sinclair (1986) concur, indicating that one of the immediate causes of sinkhole collapse may be periods of unusually heavy rain. As a result of flooding in 1978 in Pretoria, a large number of sinkholes and subsidences occurred in the residential township of Valhalla (Brink 1979).

Roux (1984) through regression analysis correlated the cumulative monthly rainfall (1971-1981) with sinkhole formation (Figure 15). He was of the opinion that the greatest percentages of sinkholes that form due to leaking services were initially associated with subsidence due to ingress rainwater. In military areas south of Pretoria many sinkholes had occurred as a result of ponding of stormwater and at least ten sinkholes occurred between 1970 and 1975 along roads that were not serviced by stormwater drains (Roux, 1984).

Schőning (1990) also noted that rainfall may have a linear relationship with occurrences, since more sinkholes were reported in the rainy season. Cumulative yearly rainfall data could not be correlated with cumulative sinkhole events; however, cumulative monthly rainfall vs. cumulative monthly sinkhole events showed a 60% (coefficient of determination[1] r^2= 0.5999) correlation, which indicates the formation of these events are influenced by seasonal variance in rainfall (Figure 16).

However only a 23% (coefficient of determination r^2= 0, 23319) correlation was shown for cumulative monthly rainfall vs. cumulative monthly subsidence events, Schőning proposes that the formation of subsidences is not directly related to cumulative rainfall, rather other factors such as leaking services. Schőning (1990) further observes that the majority of sinkholes (79%) had occurred when it rained more than 70 days per year (Figure 17).

[1] is the fraction of the variance in the two variables that is shared, it's a measure of goodness of fit i.e. It provides a measure of how well future outcomes are likely to be predicted by the model

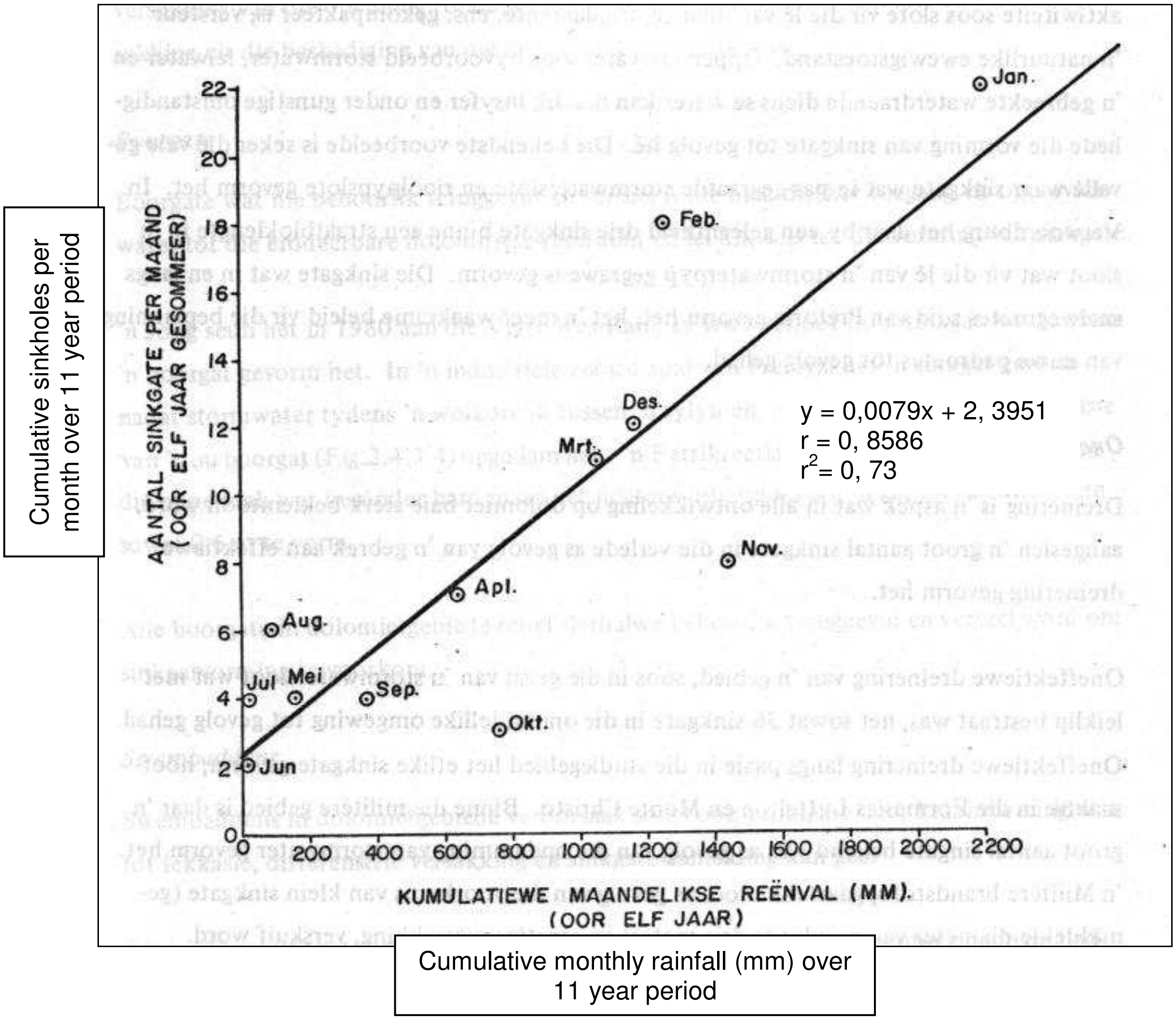

Figure 15. Regression analysis carried out by Roux 1984, cumulative monthly rainfall (1971-1981) vs. sinkhole formation

Oosthuizen (2010) also notes that the majority of sinkholes occurred during the high rainfall months, but mostly later in the rainy season i.e. January and February, concluding that "*it could be because the soil profile is completely saturated later in the rainy season".*

De Bruyn and Trollip (2000) and De Bruyn *et al* (2000) note that out of the 430 events recorded prior to 1997 in the area south of Pretoria, over 50 were associated with heavy rainfall in 1996.

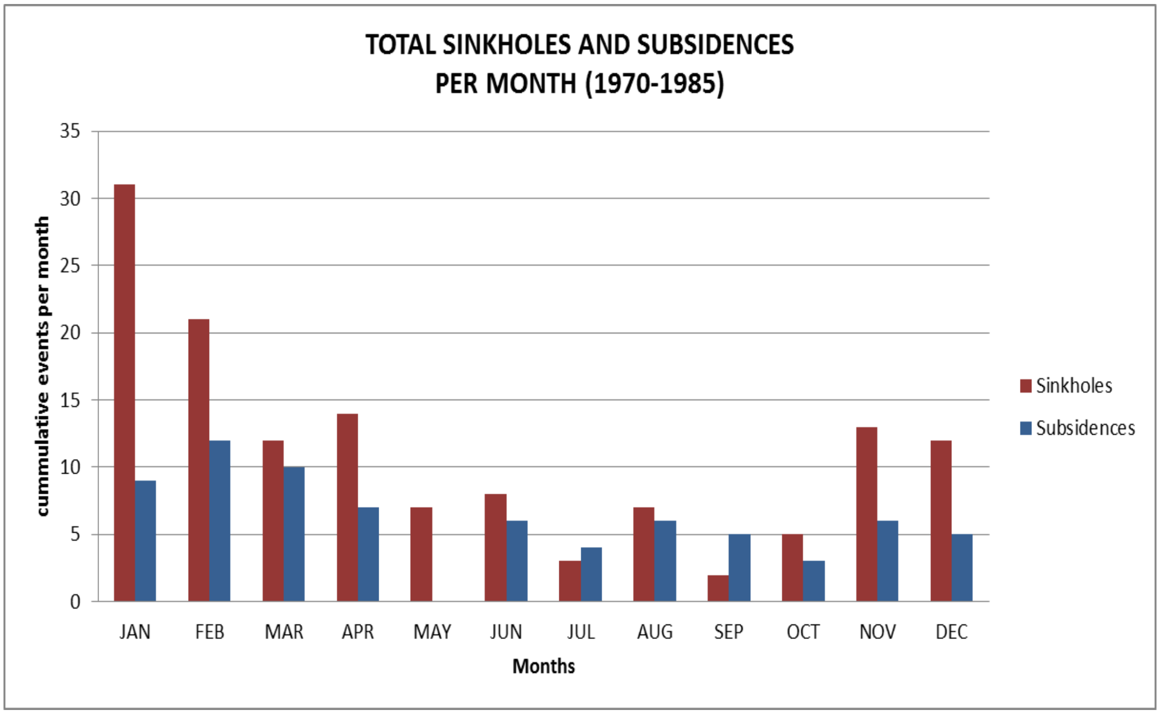

Figure 16. Graph showing cumulative sinkholes per month (*after Schőning, 1990*).

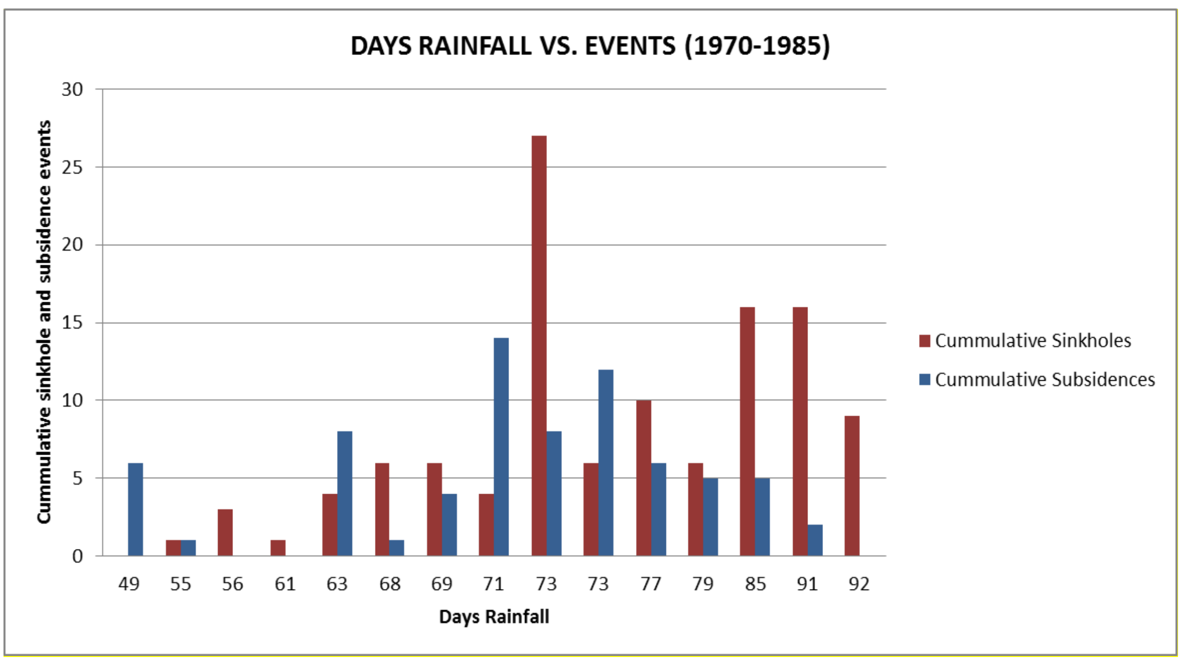

Figure 17. Graph showing cumulative sinkholes and subsidences vs. days of rainfall (*after Schőning, 1990).*

2.6.2.4 Size on the different formations

Schőning (1990) analyzed surface diameters and depths of sinkholes on the different formations (Table 8 & 9). The tables show that most sinkholes on all three of the analyzed formations had a diameter smaller than 2m. On the Eccles and Monte Christo Formations, most sinkholes had a depth of less than 1m, and on the Lyttelton Formation most had a depth less than 4m.

Table 8**.** Sinkhole diameters on the different formations (*after Schőning, 1990*)

	SINKHOLE DIAMETER					
FORMATION	**0-2m**	**2-4m**	**4-6m**	**6-8m**	**>10m**	**TOTAL**
ECCLES	42	26	12	10	36	**126**
LYTTELTON	11	8	5	2	4	**30**
MONTE CHRISTO	40	20	12	4	7	**83**
TOTAL (%)	93 (38.9)	54 (22.6)	29 (12.1)	16 (6.7)	47 (19.7)	**239**

Table 9. Sinkhole depths on the different formations (*after Schőning, 1990*)

	SINKHOLE DEPTHS						
FORMATION	**0-1m**	**1-2m**	**2-4m**	**4-6m**	**6-10m**	**>10m**	**TOTAL**
ECCLES	37	10	28	14	8	11	108
LYTTELTON	5	5	12	5	3	0	30
MONTE CHRISTO	31	19	18	10	2	4	84
TOTAL (%)	73 (32.9)	34 (15.3)	58 (26.1)	29 (13.1)	13 (5.9)	15 (6.8)	222

Honiball (1999) in a later study using Schőning data states that the occurrence of larger sinkholes (deeper than 10m) however seems to be confined to the chert – rich formations (Honiball, 1999).

Following, Heath & Oosthuizen (2008), according to analysis on the sinkhole dimensions (based on limited records) for the area south of Pretoria the largest proportion of sinkholes in this area have a diameter range of 5-15 m (Figure 18).

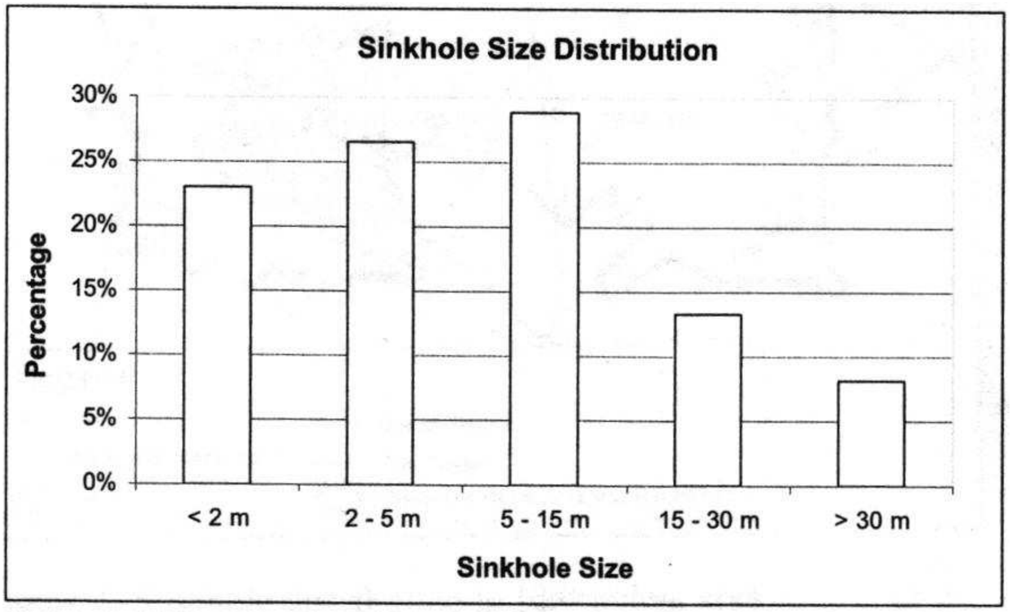

Figure 18. Graph produced by Heath & Oosthuizen (2008) showing sinkhole size distribution (using limited records for the area south of Pretoria).

2.6.2.5 Development

Jennings (1965) emphasizes that the chances of sinkhole formation are statistically small when measured as a percentage of the land area. According to Beck and Sinclair (1986), "*man's activities have accelerated the surface collapse of sinkholes in many instances, technically speaking man doesn't cause sinkholes, but he may activate them*". Kleywegt (1987) states that the sinkhole and subsidence problems experienced in Gauteng are "*a consequence of human activity. Without development large areas underlain by dolomitic rocks are normally of very low risk; events are of a very low rate of occurrence and the population of events is extremely limited*".

Schőning (1990) analysed the date of township development with regard to sinkhole and subsidence formation and concluded that most sinkholes and subsidences occurred in areas which had been developed prior to 1950, with 108 sinkholes and 16 subsidences having occurred in residential areas (a total of 25 residential areas were analyzed) and 120 sinkholes and 81 subsidences having occurred in industrial areas (seven industrial areas were analyzed). Schőning (1990) notes the significance of development density, as it varies between residential areas, stating this gives an indication of the amount of water bearing services in an area and leads to the idea that "*the higher the density of water bearing services, the higher the likelihood of leaking services and hence sinkholes and subsidence's*".

Schőning (1996) concludes that the area south of Pretoria experienced;

- 2, 37 events per 100 ha for residential areas (5232ha) and,
- 4.32 events per 100 ha for industrial areas (4650ha),

This suggests that more events can be expected in the industrial areas than residential areas. The study showed that events were dependent on geology, development, and climate and water management

Not all events can be associated with development and human interference. Schőning (1990) stated that 6% of the sinkholes recorded in the area south of Pretoria can be identified positively as natural sinkholes; in Irene Agricultural Research Farm (1), Rietvlei Dam Nature Reserve (4), Swartkop (13) and Waterkloof Air Force Base (1), the remaining 94 % can be attributed to man-made causes.

A special presidential report for dolomite risk management of the Katorus area (Katlehong-Tokoza- Vosloorus) was produced in 1996 (IGS Projects). It concluded that the frequency of sinkhole and subsidence formation had increased significantly in the past decade (1986-1996), these incidents being related to leaking and inappropriately designed, poorly installed and maintained water bearing services.

A study by Buttrick *et al.*, (2011), analyzes a number of parameters in a selected area:

- the frequency of sinkholes in each Inherent Hazard Class (IHC) after zoning (this methodology is discussed in more detail in the following subsection);
- the frequency of events that can be attributed to an anthropogenic triggering agency vs. natural causes;
- the frequency of events caused by leaking wet services in each inherent hazard class;
- the frequency of events with respect to types of services;
- building coverage in each IHC;
- co-incidence with a building and,
- percentage of buildings affected in total and cost incurred.

This study concludes that sinkholes occurred in all hazard classes, except in the low IHC 1 areas, with the most occurrences in the high hazard classes 6, 7 & 8. Ninety- nine (99) percent (%) of events were directly as a result of leaking services or other anthropogenic influences, only seven events fell in open land and a particular trigger could not be identified, and 98% of events linked to water bearing services occurs in high hazard areas. Thirty- seven point eight (37.8%) of the events caused damaged buildings; however no loss of life or injury occurred. Buttrick *et al.*, (2011), further note that generally damage occurs from sinkholes that are larger than 5 - 6 m in diameter and damages per ground movement event amount to approximately R656 000 ($80 000).

Buttrick *et al*, (2011) suggests that after the implementation of Dolomite Risk Management Strategies[1] in 2004, ground movement events were reduced from 50 events per year in the early 2000s to 5 per year, i.e. a 90% reduction in events.

2.6.2.6 Assessment systems

Buttrick (1992) for the 'Method of Scenario Supposition' used a historical frequency of sinkhole and subsidence events on a type area[2] along with geophysical surveys and borehole results to create a method to systematically characterize dolomite hazard.

Buttrick's (1992) study included a review of existing classification systems at the time, utilized for the evaluation of sites on dolomite i.e., Stephan (1975), Weaver (1979), Venter (1981), De Beer (1981), Wagener (1982), Van Rooy (1984). The systems of De Beer (1981) and Van Rooy (1984) take note of relative frequency of known sinkholes or subsidences or historical record of damage. Buttrick's method is extensively used by the engineering geology/geotechnical industry today when investigating dolomite stability and has relevance in the analysis of the data in Chapter 4, therefore it is summarized briefly below.

Buttrick (1992), Buttrick and Van Schalkwyk (1995) and Buttrick *et al.,* (2001) describe a number of factors which can be used to evaluate the possible formation of sinkholes including the nature and mobilization potential of the blanketing layer, receptacles, mobilizing agents and the maximum potential development space. The maximum size sinkhole can be assessed by estimating the maximum potential development space (Figure 19), which is associated with a receptacle and depends on the depth and 'angle of draw'. The full realization of the potential development space depends on whether the receptacle is large enough to accommodate all the material (Buttrick, 1992).

[1] policies and procedures set in place to reduce the likelihood of sinkholes occurring on dolomite land
[2] An approximately 650 hectare, developed area, south of Pretoria which had been investigated in detail (95 reports including 70 test pits, 320 auger holes, and in excess of 950 rotary percussion boreholes) and has a well recorded history of sinkhole/subsidence events (in excess of 46 incidents).

Buttrick (1992) proposed broad categories of "potential development space" and the related scale of potential maximum size sinkholes (Table 10). Buttrick and van Schalkwyk (1995) later amended the broad categories as shown in Table 11.

Once an area is assessed, it can be described in terms of low, medium or high hazard. Buttrick's (1992), initial table (Table 12) on risk was based on the study of the type area described previously. Buttrick *et al.*, (2001), provides an updated table (Table 13).

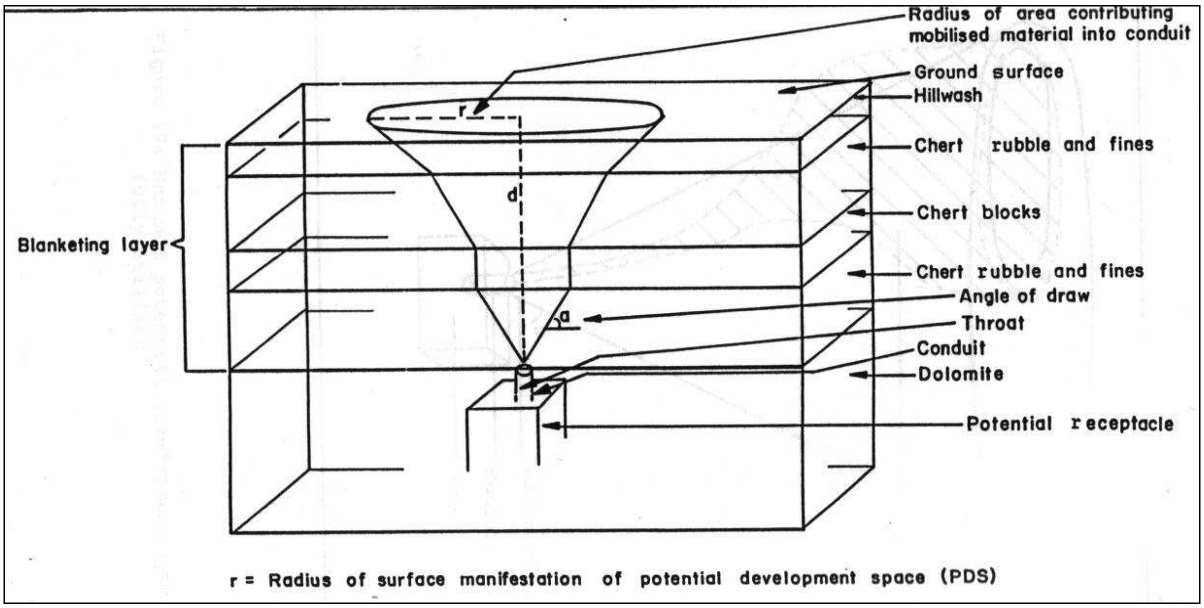

Figure 19. Diagram depicting development space and maximum size sinkhole (*taken from Buttrick, 1992*).

Table 10. Size categories (*after Buttrick 1992 and Buttrick and Van Schalkwk, 1995*).

MAXIMUM POTENTIAL DEVELOPMENT SPACE	*MAXIMUM DIAMETER OF SURFACE MANIFESTATION (m)	SUGGESTED TERMINOLOGY
Small potential development space	<2m	Small sinkhole
Medium potential development space	2-5m	Medium sinkhole
Large potential development space	5-10m	Large sinkhole
Very large potential development space	>10m	Very large sinkhole

*Dimensions are based on study of existing sinkholes.

Table 11. Size Categories (*after Buttrick et al., 2001).*

MAXIMUM DIAMETER OF SURFACE MANIFESTATION (m)	TERMINOLOGY
<2m	Small sinkhole
2-5m	Medium sinkhole
5-15m	Large sinkhole
>15m	Very large sinkhole

Table 12: Risk characterization (*after Buttrick, 1992*).

RISK CHARACTERIZATION	NO. GROUND MOVEMENT EVENTS	EVENTS PER HECTARE
Low	0	0/ha
Medium	16	0.07/ha
High	33	0.7/ha

Table 13. Inherent Risk characterization (*after Buttrick and Van Schalkwyk, 1998 and Buttrick et al. 2001*).

Inherent Risk	Anticipated events per hectare over time (magnitude of problem)*
LOW	0 up to and including 0.1 events per hectare anticipated but occurrence of events cannot be excluded
MEDIUM	Greater than 0.1 and less than and equal to 1.0 events per hectare
HIGH	Greater than 1.0 events anticipated per hectare
* that have occurred per hectare in a 20 year period in the "type" areas (statistics based on poor service design and maintenance)	

Another recent system of assessment using sinkhole data involved the design of the Gautrain Rapid Rail Link (Gautrain). The Gautrain passes through Centurion and across approximately 15 km of dolomitic ground. The viaducts for sections of the route are supported on piers spaced generally between 46 m and 56 m apart (Jacobz and Vorster, 2008).

In the assessment system used by Sartain *et al.,* (2011), sinkholes were considered one of the biggest hazards to the Gautrain infrastructure. As the alignment could not avoid the dolomitic ground, the potential sinkhole size that could occur, had to be designed for to accommodate a sudden loss of support. Initially a 30 m diameter was proposed for the design, but construction costs were extreme, and no viable solution was available for the sections founded on piles.

A study of the frequency of sinkhole occurrence with a diameter >15 m was undertaken. A database of 287 sinkholes in the Centurion region was compiled. According to Sartain *et al.,* (2011), the risk management was based on the approach of HSE[1] (2001), in which concepts of intolerable risk[2], tolerable risk[3] and broadly acceptable risk[4] are reviewed. The design needed to demonstrate that the safety risk was tolerable. A quantitative risk assessment (QRA)[5] was undertaken to estimate the sinkhole risk. Exponential probability density functions (PDFs)[6] that best represented the data for sinkhole dimensions and depth were assigned, and simulated using a Monte Carlo approach[7], for use in a QRA model.

Sartain *et al.,* (2011) suggested that large sinkholes (>20 m) are significantly over represented in the database. The diameter distribution was established, then the range of rate of formation of new sinkholes (new sinkholes per unit area per year) was modeled in the QRA. It was concluded that the most appropriate sinkhole diameter to design for was 15 m; this gave a tolerable risk with 95% confidence (Figure 20).

[1] Health and Safety Executive, United Kingdom.
[2] Are not permitted.
[3] Lie between intolerable and broadly acceptable and must be mad "as low as reasonably possibly" (ALARP).
[4] Are sufficiently low so as not to be of concern.
[5] Risk assessment using numerical methods with quantifiable input parameters.
[6] Represents a probability distribution in terms of integrals i.e. a 'smoothed out' version of a histogram.
[7] computational algorithms that rely on repeated random sampling and probability statistics to compute their results

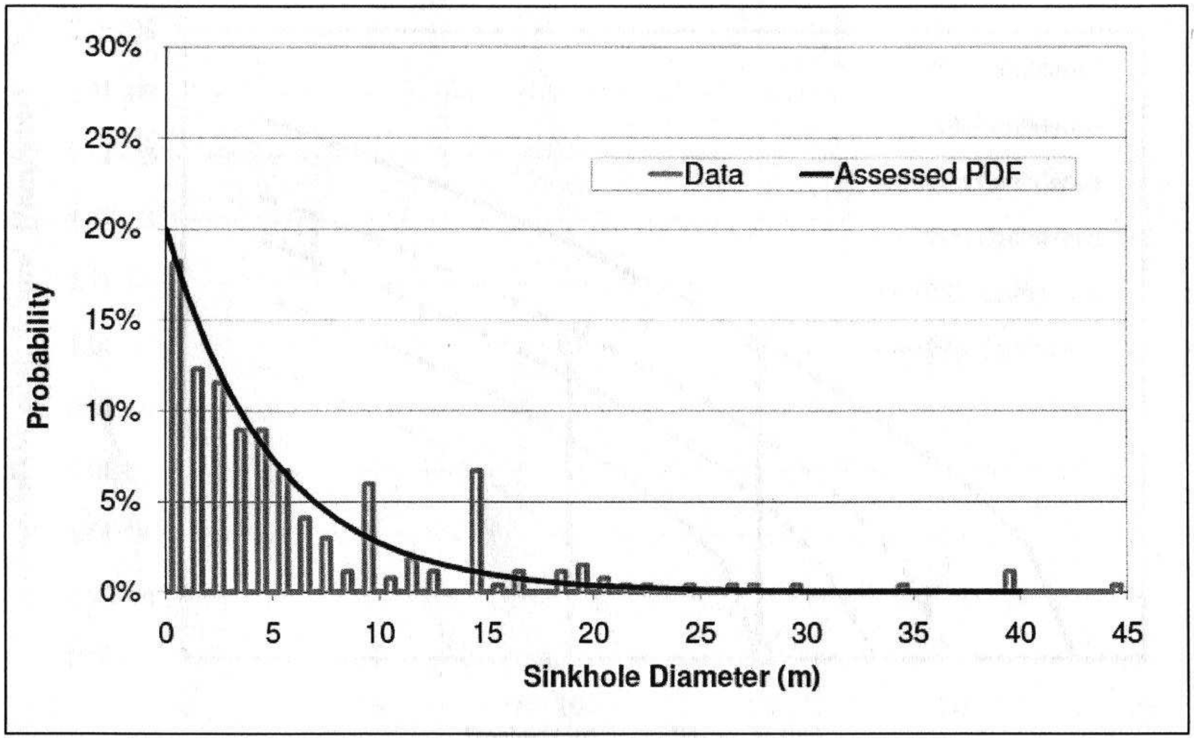

Figure 20. Sinkhole diameter distributions produced from the available data *(taken from Sartain et al., 2011).*

2.6.2.7 Shallow Bedrock

Heath and Keyter (1996) state that the shallower the bedrock the more vulnerable an area is to sinkhole formation. Exceptions may exist where continuous solid rock dolomite is present at shallow depths. In other high risk dolomite areas, where dolomite is deeper than 10 m, the resultant sinkholes are usually larger (>5 m). Where erodible and compressible material overlies shallow dolomite, a high risk of sinkholes can be expected.

2.7 ENGINEERING CLASSIFICATION OF KARST

In South African literature ground movement events related to dolomite are broadly termed a sinkhole or subsidence (or previously doline). Internationally they may be further classified with respect to the mechanism of ground failure and the nature of the material which fails, i.e.

- Dissolution sinkholes (formed by slow dissolutional lowering of the outcrop or rockhead, aided by undermining and small scale collapse),
- Collapse sinkholes (formed by instant or progressive failure and collapse of the limestone roof over a large cavern or small group of caves),

- Caprock sinkholes (are comparable to collapse sinkholes, except there is undermining and collapse of an insoluble caprock over a cavity in the underlying limestone),
- Dropout sinkholes (formed in cohesive soil cover where percolating rainwater has washed the soil into fissures and caves in the underlying limestone. Rapid failure of the ground surface occurs) or,
- Suffusion sinkholes (formed in non-cohesive soil cover, where percolating rainwater has washed the soil into fissures and caves in the underlying limestone.

Slow subsidence of the ground surface occurs as the soil slumps and settles, as classified by Waltham and Fookes (2003) (Figure 21).

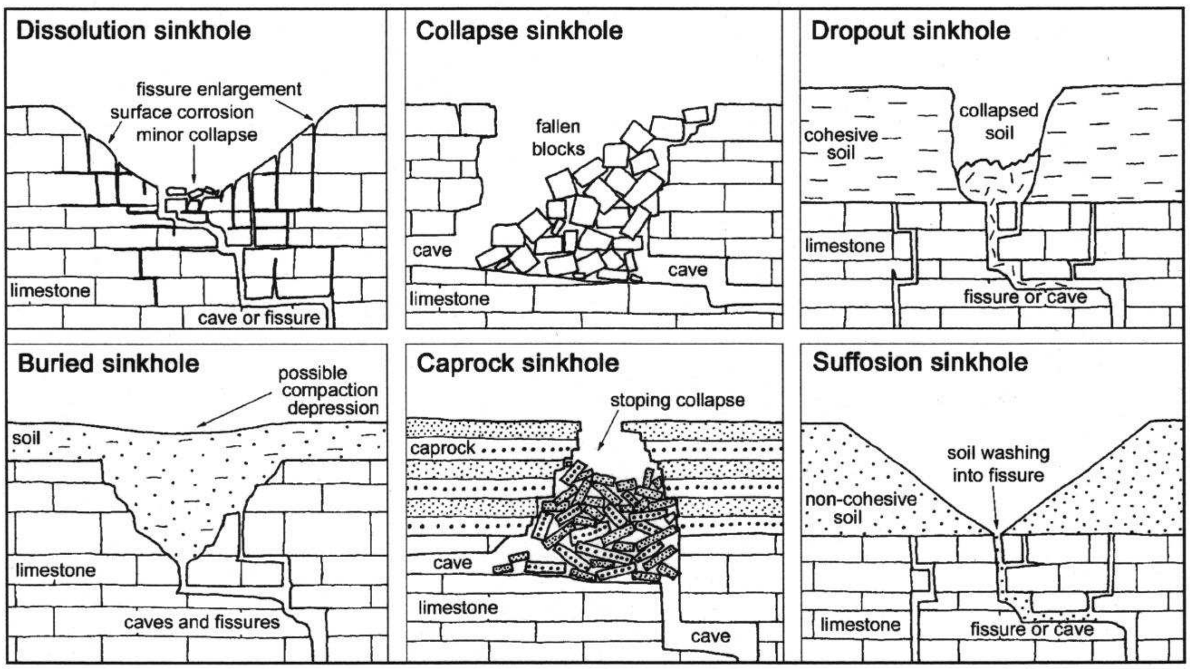

Figure 21. Classification of sinkholes (*taken from Waltham and Fookes, 2003*).

According to Waltham and Fookes (2003), a classification of karst ground conditions should broadly quantify rockhead variability, the spatial frequency of sinkholes, and the sizes of underground cavities. The five classes described by Waltham and Fookes (2003) and a description of the parameters are shown in Figure 22 & Table 14 respectively. Waltham and Fookes (2003) further indicate that "*the classes provide the basis of an engineering classification that characterizes karst in terms of the complexity and the difficulty to be encountered by the foundation engineer*".

Mean sinkhole density is equated to sinkholes per unit area and the rate at which new sinkholes occur (NSH) equals events per km^2 per year (Waltham and Fookes, 2003).

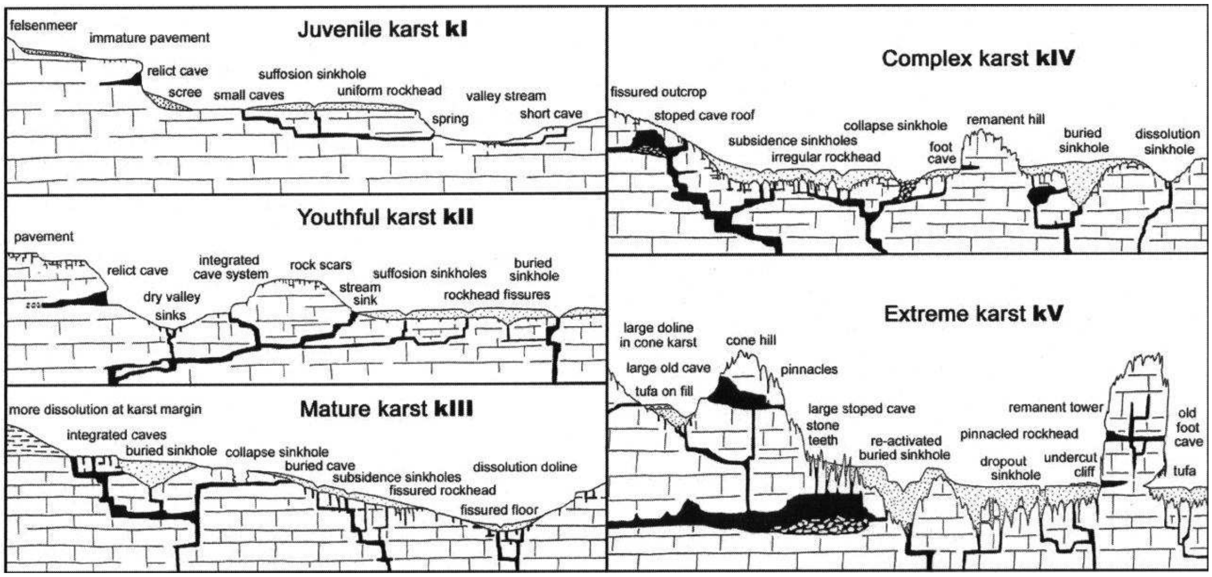

Figure 22. Concept diagrams of typical morphological features of karstic ground conditions within the five classes of the engineering classification *(taken from Waltham & Fookes, 2003).*

Table 14: Outline Descriptions of selected parameters (after Waltham & Fookes, 2003)

Karst Class	**Location**	**Sinkholes**	**Rockhead**	**Fissuring**	**Caves**
kI Juvenille	Deserts, periglacial zones or on immature carbonates	Rare: *NSH<0.001	Almost uniform, minor fissures	Minimal	Rare and small
kII Youthful	The minimum in temperate regions	Small suffusion or dropout sinkholes NSH 0.001-0.05	Many small fissures	Widespread near surface	Many small caves most < 3m across
kIII Mature	Common in temperate regions; the minimum in the wet tropics	Many suffusion and dropout sinkholes; small collapse and buried sinkholes NSH 0.05-1.0	Extensive fissuring: relief of <5m: loose blocks in cover soil	Extensive secondary opening of most fissures	Many caves < 5m across at multiple levels
kIV Complex	Localized in temperate regions; normal in tropical regions	Many large dissolution sinkholes; numerous subsidence sinkholes; scattered collapse and buried sinkholes. NSH 0.5 -2.0	Pinnacled: relief of 5-20m: loose pillars	Extensive large dissolution openings	Many >5m across at multiple levels
kV Extreme	Only in wet tropics	Very large sinkholes and all types: soil compaction in buried sinkholes NSH >1	Tall pinnacles: relief of 20m: loose pillars undercut between deep soil fissures	Abundant and very complex dissolution cavities	Numerous complex cave systems

*NSH = rate of formation of new sinkholes per km^2 per year.

2.8 SINKHOLE INVENTORIES IN OTHER COUNTRIES

The challenges and aim of creating a sinkhole inventory is best summarised by Brinkman *et al* (2008); "*mapping of sinkholes always represents a very difficult task; they are often subtle phenomenon, can be easily modified or even canceled by human activities, and range in size from very small to very large. Nevertheless, it is worth producing an effort to define and map sinkholes using existing as well as properly built databases to better understand the geologic history and the hazard associated with living within an active karst environment. The outcomes from this type of study can provide the basis for future and more detailed analysis and, at the same time, for land use management in densely populated karst areas"*.

As De Beer (1987) pointed out for a study area in Blyvooruitzicht; "*valuable indications of a town's vulnerability, with regard to sinkhole or subsidence formation, may be obtained from knowledge of past events that may have taken place in the area"*.

While there is plentiful South African literature on the occurrences of sinkholes and subsidences, literature on inventories and analysis is rare. Roux (1984) and later Schőning (1990) had created a database on index cards which for the most part described the most important points needed for analysis of the data. Buttrick (1992) compiled the number of sinkholes in a study area in order to compare with the gravity data and underlying conditions revealed by borehole logs in order to create a system for dolomite stability analysis called the "Method of Scenario Supposition", but as far as can be ascertained, no literature could be found in the South African context detailing sinkholes inventories and the factors to be noted. Buttrick and Van Schalkwyk (1995) suggested local authorities should create a database of ground subsidence events and reported structural damage, as these detailed records are useful in developing a clear perspective of the stability situation in a township, highlight areas of weakness and assist in the installation and development of proactive maintenance strategies. Heath and Oosthuizen (2008), state that risk assessment and appropriate development on dolomite has to be based on a reliable sinkhole record.

Previous work on sinkhole and subsidence inventories, databases and analysis is more common and recent in Europe and the United States. Denizman, (2003), used GIS to examine the 'morphometric and spatial distribution' of karstic depressions in Florida USA. The parameters calculated included length, width, orientation, area, depth, circularity index, depression density, pitting index and nearest neighbour index. Brinkmann *et al* (2008) is an example of how a database was compiled and used for sinkholes occurring in Tampa, Florida, USA. Two databases were used to analyze the characteristics of sinkholes; a database of collected historical reports and a topographic database created from photo imagery. Brinkmann *et al.,* (2008) also recognized the expediency of using a GIS system for spatial distribution analysis and used it to analyze relationships between the distributions of events and other relevant factors such as geology, hydrology and the anthropogenic environment. Each sinkhole or subsidence was assigned the following attributes: size (m^2), perimeter (m), longest axis (diameter), orientation of the longest axis, circularity index (measured by comparing the diameter and area of a sinkhole with the area of a circle of the same diameter). A circularity index of 1 is a perfect circle, (sinkholes have a circularity index of less than 1). The density of occurrences is also calculated as number per unit area.

Gutierrez *et al.* (2008) also highlights the importance of recognizing and identifying existing sinkholes and gathering information on size and frequency of events. They indicate that the sinkhole frequency or probability of occurrence can be considered as the number of sinkhole events per year per unit area (i.e. a probability of occurrence of 0.1 sinkhole/ km^2 year means that on average in a 10km^2 area, one sinkhole a year is expected to occur). Beck (*in* Gutierrez *et al.,* 2008) emphasizes that '*the calculation of the probability of occurrence must be based on a sinkhole inventory, which should be as complete as possible covering a representative period of time*'. Further to this point Gutierrez *et al*. (2008) states that the validity of the obtained frequency will depend on the completeness and quality of the available data, in most cases only a minimum or optimistic sinkhole frequency can be obtained due to data incompleteness. Data also usually shows a bias towards major events, which are easily remembered and recorded while small events may not be noted. The chronological data makes it possible to calculate a preliminary probability of the occurrence of sinkholes i.e. sinkholes/km^2/year and an annual probability the occurrence of sinkholes i.e. sinkholes/km^2/year x 100 x area (km2) (Gutierrez *et al*., 2008).

Gutierrez *et al.* (2008), indicates that a crucial design parameter is the maximum diameter of the sinkholes at the time of formation, as it is the distance that has to be spanned to prevent the buckling of the structure.

Galve *et al.* (2009), sets out 5 steps in the methodology on constructing a sinkhole inventory for a study area:

(1) Interpretation of aerial photos from different dates

(2) Examination of topographic maps
(3) Detailed field surveys including checking of the features mapped with aerial photos and topographical maps
(4) Inspection of human structures and
(5) Interviews with local residents.

The aim of this strategy was to produce sinkhole inventories as complete and more importantly, as representative as possible. The information related to each sinkhole was recorded using a database template (Galve *et al,* 2009).

The methodology used in this study draws from previous studies and is detailed in the following Chapter.

CHAPTER 3 – DATA CAPTURING & METHODOLOGY

This section details the methodology used in data capturing and data preparation for analysis.

3.1 IDENTIFICATION OF SINKHOLE AND SUBSIDENCE AREAS

- This would encompass all 'dolomitic land' within the Gauteng province, as shown on the maps in Appendix A.

3.2 GATHERING DATA

Data originates from;

- Records (reports from the dolomite databank and historical maps, examples shown in Figure 23 - 25) held at the Council for Geoscience,
- Research theses, papers, articles etc. (examples of newspaper articles collected by CGS personnel are supplied on DVD in Appendix B),
- Databases compiled by CGS, and supplied to the CGS by various consultants, companies and state authorities. These databases, while held at the CGS, are not supplied in the appendices as data may be confidential and must be sought from relevant/responsible person/s.
- Topographic maps[1] (1:50 000) covering dolomitic areas, published in 1984 (example shown in Figure 26 (a)),
- Aerial photographs (Quick Bird, 2004) (example shown in Figure 26 (b) covering the study areas viewed on a Geographic Information System (GIS) were also utilized.

Large percentages of the data collected was incomplete, with one or more of the parameters missing i.e. a data point may be recorded as a sinkhole with a date and diameter, but no depth or cause recorded etc. Therefore the number of samples used in analysis differs for each parameter.

3.3 DATA COMPILATION

- Data was compiled on GIS (Arcview 9.3) in a geographic database (Figure 27) and maps were produced using this software. Only karst related sinkholes and subsidences were considered in this study. The geographic database contains information, as far as available, on the location, dimensions, geological formation, cause and date of

[1] 2527BD, 2528BA, 2528AC,2528AD, 2528BC,2527DB, 2525CA, 2528CB, 2528DA, 2528DB, 2529CA, 2527DC, 2527DD, 2528CC, 2528CD, 2528DC, 2528DD, 2627AB, 2627BA, 2627BB, 2628AA, 2628AB, 2627AD, 2627BC, 2627BD, 2628AC, 2628BAD, 2628BC, 2628BD, 2627CB, 2627DA, 2628CA, 2628CB, 2628CC, 2628CD.

occurrence of events. This study makes use of sinkhole and subsidence data from late 1950's to end of 2011.

3.4 DATA VERIFICATION

- Data from databases supplied was verified as far as possible by systematically reviewing historical maps and records, reports, research and topographic maps and aerial photos;
  - Historical maps were georeferenced in a GIS system,
  - Records or reports without maps usually indicate a street address or road name,
  - Sinkholes are indicated as such on topographic maps, and
  - High resolution aerial photographs make it possible to identify circular depressions on the dolomite areas, i.e. Figure 26 (b)).
- While locations may be approximate, generally it is assumed that if an event has been noted/recorded or indicated on a map, that it has occurred in close proximity to the co-ordinate, map position or locality description given.
- Field verification for historical occurrences was not possible as many sinkhole and subsidence events are no longer visible, having been rehabilitated. Also the large number of events (as estimated by Heath & Oosthuizen, 2008) would have required an inordinate amount of time. Therefore confidence levels vary for the different databases supplied as well as those compiled by the CGS. The accuracy of these databases cannot be guaranteed and further verification may still be necessary in some cases. These data sets are only an estimation of the number of events that have occurred in Gauteng, as many sinkholes and subsidence were probably not reported, as it was not legally required, and reporting procedures were not formalized. Also there may be an associated loss of value to property and loss of confidence in the area when events are reported.

3.5 ANALYSIS

- Once all available sinkhole and subsidence data were collected and compiled, previous work on sinkhole and subsidence inventories and databases were reviewed for method guidance on factors to be analyzed (Section 2.8). The previous studies by Wolmarans (1984), Roux (1984) and Schőning (1990) were also reviewed. Although many parameters are included in the methodologies of the sinkhole inventories described in the previous chapter, as a consequence of limited and incomplete information, the main attributes considered in analysis were as follows;

- The date of occurrence; this was investigated to determine if the numbers are increasing or decreasing or staying relatively the same. Dates were also used to try and correlate events with rainfall and the time period was used in the calculation of rate of new sinkhole formation.
- The type of occurrence; to examine which is more prevalent, whether sinkhole, subsidence or crack, for the entire study area and for the different dolomite formations.
- The number of events on the different dolomite formations and in the different groundwater compartments (Far West Rand).
- Which triggering mechanisms were more prevalent, as well as natural vs. man-made occurrences.
- The size and depth distribution of events across the entire study area and on the different dolomite formations.
- The rate of new sinkhole formation or sinkhole frequency.

The summary table (Table 15) gives an indication of the areas that contributed the most events to the data analysis and highlight the differences in numbers of available data for each parameter and the large percentage of missing data. Events are separated into municipal areas as each municipality has a different history of development, dolomite risk management and recording of events:

- **West Rand District Municipality**

  The West Rand District Municipality (Map A1, Appendix A) includes the areas from Westonaria to Carletonville, historically known as the Far West Rand. This area is notorious for the accelerated sinkhole development that occurred during the 1960's - 70's due to dewatering. Wolmarans (1984) produced the first sinkhole survey for this area up to 1984, however no specific event information was found, except for historical maps indicating event positions. However at least 733 events are known to have occurred in the period pre 1957 to 1984, based on Wolmarans, (1996). Incidents would have been reported by the Far West Rand to the State Technical Coordinating Committee on Sinkholes and Subsidences (SCTC) operating at the time. After 1984, the Gold Fields Geological Center has kept a very comprehensive database of such events.

- **Tshwane Metropolitan Municipality**

  The main area of concern in the Tshwane Metropolitan Municipality (Map B1, Appendix A), due to rapid development on dolomite, is the Centurion area (previously known as Verwoedburg). Development in this area moved from large agricultural holdings (1960's) to densely packed townhouses (2000's). This area also encompasses the Waterkloof and Swartkop Air Force Bases and related military areas, which have a long history of sinkhole and subsidence incidents and associated damage to buildings and infrastructure. Roux (1984) and Schőning (1990) produced the first sinkhole survey for this area up to 1990, although the data quality can be considered poor to fair as many attributes were missing. Essentially three databases have been collated over the years by separate entities for the Tshwane Metropolitan Municipality. These databases range from fairly comprehensive to rather limited. The data has been combined and a small *percentage of duplication* may exist, but due to the large portions of missing data, duplicate events could not always be distinguished, therefore events from Tshwane may be slightly overestimated.

- **Ekurhuleni Metropolitan Municipality**

  Areas directly underlain by dolomite within Ekurhuleni occur in the northern (Olifantsfontein to Bapsfontein), south western (Katlehong and Vosloorus) and eastern (Daveyton to Bakerton) portions of the municipality. Large areas of the eastern and central portions of the municipality are covered by Karoo Supergroup sediments (approximately 44% of surface area) which overly the dolomite. Western portions of the municipality are underlain by granodiorite (approximately 5% of surface area), Witwatersrand Supergroup (approximately 11% of surface area) and Ventersdorp Supergroup (approximately 8% of surface area) rocks (Map C1, Appendix A). Much of the development has taken place on the Karoo, Witwatersrand or Ventersdorp Supergroup, however developments directly on dolomite show a number of events to have occurred. Various consultants have been appointed by Ekurhuleni Metropolitan Municipality since the early 2000's, to introduce a Dolomite Section within the municipality and compile a database as well as manage the dolomite hazard. The CGS has also kept its own database of events.

- **City of Johanesburg**

  The City of Johannesburg (Map D1, Appendix A) has recorded very few events (16) over the past 60 years, and thus detailed analysis was not considered useful.

- Organisation of data was done with the aid of the Statistics Department of the University of Pretoria.
  - Data was exported from GIS attribute tables (where it was captured) into Microsoft Excel.
  - Microsoft Excel files were then imported into SAS V9.3, statistical analysis and visualization software running on a desktop computer using a Windows XP service pack 3 operating system.
  - Frequencies of variables were tallied.
  - Multiwave frequency tables were produced, from which data was further categorized to produce frequency tables of direct significance to the factors to be investigated.
  - For the probability plot the size categories were converted to probabilities by dividing the percentage of each category by 100. The probability was plotted against the size category and the maximum likelihood (average) was used to fit the exponential distribution to the data in Microsoft Excel (2010).

- Tables and graphs were produced and linear regression was undertaken (Results Chapter), in Microsoft Excel (2010) from outputs. Raw data is provided in Appendix B.

Table 15. Summary of available data for each parameter.

Municipality	Est. number of events∞	Indicate a year of occurrence	Indicate a month of occurrence	Indicate a type of occurrence	Number of events on different formations #	Recorded Triggering mechanisms	Recorded Diameter	Recorded Depth
WEST RAND (%)	1473	604 (41)	568 (38.6)	1411* (95.8)	1473 (100)	1240^ (84.2)	587 (39.8)	490 (33.3)
TSHWANE (%)	1393	747 (53.6)	457 (32.8)	1268 (91.0)	1393 (100)	376 (26.9)	503 (36.1)	356 (25.6)
EKURHULENI (%)	166	111 (66.8)	92 (55.4)	144 (86.7)	166 (100)	105 (63.3)	116 (69.8)	97 (57.8)
JOHANNESBURG (%)	16	4 (25)	0 (0)	16 (100)	16 (100)	16 (100)	9 (56.3)	9 (56.3)
Total	3048	1466	1117	2839	3048	1715	1215	952
% available		**48.1**	**36.6**	**93.1**	**100**	**56.3**	**39.8**	**31.2**

∞ Events to refers to sinkholes, subsidences and cracks.

* Events prior to 1983 had to be inferred from historical maps.

based on 1:50 000 and 1:250 000 scale maps, some extrapolation was used on areas not covered by detailed mapping.

^ Based on Wolmarans (1984) Table 1 & 2, & database supplied

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COUNCIL FOR GEOSCIENCE
RAAD VIR GEOWETENSKAP

NOTICE OF SINKHOLE OR DOLINE FORMATION
KENNISGEWING RAKENDE SINKGAT OF DOLINEVORMING

1.	LOCATION LIGGING	Jeanlaan/R28-kruising, Lyttelton, CENTURION
2.	COORDINATES KOöRDINATE	X + 2 858,80 Y + 81,80 Z 1 455 m
3.	TYPE OF FEATURE TIPE VERSKYNSEL	Sinkhole / Sinkgat X Subsidence / Versakking Structural cracks / Strukturele krake Surface cracks / Oppervlakkrake
4.	DIMENSIONS MATES	Length 7 m / Lengte Width 5 m / Wydte Depth 2 m / Diepte
5.	DATE OF OCCURRENCE DATUM VAN VORMING	± 19 November 1995
6.	DATE VISITED DATUM BESOEK	21 November 1995
7.	CAUSE OORSAAK	Lekkende stormwaterkanaal - betongeut op vulmateriaal (Leaking storm water canal)
8.	GEOLOGY GEOLOGIE	Monte Christo Formasie
9.	REMEDIAL WORK REHABILITASIE	Druklugboorwerk word in die vooruitsig gestel om omvang van skade te bepaal (Drilling to be undertaken to ascertain extent of conditions)
10.	PROFILE PROFIEL	0 - 0.5 m: versteurde deklaag, 0.5 - 2 m +: dol.- en chert residuum (Transported material overlying dolomite and chert residuum.)
11.	NOTES NOTA'S	Op eiland tussen noordelike en suidelike bane van snelweg, binne 1 m vanaf beide ryvlakke, naby posisie van twee vorige sinkgate (On island between north and south bound lanes on highway, within 1m of road surface. Near the position of two pervious sinkholes)

Photo attached : JA.
Foto aangeheg :

Described by :
Beskryf deur :

SITE PLAN
TERREINPLAN

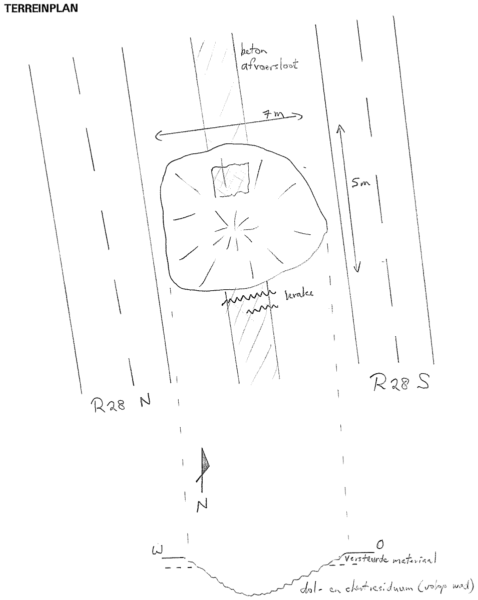


Figure 23. An example of one of the more comprehensive historical records kept at the CGS

Sinkhole at Rand school

DAILY MAIL 17/4/72

By DAVID GODDIN

A SINKHOLE about 10 m deep and 20 m in diameter opened in a school playing field at Oberholzer, near Carletonville, on the West Rand, early yesterday.

Three years ago the Government said sinkhole dangers in the area were over.

Almost immediately a fleet of heavy lorries was called in to dump rock and earth into the yawning chasm at the school, Dagbreek Primary.

The field had been suspected as a sinkhole risk and was cordoned off last year.

Last night Mr. R. Kleywegt of the Government's Geological Survey, said the cause of the sinkhole would be probed.

The sudden appearance of the sinkhole shocked local residents.

They believe it was triggered by a series of earth tremors between sunset on Saturday and dawn yesterday. Nobody knows exactly when it opened.

A South Street resident, whose house overlooks the field, said: "There was a slight subsidence in the road on the other side some months back, then a small dip appeared in the field itself."

Police kept sightseers outside the field's perimeter fence yesterday.

SCARE

Mr. Louis Venter, who lives in Vlei Street, a block from the sinkhole, said: "When the sinkhole scare started some years ago, I was all for yeaving town but now I accept sinkholes as things which do not effect me."

The school principal, Mr. P. Z. Oberholzer, said: "We have regarded the field as being no longer part of the school grounds for almost a year — since the danger first became apparent. No children have been allowed near it."

The townspeople were told the days of sinkholes in the This was the conclusion area were ended. reached after extensive geological surveys by the Government, mining companies and the town council.

Last year four familes were evacuated from homes at Blyvooruitzicht mine near Carletonville after a sinkhole threat became apparent.

In November, 1970, a snkhole developed on the playing fields of the Westonalma English Primary School.

Why games are off on this school field

The hole

BELOW: the sinkhole from the air yesterday, with the school buildings at the top. Police kept sightseers away as lorries tipped rock and earth into the chasm.

Figure 24. Example of Newspaper article collected by CGS personnel over the years (Sinkhole at Dagbreek Primary School in Oberholzer, 1972, Picture from the Daily Mail Newspaper, 17 April 1972).

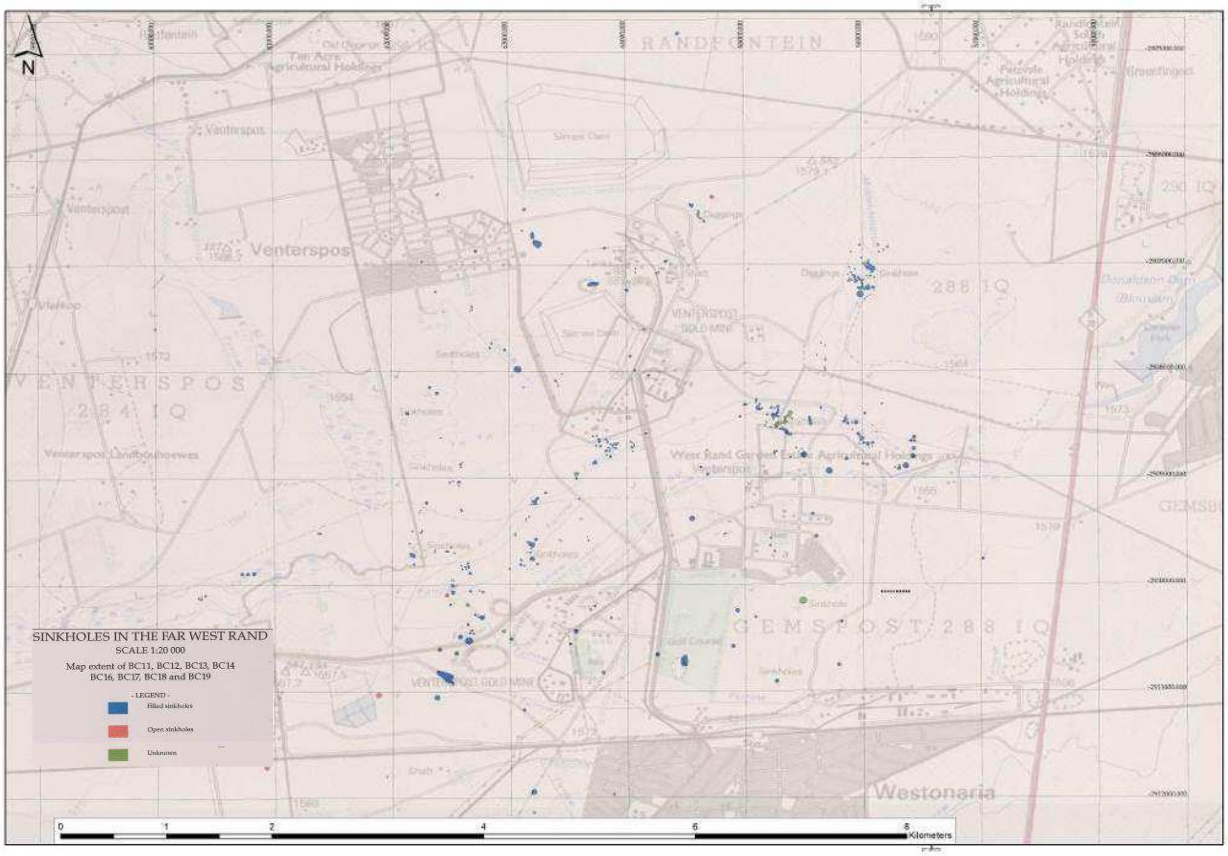
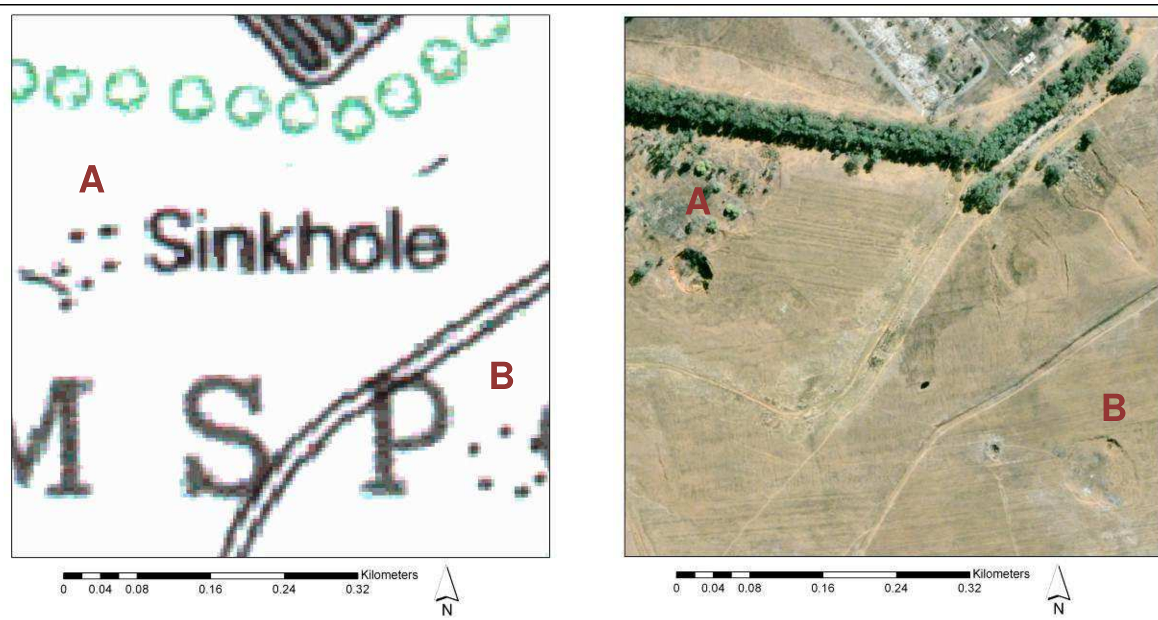


Figure 25. An example of georeferencing historical maps for plotting instability events in the Far West Rand.



26 (a) 26 (b)

Figure 26 (a) & (b). The same area is shown in Figures 26 (a) & (b), sinkholes from the 1:50 000 topographic sheet are still visible on colour aerial Quick bird images.

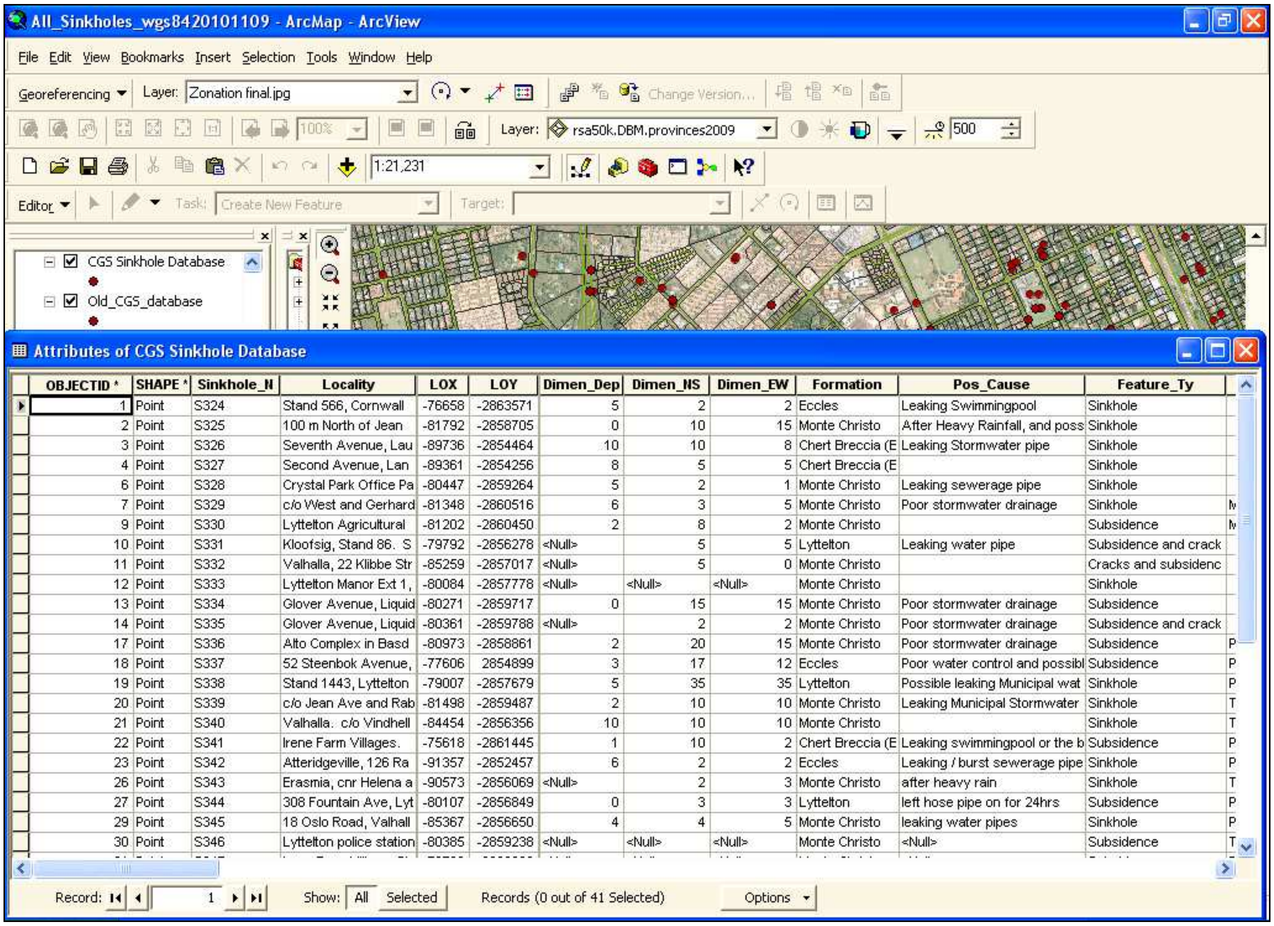


Figure 27. An example of data compiled on GIS (Arcview 9.3) in a geographic database.

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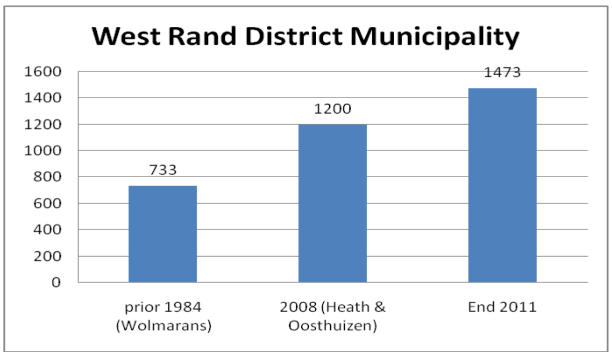
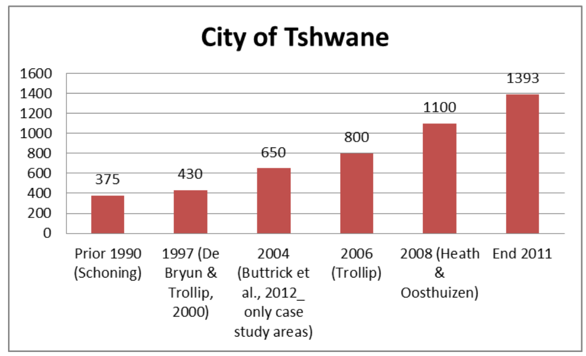
CHAPTER 4 – RESULTS AND INTERPRETATION

The following sections discuss results of analysis undertaken for attributes discussed in section 3.5. Table 15 should also be consulted when reviewing these results, as it indicates the overall percentages of available data for each parameter.

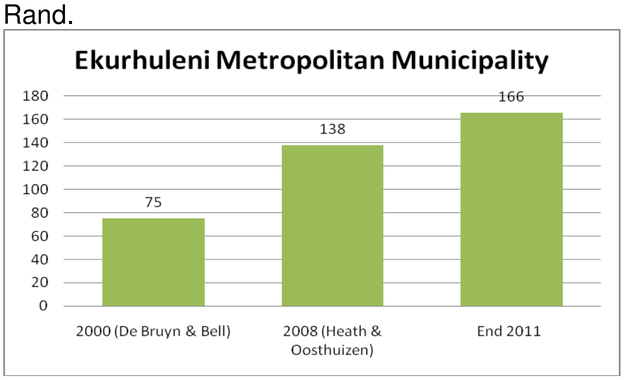
The number of events in each area as reported in literature over the years to present is summarised in Graphs 1a-1c.



Graph 1a: Events reported in literature for West Rand.



Graph 1b: Events reported in literature for Tshwane.



Graph 1C: Events reported in literature for Ekurhuleni.

4.1 DATE OF OCCURENCE

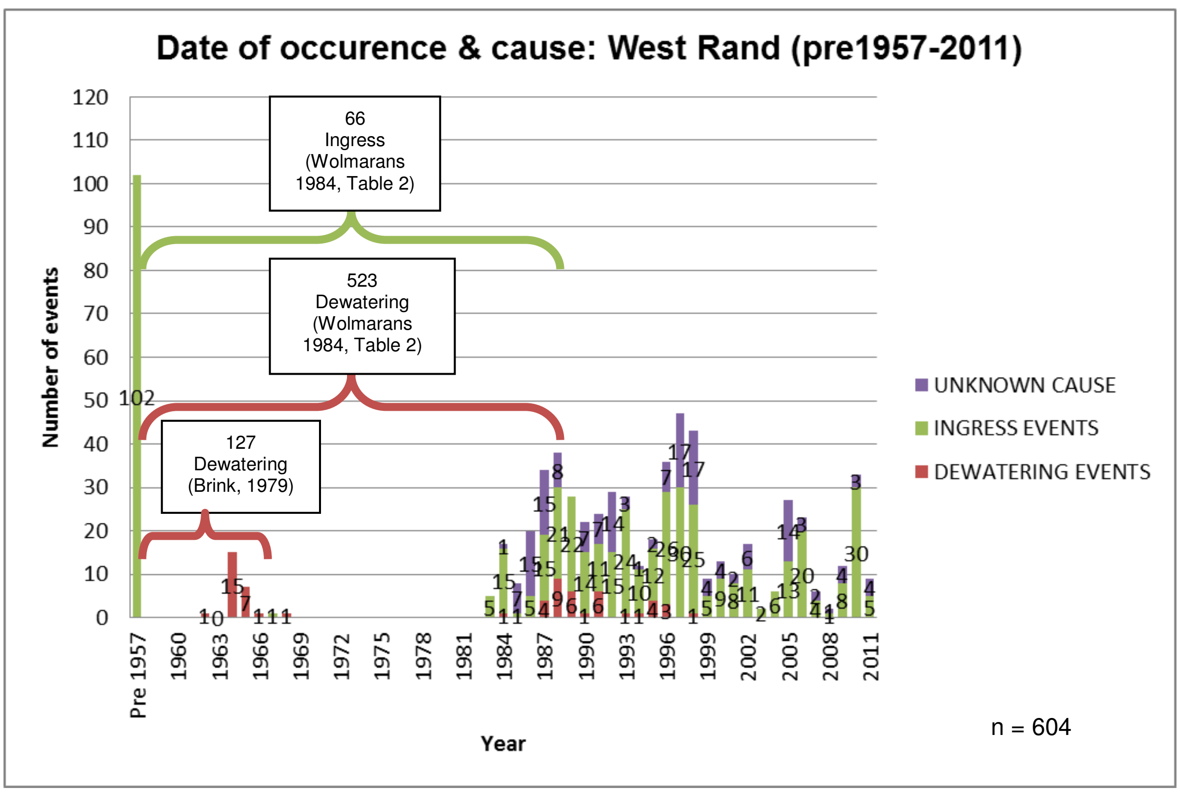
4.1.1 West Rand District Municipality

Out of the estimated 1473 events for the West Rand, only;

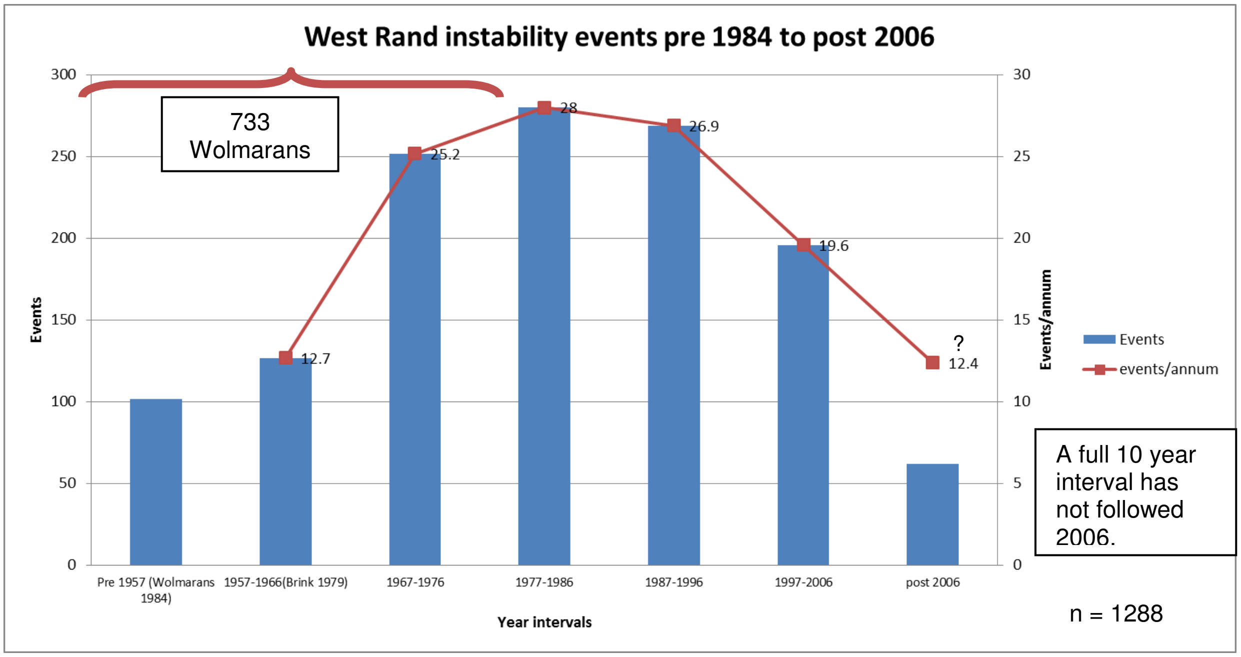
- 604 (41%) have specific chronological data (Table 15) recorded; these are mainly from post 1984 (Graph 2).
- If we consider year ranges (i.e. 10 year increments), 1288 (87.4%) of the events can be plotted in similar increments (Graph 3). It is difficult to divide events prior to 1984 into year intervals, due to the lack of any chronological information except that they occurred prior to 1984; Wolmarans (1984) suggests at least 102 sinkholes and

subsidences had occurred on the Far West Rand before the start of dewatering in 1957. Brink (1979) details 5 very large sinkholes and subsidences and 122 smaller ones on the Far West Rand due to dewatering, by 1966. Therefore between 1966 and 1984, the remainder of Wolmarans's 733 events is divided into 10 year increments so as to give a general representation of reported instability events.

- Overall considering 1371 events in 54 years (1957 - 2011), an average of 25.4 events per annum have occurred.
- If we consider the years when more specific chronological data was recorded; the 10 years post 1986 (1987-1996) shows an average of 26.9 events per annum, while the following 10 years (1997-2006) shows an average of 19.6 events per annum (Graph 3). Post 2006, although a full 10 year interval has not yet occurred, if we assume the same number of events in the next 5 years, we could expect an average of at most 12.4 events per annum. This shows a decreasing trend.
- Almost all the events on the Far West Rand have occurred on the southern limb of the dolomite outcropping in that area (Map A1**,** Appendix A); this is the area where mining activities led to the dewatering of the groundwater compartments, but also includes compartments that were not dewatered (i.e. Boskop-Turffontein).



Graph 2. Reported Instability occurrences in Far West Rand prior 1959 – 2011 (data limited to events with chronolgical data).



Graph 3. General representation of reported instability occurrences in West Rand 1957 – 2011, in 10 year intervals(data limited to events with chronological data).

4.1.2 City of Tshwane Metropolitan Municipality

An estimated 1393 events have been recorded in Tshwane prior to the end of 2011;

- Only 747 (53.6%) entries have specific chronological data recorded (Graph 4).It is not known in which year the remaining 646 (46.4%) events occurred.
- An additional 146 (10.5%) entries have at least indicated the year range.
- Looking at the available data only in 10 year increments (Graph 4), it is evident that very few events were reported before 1970 and a marked increase in the number of events can be seen between 1970 and 1989. The numbers peak in the 1980's and decrease slightly in the 1990's and more dramatically in the 2000's. The peak could be attributed to increased awareness and reporting and/or increased development densities (and associated increase in services) or both, leading to the increase in reported events. The downward trend is ascribed to better investigation, leading to exclusion of high risk areas and/or better water management, as guidelines came into place around 2004.

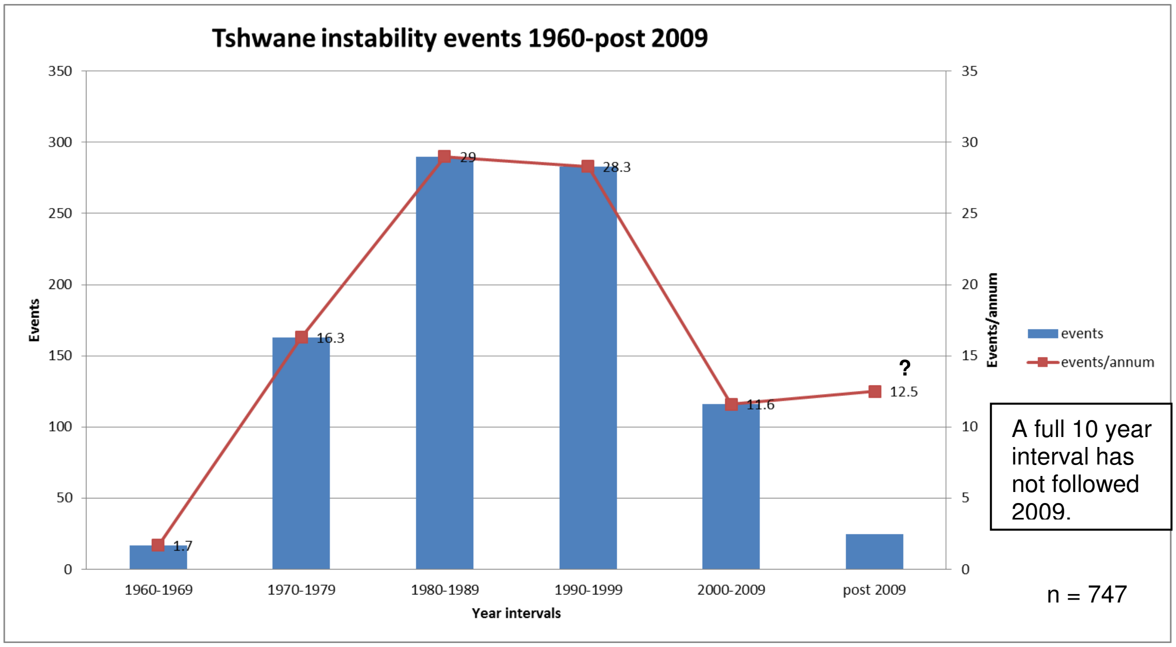
- Overall, if we consider 1393 events in the past 52 years (1959 - 2011), the average number of events 26.8 events per annum. The highest number of events recorded in a year occurred in 1996 (74 events), and can be attributed to unusually, above average, rainfall figures in that period (Graph 5).

- The average number of events before 2000 is 18.8 events per annum (based only on entries with year dates recorded). The number of events appears to have decreased in the period 2000 to 2009, averaging only 11.5 events per annum, (based only on entries with year dates recorded). Post 2009, although a full 10 year interval has not yet occurred, if we assume the same number of events in the next 8 years, we could expect a similar average.

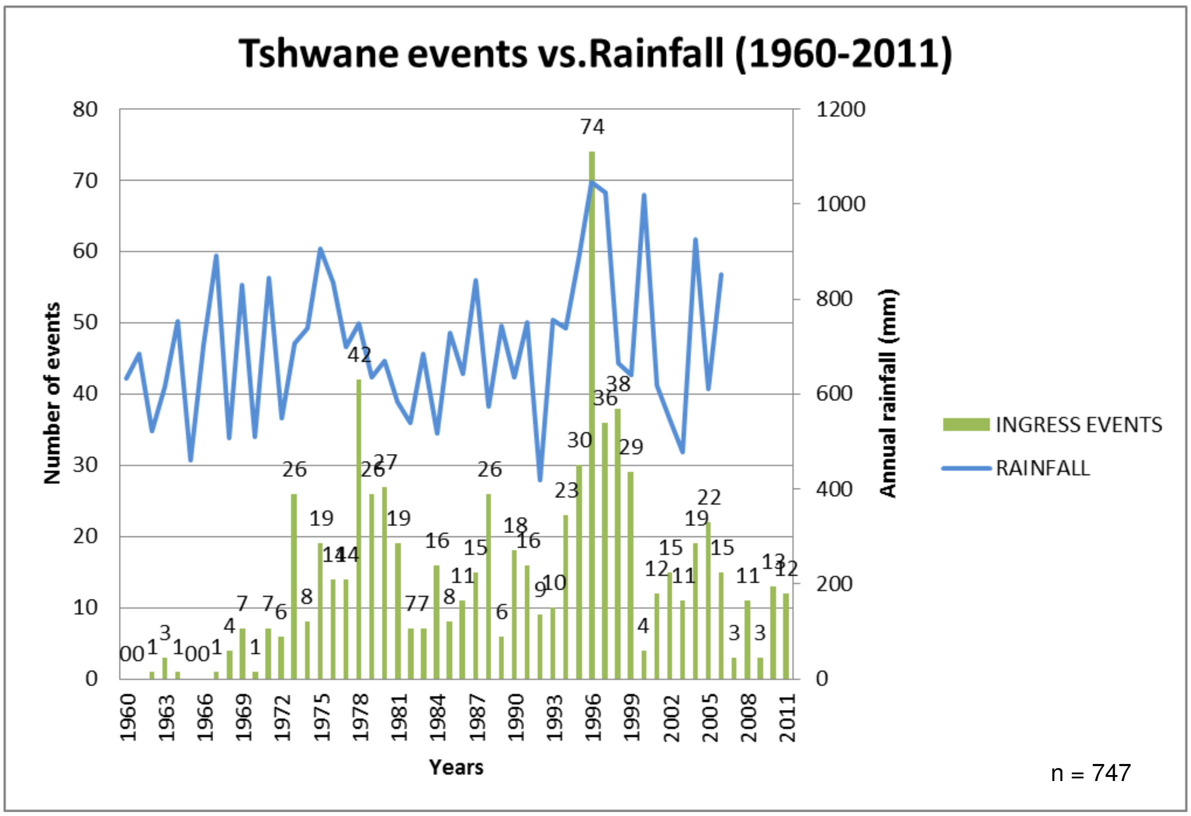
Roux (1984) and Schőning (1990) attempted to correlate cumulative monthly rainfall with sinkhole incidence in the area south of Pretoria, where much of the rain falls in the form of convectional showers of high intensity, limited chiefly to the summer months between October and March. Roux and Schőning used an 11 and 16 year period respectively. As ingress (which is related to rainfall in some cases) is the primary cause of sinkholes within the Tshwane area, current data is used to investigation Roux and Schőning findings. This was not done for the West Rand, as dewatering must be taken into consideration, or Ekurhuleni.

- Only 457 (32.8%) have month dates recorded over a 50 year period. It is not known in which months the remaining 936 events occurred.
- Cumulatively, 66.9% of the sinkhole events and 61.5% of the subsidence events occur in the summer rainfall months October to March (Graph 6), and particularly towards the end of the rainfall season (February), which suggests a lag. From Graph 5 and 6 in general, more events occur in high rainfall months or years, due to increased ingress water entering the ground profile, which concurs with Oosthuizen (2010).
- Following work by Roux and Schőning, when undertaking linear regression analysis on data from 1960 - 2010, sinkholes show an correlation coefficient [13] $r = 0.639$ and coefficient of determination[14] $r^2 = 0.409$ (Graph 7), which shows a poor fit and implies that the two variables tend to increase or decrease together, but knowing rainfall doesn't necessarily allow one to predict the number of sinkholes.

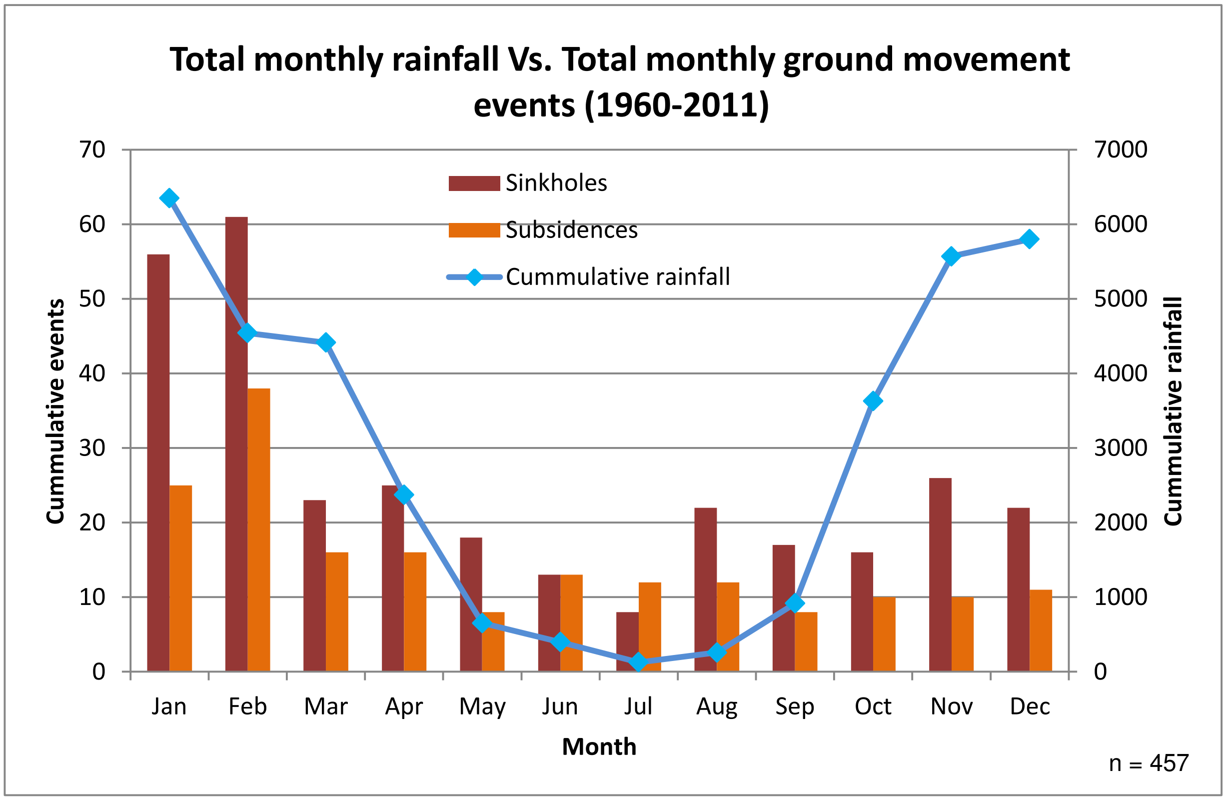
[13] A measure of the strength of the straight-line or linear relationship between two variables.
[14] The fraction of the variance in the two variables that is shared, it's a measure of goodness of fit i.e. It provides a measure of how well future outcomes are likely to be predicted by the model. $r^2=1$ indicates a good fit, r^2 closer to 0 indicates a poor fit



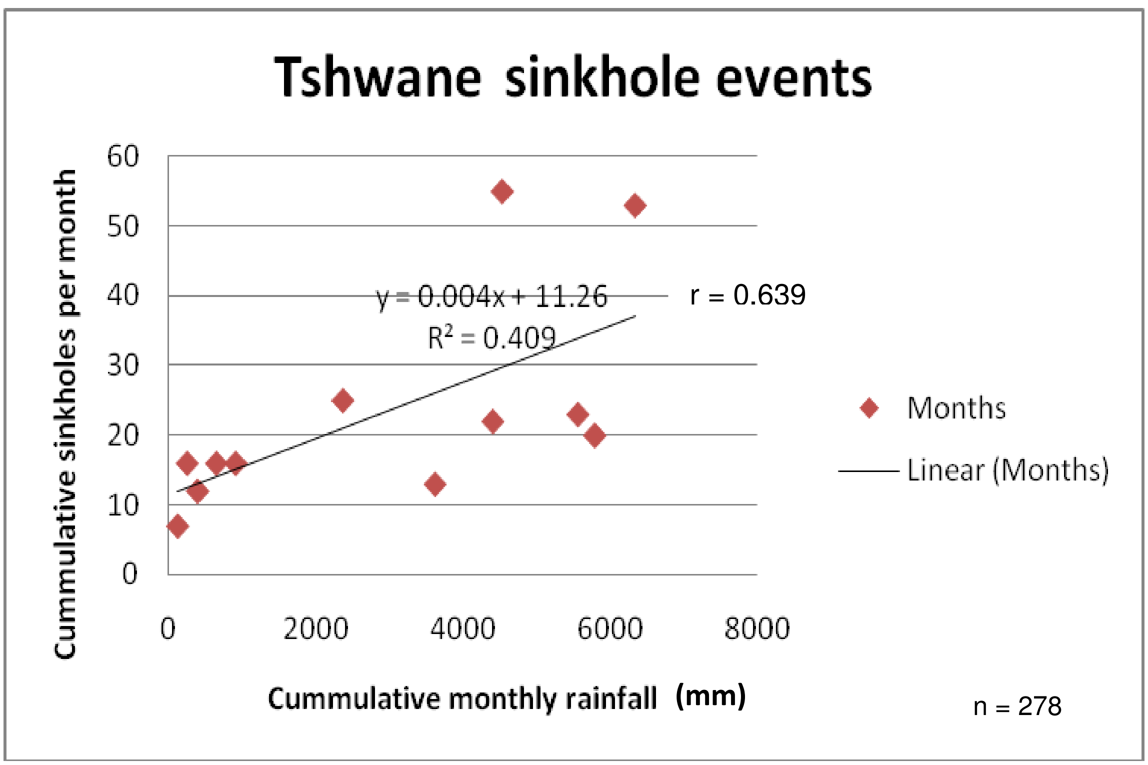
Graph 4: General representation of reported instability occurrences in Tshwane 1960 – 2009, in 10 year intervals (data limited to events with chronological data).



Graph 5: Events reported for Tshwane vs. Annual rainfall (rainfall data supplied by the SA Weather Service for the Irene Station) (data limited to events with chronological data).



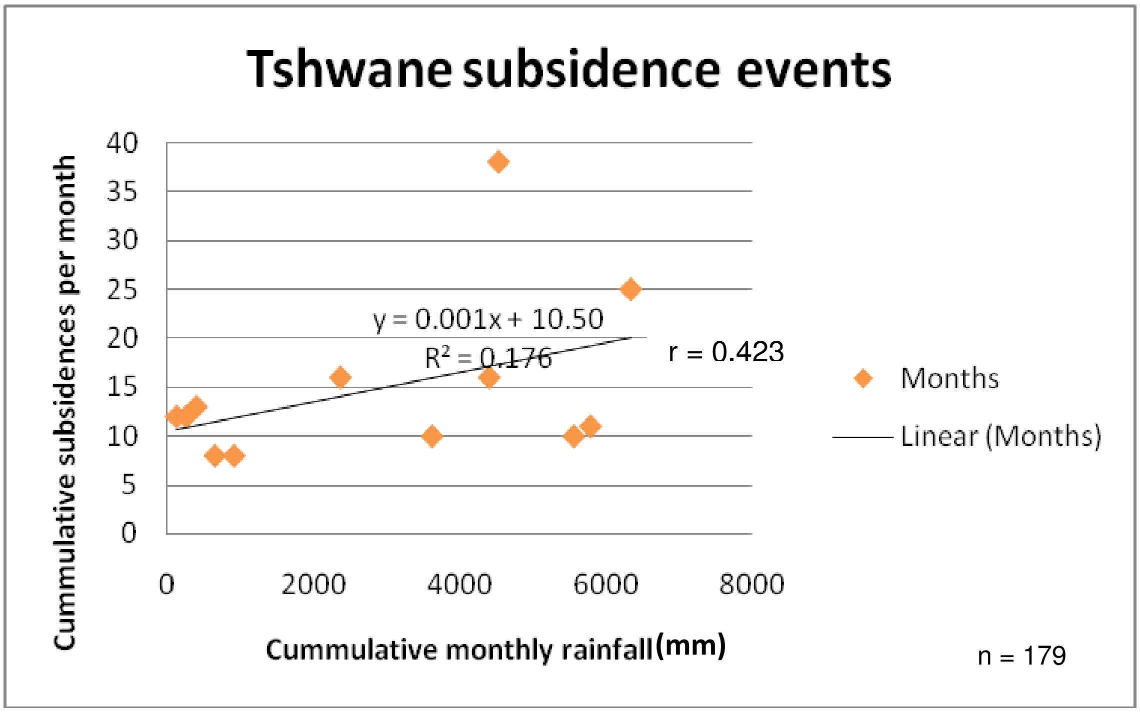
Graph 6: Total monthly rainfall vs. total events reported for Tshwane (data limited to events with month of occurence recorded).(Rainfall data supplied by the SA Weather Service for the Irene Station).



Graph 7: Linear regression: Tshwane sinkholes (1960-2011) (data limited to events with month of occurence recorded) . (Rainfall data supplied by the SA Weather Service for the Irene Station)

- Subsidence's show an r = 0.423 and r^2 = 0.176 (Graph 8), which shows a poor fit.
- Roux (1984) and Schőning (1990) results (Table 16) indicate a much better fit than found in this study. This may be due to the differences in number of events or the time period used.

Linear regression was undertaken in this study to compare it to past studies (Roux and Schőning); however this doesn't appear to be a very meaningful analysis.



Graph 8: Linear regression: Tshwane subsidences (1960-2011) (data limited to events with month of occurence recorded). (Rainfall data supplied by the SA Weather Service for the Irene Station).

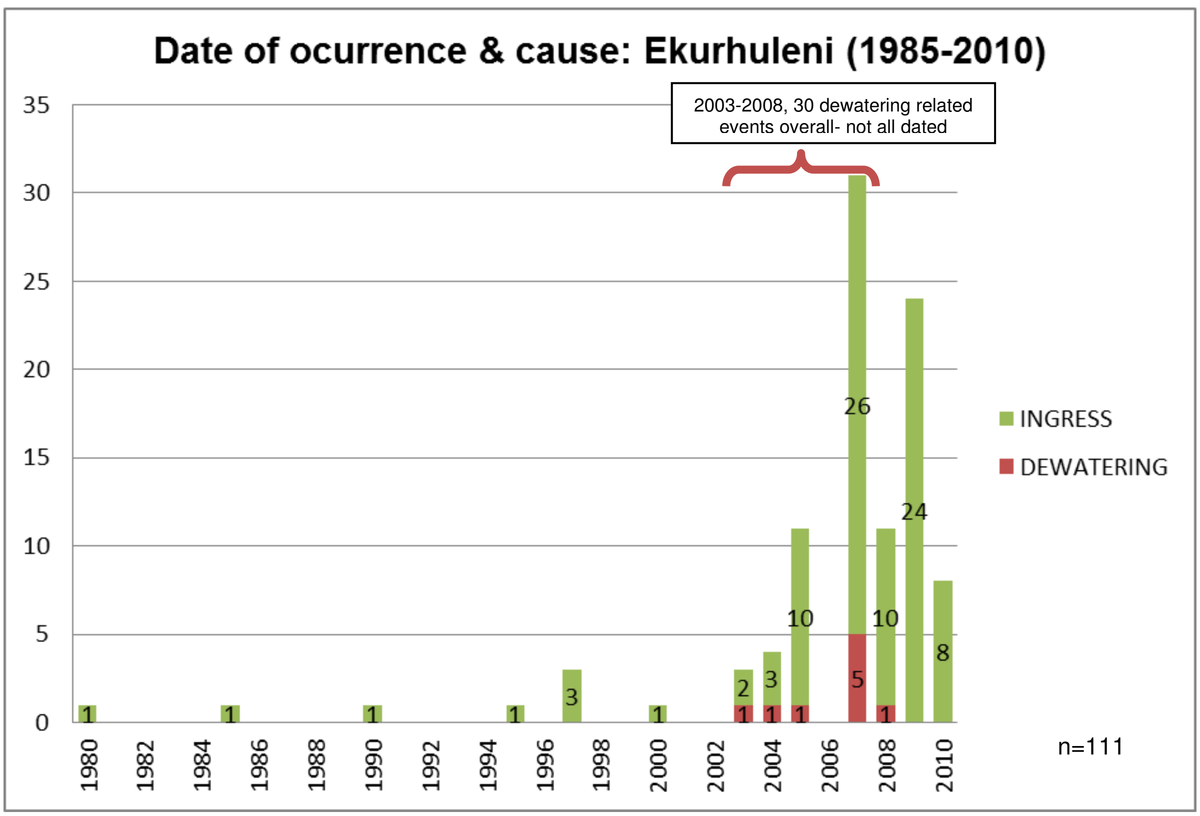
Table 16. Correlation coefficients and coefficient of determination, reported in literature for events vs. rainfall.

	Roux (1984)	Schőning (1990)	2012
r (sinkholes)	0.85	0.77	0.639
r^2 (sinkholes)	0.73	0.599	0.409
r (subsidence)	-	-	0.423
r^2 (subsidence)	-	0.233	0.176

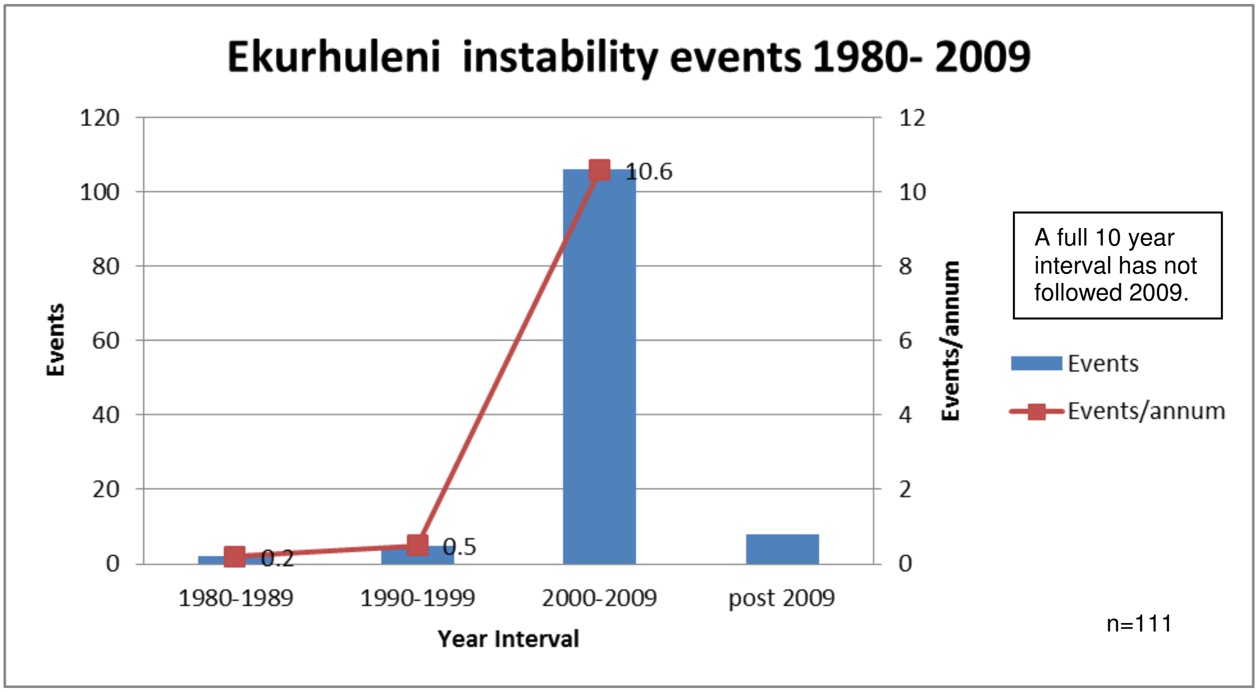
4.1.3 Ekurhuleni Metropolitan Municipality

An estimated 166 events have occurred in Ekurhuleni from 1985 -2010;

- 111 (67%) events have chronological data recorded (Graph 9), it is not known in which years the remaining events occurred, but were recorded after 1985.
- Very few occurrences are noted in the 1980's - 90's and a marked increase can be seen from the 2000's (Graph 10). This may be due to better recording and organization of information; the Dolomite Section of the Ekurhuleni Metropolitan Municipality was introduced around 2004, and/or the dewatering taking place in the Bapsfontein Groundwater compartment, which resulted in 30 events (18%) occurring between 2003 and 2008.
- Considering 166 events have occurred from 1980 to 2010, the overall average is 5.53 events per annum.
- Using data between 2000 and 2009 the period showing a dramatic increase in events, the average is 10.6 events per annum.



Graph 9 Reported instability occurrences in Ekurhuleni 1985-2010 (data limited to events with chronological data).



Graph 10. General representaion of reported instability occurrences in Ekurhuleni 1980 – 2009, in 10 year intervals (data limited to events with chronological data).

4.1.4 City of Johannesburg District Municipality

An estimated 16 events have occurred in City of Johannesburg from 1960 - 2011; 10 events occurred between 1960 and 1970 and three events occurred between 1990 and 2000, the dates of the remaining three events are unknown.

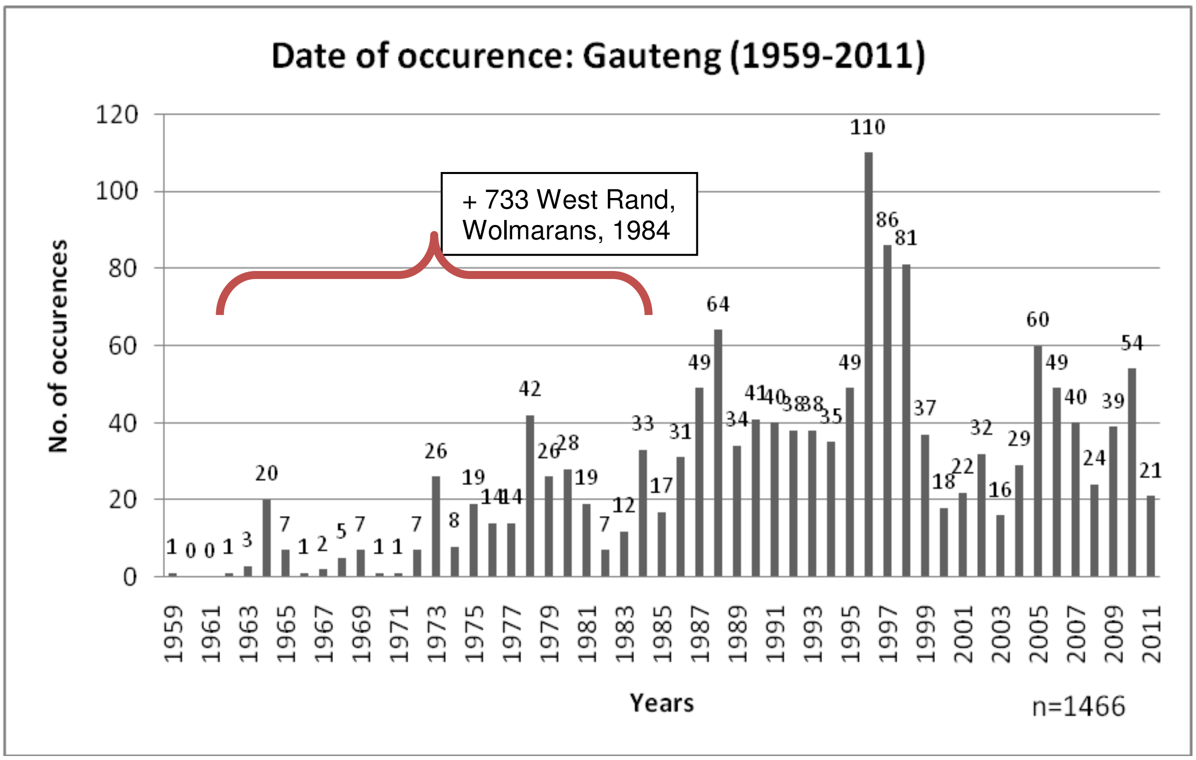
4.1.5 Gauteng Overall

An estimated 3048 events have occurred overall in Gauteng;

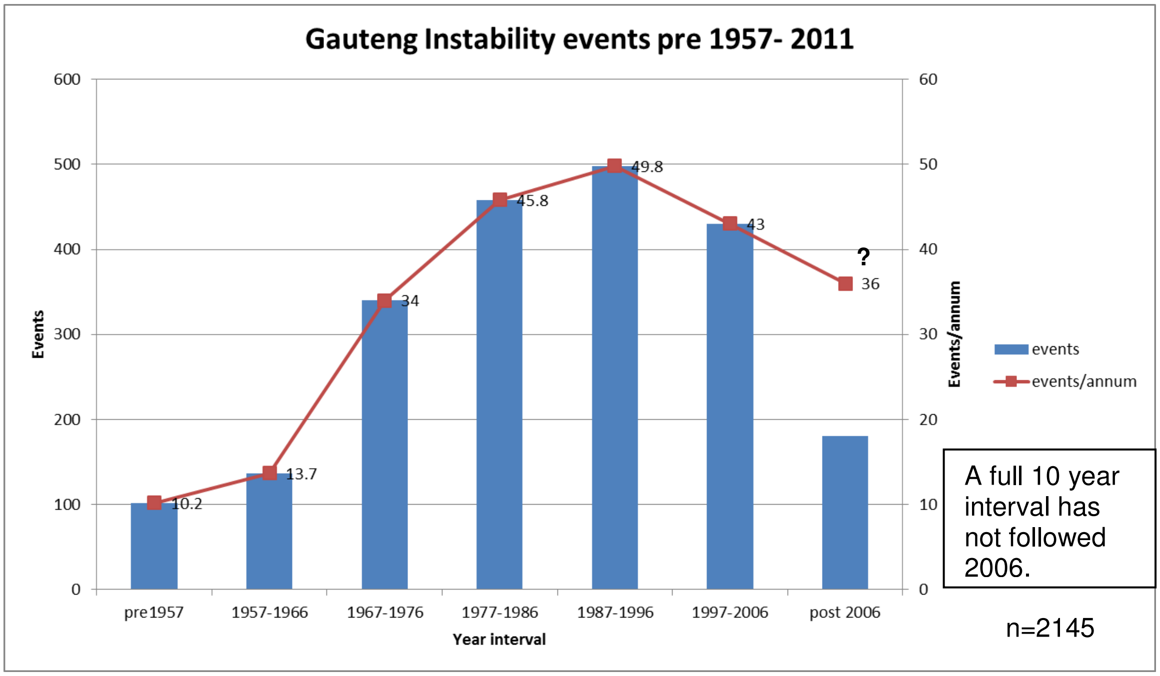
- Only 1466 (48%) of these events recorded for Gauteng indicate the year of occurrence as shown in Graph 11 and an additional 679 (22%), at least indicate a year range;
- The overall trend using limited data (only those with year dates or ranges recorded i.e. 2145, 70%) (Graph 12) shows an increase in the number of events till the late 1980's, early 1990's, then a decreasing trend from the late 1990's. Post 2006, a full 10 year interval has not elapsed, however if we assume a similar number of occurrences in the next 5 years, the trend is still decreasing.
- The increase from 1957 would largely be explained by the accelerated formation of sinkholes on the West Rand due to dewatering and increasing urbanization in the

Tshwane area and associated increased density of services and time for services to deteriorate since township establishment.

- The decrease in the late 1990's and early 2000's could be explained due to increased investigations on dolomite land (development of better methodologies and guidelines) and/or better management and awareness.
- As can be seen from Table 15, the number of events having occurred in Tshwane over the past 60 years is similar to the number of events in the West Rand, even though two different scenarios (i.e. ingress & dewatering) were prevalent in each of these areas.
  - The West Rand's record of events prior to 1984 (the time when sinkhole formation was accelerated due to dewatering) is similar to that post 1984, where most instances are attributed to ingress. After dewatering began, development largely stopped (i.e. Bank) or progressed slowly on the West Rand.
  - Tshwane's record is almost entirely attributed to ingress associated with rapid increase in development.



Graph 11. Reported instability occurrences in Gauteng 1959-2011 (data limited to events with year dates recorded).



Graph 12. General reported instability occurrences in Gauteng before 1984 – after 2005, in 10 year intervals (data limited to events with chronological data).

4.2 TYPE OF EVENT

The total estimated events in Gauteng Province shows 69.9% of occurrences were recorded as sinkholes, 17.9% as subsidences, 5.2% as cracks and 7.0 % of events were undefined (Table 17 & Graph 13). A large percentage of the type of events for the West Rand prior to 1984 had to be determined from historical maps, which may have generalized the events and some degree of error may be present.

Difficulties in comparing areas arise due to the limited accurate data. Both Tshwane and Ekurhuleni indicate approximately 60% of occurrences are sinkholes, while in West Rand approximately 80% are sinkholes. However events in Tshwane and Ekurhuleni were positively indicated as sinkholes, while a large portion of events in West Rand had to be inferred (56%). Therefore the former two areas are more likely to be accurate with regards to the percentage of sinkholes.

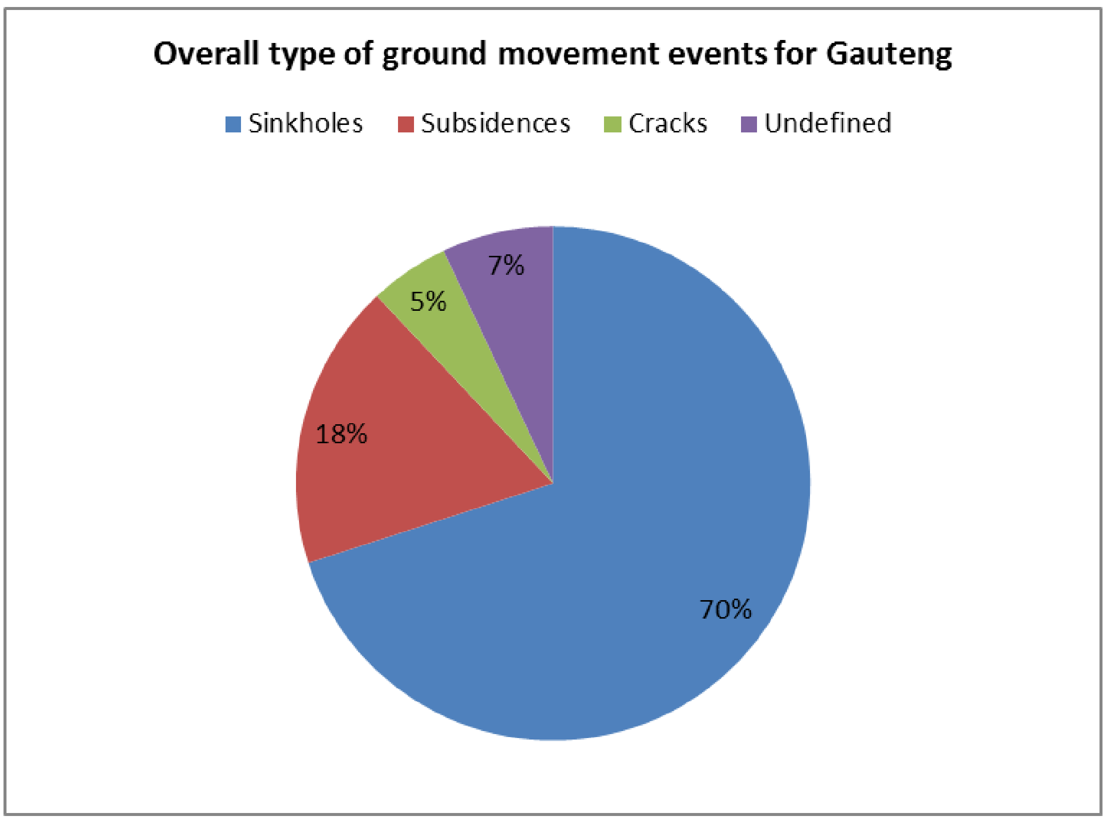
The same case can be argued for subsidences, Tshwane and Ekurhuleni indicate between 25-30% as subsidences, while the West Rand only 7.5%. The former two areas percentages are more likely to be correct and instances of subsidence were either undefined or indicated as sinkholes on historical maps on the West Rand. Graph 13 is based on data limitations, therefore a more generalized percentage of the type of events is proposed in Graph 14.

Category of events; whether sinkhole, subsidence or cracks are shown symbolically on Maps A1- D1, Appendix A.

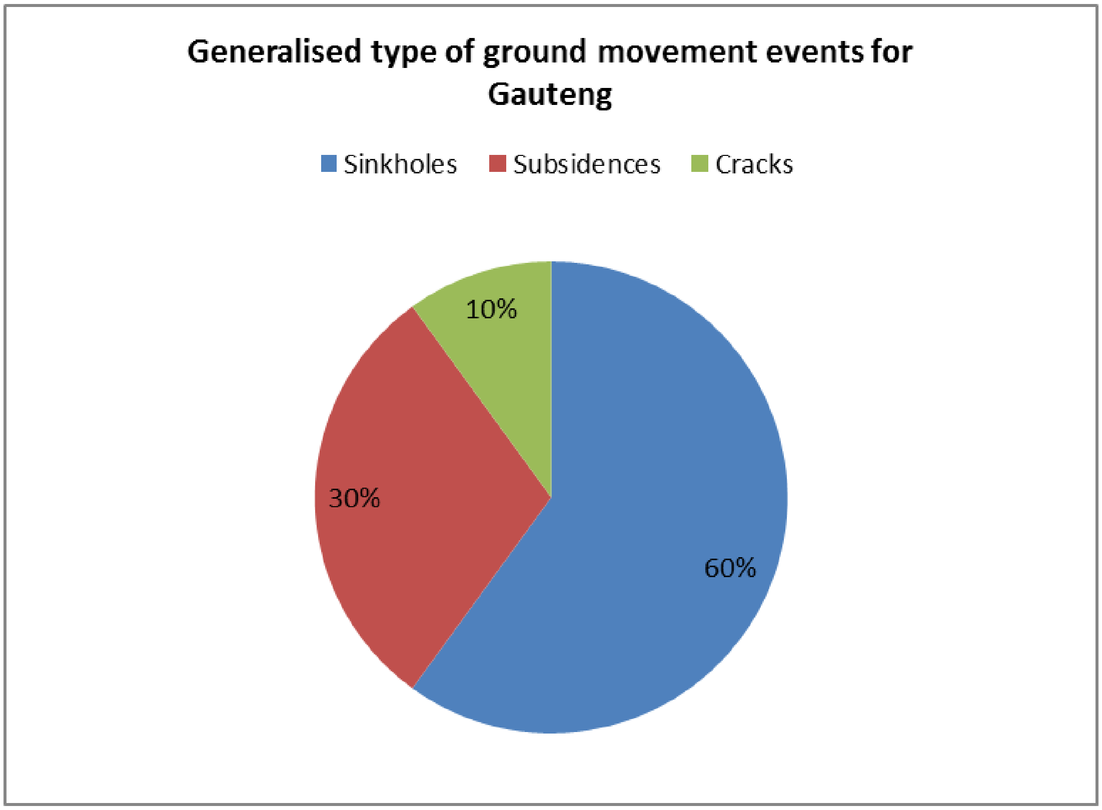
Table 17. Types of instability events for Gauteng Province.

	SINKHOLES	SUBSIDENCE	CRACKS	UNDEFINED	TOTAL	%
TSHWANE (%)	824 (59.2)	398 (28.6)	46 (3.3)	130 (9.3)	1393	**45.70**
WEST RAND (%)	1195* (81.1)	110 (7.5)	106 (7.2)	62 (4.2)	1473	**48.33**
EKHURHULENI (%)	96 (57.8)	41 (24.7)	7 (4.2)	22 (13.3)	166	**5.45**
JOHANNESBURG (%)	16 (100)	0	0	0	16	**0.52**
TOTAL	**2131**	**544**	**159**	**214**	**3048**	
%	**69.9**	**17.9**	**5.2**	**7.0**		**100**

* Events prior to 1983 had to be inferred from historical maps which may have generalized the event as a sinkhole.



Graph 13. Overall types of events, based on Table 17.



Graph 14. Generalised types of events.

4.3 GEOLOGICAL FORMATIONS

The 1: 250 000 scale Geological series (2626 West Rand, 2528 Pretoria, and 2628 East Rand) cover the study area, and indicates the position of the Malmani Subgroup dolomite. Not all of these areas are however covered by detailed, 1:50 000 scale geological mapping, from which the different formations within the dolomite and be discerned. Areas in the West Rand, or instance are not covered by this detailed mapping and extrapolation was necessary in some cases.

Digitized geological maps were viewed on a GIS and point positions of events were overlain as accurately as possible, according to co-ordinates or descriptions. Table 18 was produced using the position of the data point on the geological map to determine the geological formation.

Some extrapolation was necessary in areas not covered by detailed geology information (1: 50 000 maps). Some events occur on the Pretoria Group rocks or Ecca Group etc. (*referred to in tables or graphs as 'other'*). These are underlain by dolomite at varying depths, and are therefore considered dolomitic land. Events on the different dolomite Formations are shown on Map A2- D2, Appendix A.

Table 18. Events on the dolomite Formations.

	ECCLES	LYTTELTON	MONTE CHRISTO	OAKTREE	'OTHER'	TOTAL
WEST RAND (%)	394 (26.7)	117 (7.9)	568 (38.6)	221 (15)	173 (11.7)	**1473**
Wolmarans (1984) (%)	135 (19.5)	32 (1.1)	483 (69.9)	6 (0.86)	35 (5.1)	691
Current data using Wolmarans (1984) formations map (%)			609 (41.4)	5 (0.3)		
TSHWANE (%)	545 (39.1)	408 (29.3)	385 (27.6)	4 (0.3)	51 (3.7)	**1393**
Schőning (1990, 1996) (%)	201 (54.9)	47 (12.8)	118 (32.2)	0 (0)	- -	366
EKHURHULENI (%)	14 (8.4)	2 (1.2)	123 (74.1)	0 (0)	27 (16.3)	**166**
JOHANNESBURG (%)	0	0	16 (100)	0	0	**16**
TOTAL (%)	**939 (30.81)**	**527 (17.29)**	**1093 (35.86)**	**225 (7.38)**	**264 (8.66)**	**3048**

4.3.1 West Rand District Municipality

When overlying events on the geology maps for the West Rand (Map A2, Appendix A), it was found that a large area between Blybank and Khutsong is not covered by detailed (1:50 000 scale) mapping. Some extrapolation was therefore necessary and Wolmarans's map (Figure 11) was used where possible to extrapolate the formation contacts. A degree of error may therefore be present.

Wolmarans (Table 6 & Table 18) initially showed that the chert-rich Monte Christo Formation had experienced the most occurrences prior to 1984, followed by the chert–rich Eccles Formation. This table indicates the majority of the events had occurred on the Monte Christo Formation (69.9%), followed by a substantially smaller percentage on the Eccles Formation (19.5%), on the Lyttelton Formation (1.1%) and Oaktree Formation (0.9%). Current results indicate a much smaller difference between the number of events on the Monte Christo and the number of events on the Eccles Formation.

Based on the available data; the largest percentage (38.6%) of events have occurred on the Monte Christo Formation (Table 18), followed by the Eccles Formation (26.7%), followed in turn by the Oaktree Formation (15%) and then the 'other' formations (11.7%) which may be underlain by dolomite at depth and the Lyttleton Formations (7.9%).

The Oaktree Formation now also shows a much greater percentage of events compared with the 1984 results. The current percentages may be an overestimation as a large portion come from historical sources that may need further verification. In total 15% of these events are visible on Quick Bird aerial images (2004). These events fall mostly in the flood plain area of the Wonderfonteinspruit and close to the Oaktree- Monte Christo contact, based on the 1: 50 000 scale map (Figure 29). Wolmarans's map (Figure 12 & Figure 28) shows the contact more to the north of the Wonderfonteinspruit than the 1:50 000 geological map (unpubl). Brink (1979) also notes that the vast majority of the sinkholes had formed in the pediment and the flood-plain of the Wonderfonteinspruit, where the effect of the lowering of the water table has been critical.

If the occurrences are superimposed on Wolmaran's (1984) geology map, 41.4% of the events have occurred on the Monte Christo Formation and only 0.3 % on the Oaktree Formation. This is still not as high a percentage on the Monte Christo Formation as Wolmarans (1994), but Oaktree Formation occurrences are then similar.

Based on the available information, it appears the chert-rich formations have experienced the most sinkholes and subsidences in the Far West Rand area.

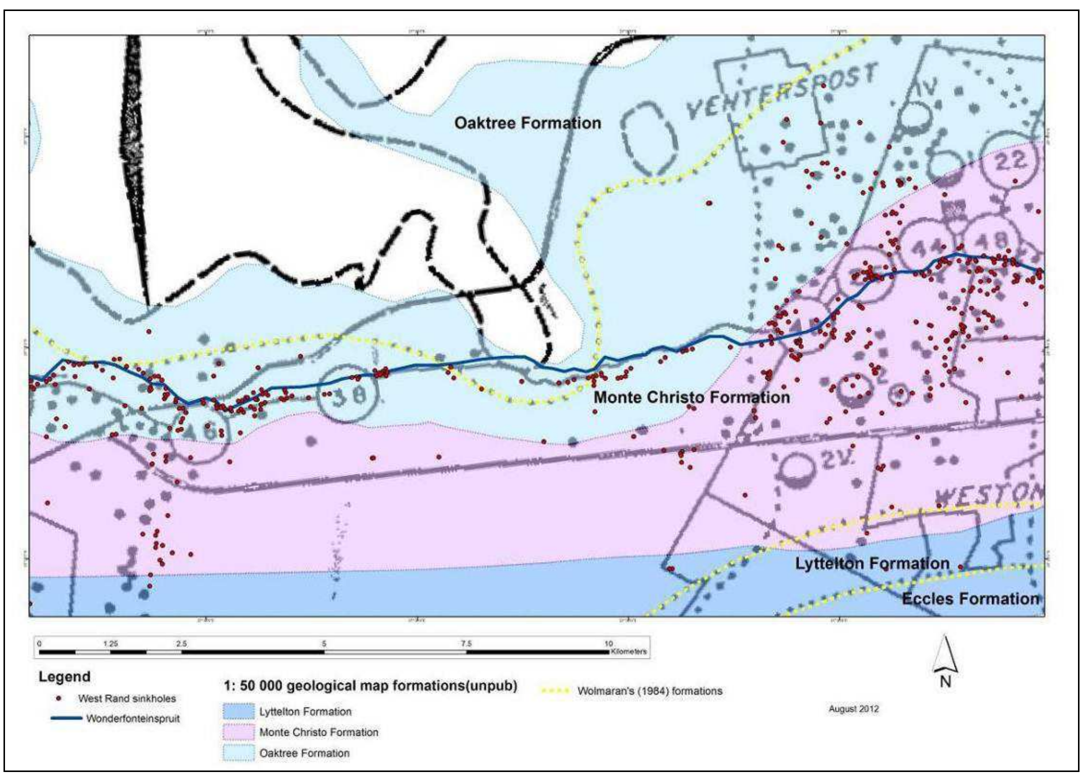


Figure 28. Wolmarans's (1984) map overlain on 1: 50 000 scale Geological map (unpubl.), CGS.

4.3.2 City of Tshwane Metropolitan Municipality

In trying to understand which Formation in the area south of Pretoria is most vulnerable to sinkhole and subsidence formation, Schőning (1990) showed that 201 (54.9 %) events occurred on the Eccles, 47 (12.8%) events on the Lyttelton and 118 (32.2%) events on the Monte Christo Formation. Schőning (1990) stated that the Eccles and the Monte Christo Formations are approximately 2 times and 3.8 times larger in surface area respectively than the Lyttelton Formation in the area south of Pretoria. Therefore we might expect there to be more sinkholes on these Formations.

When superimposing events and the dolomite Formations (1:50 000 Centurion) for the City of Tshwane, 545 (39.1%) have occurred on the Eccles Formation, 408 (29.3%) have occurred on the Lyttelton Formation, 385 (27.6%) have occurred on the Monte Christo Formation, and only 4 (<1%) are recorded on the Oaktree Formation. A total of 51 (3.6%) have occurred on Pretoria Group or Karoo Supergroup rocks ('other') that are underlain by dolomite at depth (Table 18) (Map B2, Appendix A).

Schőnings results are similar to current data in so far that the chert- rich Eccles Formation shows the most instability events, however the Lyttelton Formation almost has the same percentage as the Monte Christo Formation (Table 18). This can be attributed to the fact that more data covering the Lyttelton area was available for the current analysis, than was previously available for Schőning's study. Based on the results for these three formations, there appears not to be a preference for sinkholes to happen on chert rich Formations. If however the chert-poor Oaktree Formation (with only 4 recorded events and very little development) is taken into account, more events have occurred on the chert-rich Formations.

4.3.3 Ekurhuleni Metropolitan Municipality

In Ekurhuleni, 123 (74.1%) events have occurred on the Monte Christo Formation, only 14 (8.4 %) have occurred on the Eccles, 1.2 % on the Lyttelton Formation and 27 (16.3%) occur on 'other' formations (Table 19), which may be underlain by dolomite at depth (Map C2, Appendix A). Most of the development on dolomite within Ekurhuleni has taken place on the Monte Christo Formation. These include Vosloorus and Katlehong. Large portions of Ekurhuleni are covered by Karoo Supergroup sediments (approximately 44% of surface area) which overly the dolomite and offer a measure of protection against water ingress and aid in mitigating sinkhole development.

4.3.4 City of Johannesburg

The few events on dolomite in the City of Johannesburg have all occurred on the Monte Christo Formation, according to the 1:50 000 geological map (Map D2, Appendix A).

4.3.5 Gauteng Overall

Overall the largest percentage of events have occurred on the chert–rich sediments of the Monte Christo Formation (35.86%), followed by the Eccles Formation (30.81 %). The Lyttelton Formation follows in turn with (17.29%), 'Other" formations (8.66 %) and the Oaktree Formation (7.38%).

4.4 TRIGGERING MECHANISMS

The triggering mechanisms that are considered in this section are dewatering and ingress water, which are most commonly recorded as the cause of sinkholes in Gauteng. Other triggers i.e. ground vibration may also play a role but little information exists.

4.4.1 West Rand

Figure 30 shows the distribution of events across the groundwater compartments in the West Rand. Dewatering greatly accelerated sinkhole and subsidence development in the Oberholzer, Bank and Venterspost Groundwater compartments.

Wolmarans (1984) indicated:

i. A number of sinkholes occurred prior to the start of dewatering in the various compartments which could be attributed to water ingress. Many of these were in the non- dewatered Boskop-Turffontein Compartment (177 events).
ii. The majority of events (71.4%) prior to 1984 were as a result of dewatering (Table 19).
iii. A few events that took place after the start of dewatering but prior to 1984 could be attributed also to water ingress.

Post 1984 most events (64.2 %) can be attributed to ingress based on the recorded "cause" (Table 20). However some causes attributed to ingress may be related to dewatering. Very few events after 1984 are attributed to dewatering (4.3%), but the "unknown cause" cases in the dewatered compartments (28.8%) may fall into this category.

Overall, when combining the data from 1960 - 2011 for the West Rand (Table 21), 46% of events can be attributed to ingress, 38 % of events are as a result of dewatering and 14.4%

are likely due to dewatering as they occurred in dewatered compartments, while in 1.4% the cause was not indicated (Graph 15). Most events have occurred in the Oberholzer Groundwater Compartment (29.9 %), and the Bank and Venterspost compartments show only slightly smaller percentages. The Boskop-Turrfontein compartment shows 20.2% of events, these events occur in two groupings around the Khutsong Township (most occurring post 1980) as can be seen in the cluster north of the Wonderfonteinspruit (Figure 29) and the Doornfontein Mine (southern Cluster).

According to Brink and Partridge (1965) many ancient (i.e. natural) sinkholes and subsidences have occurred in this area. No further information regarding these occurrences could however be retrieved.

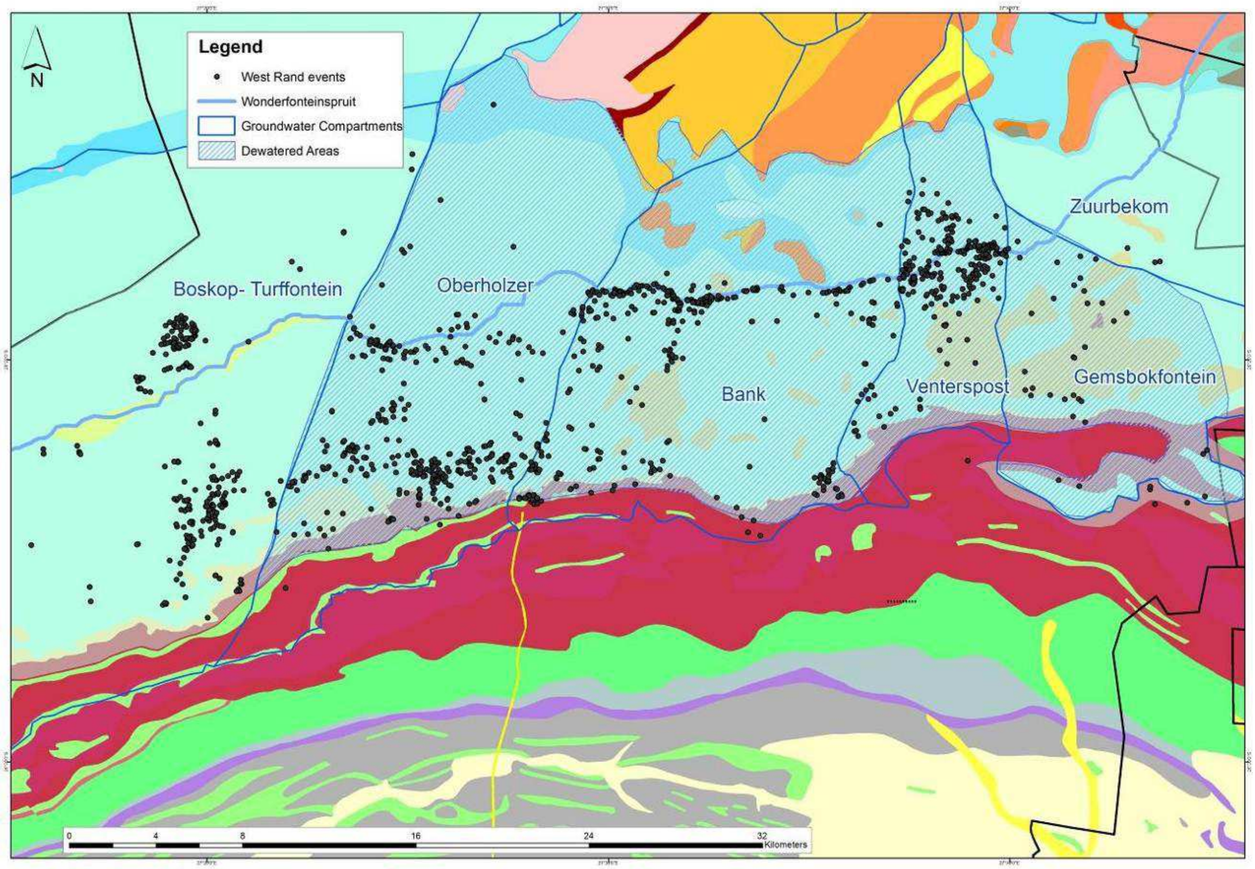


Figure 29: Distribution of events on the West Rand across the Groundwater Compartments (Geology: 1: 250 000, Council for Geoscience).

Table 19. Causes of events occurring in the West Rand Groundwater Compartments prior to 1984.

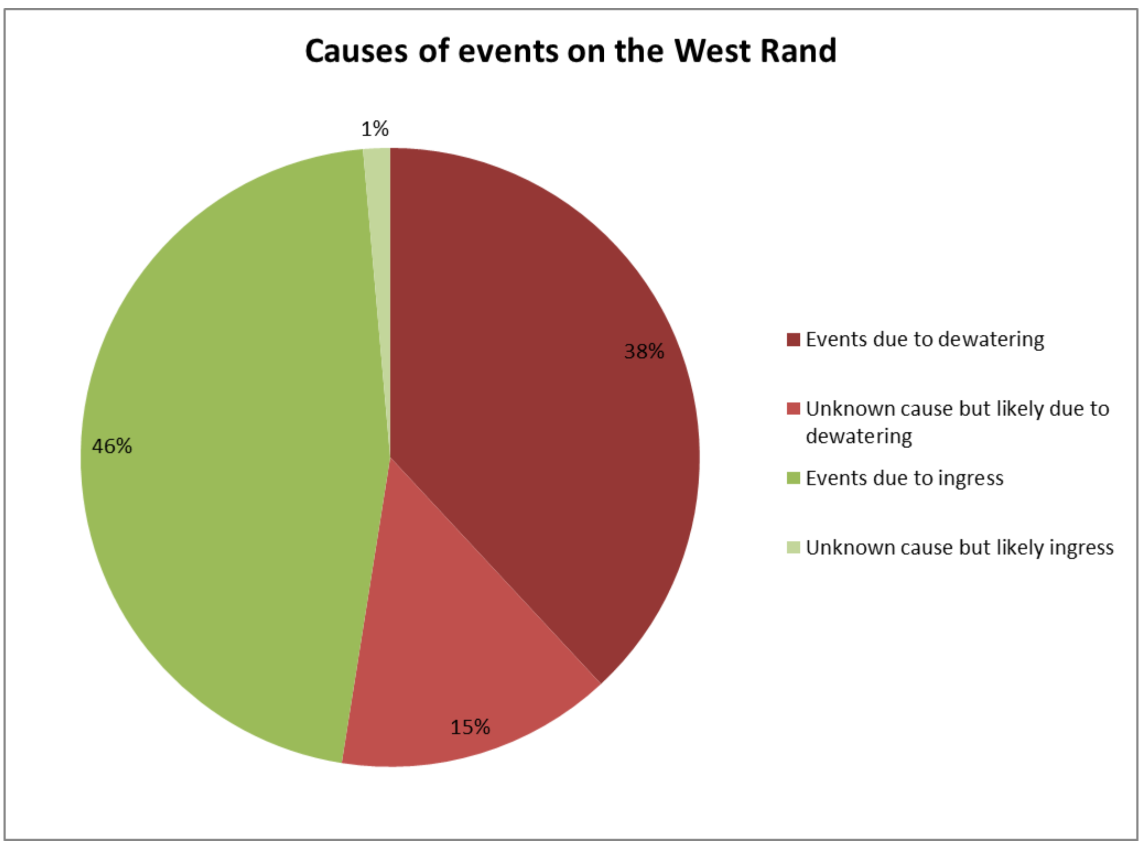
COMPARTMENT	EVENTS DUE TO DEWATERING	EVENTS DUE TO UNKNOWN CAUSE	EVENTS DUE TO INGRESS	TOTAL	%
Prior 1984 (combined Table 1 & Table 2 after Wolmarans)					
BOSKOP-TURFFONTEIN	0	-	117	**117**	**16**
OBERHOLZER	75	-	68	**143**	**19.5**
BANK	186	-	22	**208**	**28.3**
VENTERSPOST	262	-	3	**265**	**36.2**
TOTAL	**523**	**-**	**210**	**733**	**100**
%	**71.4**	**-**	**28.6**		**100**

Table 20. Causes of events occurring in the West Rand Groundwater Compartments post 1984.

COMPARTMENT	EVENTS DUE TO DEWATERING	EVENTS DUE TO UNKNOWN CAUSE (* Likely dewatering related)	EVENTS DUE TO INGRESS	TOTAL	%
data post 1984 – end 2011					
BOSKOP-TURFFONTEIN	0	17	163	**180**	**24.3**
OBERHOLZER	7	91*	200	**298**	**40.4**
BANK	12	59*	105	**176**	**23.8**
VENTERSPOST	12	22*	6	**40**	**5.4**
GEMSBOKFONTEIN	0	41*	-	**41**	**5.6**
ZUURBEKOM	0	3	-	**3**	**0.4**
TOTAL	31	233	474	**738**	
%	**4.3**	**31.5**	**64.2**		**100**

Table. 21. Combined data of causes of events occurring in the West Rand Groundwater Compartments 1960- 2011.

COMPARTMENT	EVENTS DUE TO DEWATERING	EVENTS DUE TO UNKNOWN CAUSE (* Likely dewatering related)	EVENTS DUE TO INGRESS	TOTAL	%
		Combined data 1960- 2011			
BOSKOP-TURFFONTEIN (%)	0	17 (5.7)	280 (94.3)	**297**	**20.2**
OBERHOLZER (%)	82 (18.6)	91 * (20.6)	268 (60.8)	**441**	**29.9**
BANK (%)	198 (51.6)	59 * (15.4)	127 (33.1)	**384**	**26.1**
VENTERSPOST (%)	274 (89.8)	22* (7.2)	9 (3.0)	**305**	**20.7**
GEMSBOKFONTEIN (%)	0	41* (100)	-	**41**	**2.8**
ZUURBEKOM (%)	0	3 (100)	-	**3**	**0.2**
TOTAL	**554**	**233**	**684**	**1471**	**100**
%	**37.6**	**14.4*** **1.4**	**46.4**		



Graph 15. Overall causes of events on the Far West Rand.

4.4.2 City of Tshwane

Events occurring in Tshwane are primarily considered to be as a result of ingress water, either directly associated with anthropogenic influences or natural factors.

- Natural vs. man made

Schőning (1990) ascribed only 20 (6%) of the total 375 events he had compiled for the entire area south of Pretoria to be from natural causes. Buttrick *et al*, (2011) indicates 99% of events in a study area south of Pretoria were found to be directly attributed to leaking services; only seven (7) events fell in open land and could not be ascribed to any particular triggering agency.

Only 26.9% of the data compiled for Tshwane has a cause/trigger recorded, therefore the spatial distribution of the data (excluding Schőning, 1990, and Buttrick *et al. 2011*), was looked at in relation to proximity of urban development, infrastructure etc.

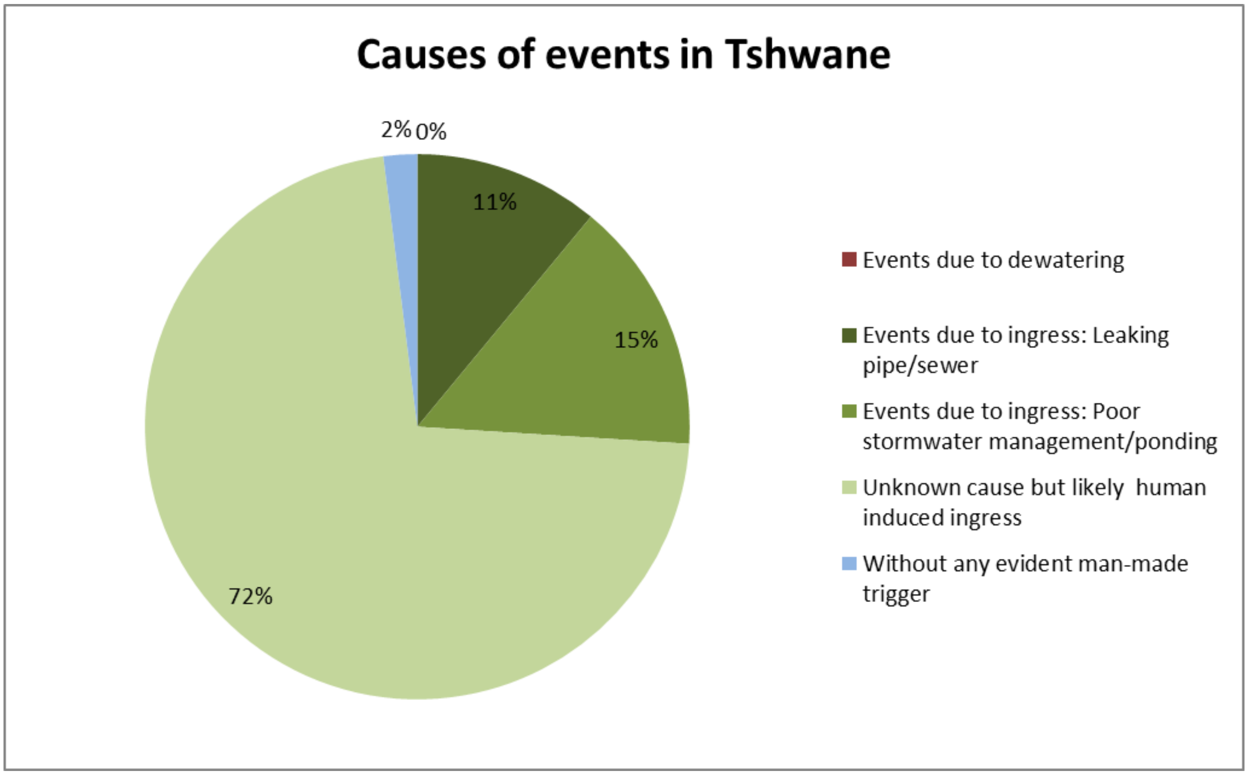
- Events occurring in or in close proximity to urban development and infrastructure were disregarded as leaking services or ponding stormwater were more likely the cause.
- In open areas where events showed linear alignment to other events, these were disregarded, as this may indicate underground bulk services, also events in line with roads or tracks may suggest stormwater run-off as the likely cause, and were disregarded.

No other events could be positively identified as naturally occurring.

If one considers no other occurrences except those 27 noted in literature (Schőning, 1990, and Buttrick *et al. 2011*) and assuming these are all different events; compared to the overall number of 1393 events for Tshwane, this translates to at least 2% that may be considered as natural occurrences without any evident man-made trigger (Graph 16), within the Tshwane dolomite area. In summary (Table 22), 0% are attributed to dewatering, 98% are as a result of ingress and 2% are considered to be natural occurrences.

Table. 22. Causes of events within the Tshwane area 1960-2011.

	EVENTS DUE TO DEWATERING	EVENTS DUE TO INGRESS	EVENTS DUE TO UNKNOWN CAUSE (* Likely ingress related)	EVENTS WITHOUT ANY EVIDENT TRIGGER	TOTAL	%
Tshwane	0	359	1007	27	**1393**	
%	**0**	**25.8**	**72.3**	**1.9**		**100**



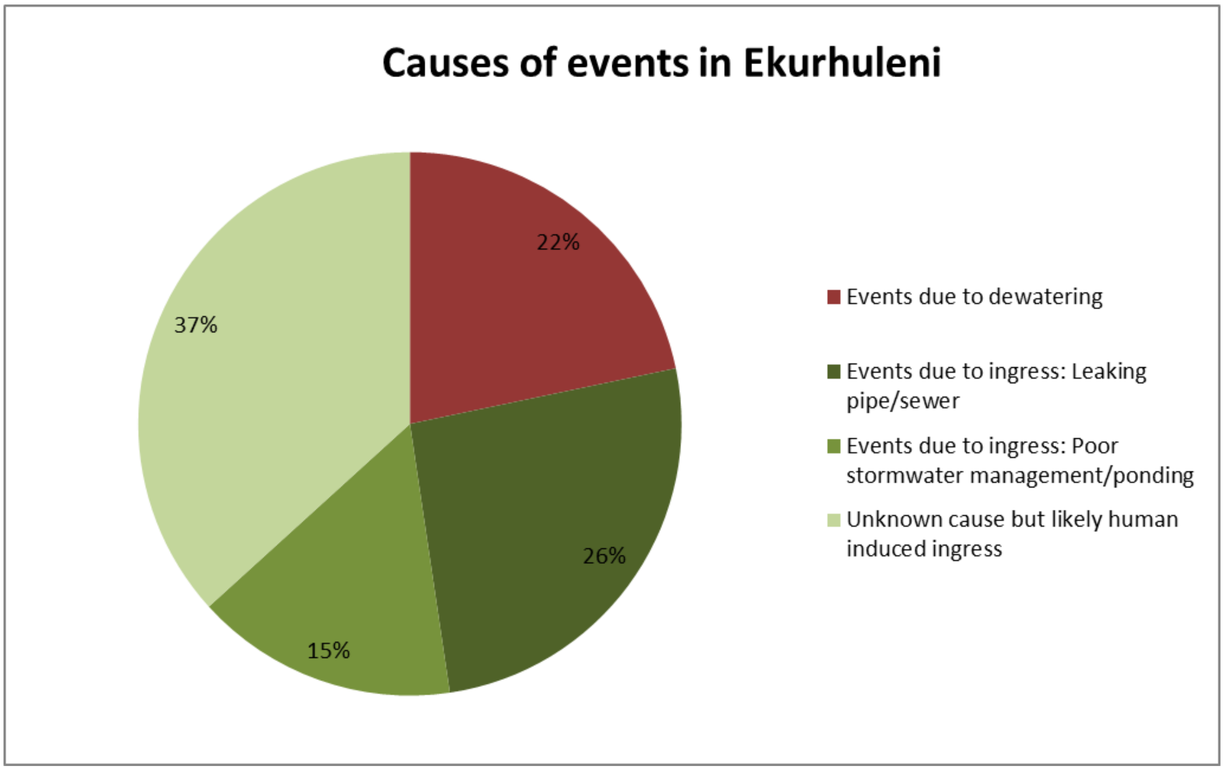
Graph 16. Overall causes of events within Tshwane.

4.4.3 Ekurhuleni

For Ekurhuleni, out of the estimated 166 events, 63.3% of the data had a cause/trigger recorded. All events in Ekurhuleni were within or in close proximity to developed areas (i.e. Katlehong, Tokoza and Vosloorus) these incidents being related to leaking and inappropriately designed, poorly installed and maintained water bearing services (GSI Projects, 1996), or identified as due to dewatering (Bapsfontein and Elandsfontein) and therefore no natural occurrences could be positively identified. In total 22% of events recorded were related to dewatering, and the remaining 78% of events were related to water ingress (Table 23 & Graph 17).

Table. 23. Causes of events within the Ekurhuleni 1980-2010.

	EVENTS DUE TO DEWATERING	EVENTS DUE TO INGRESS	EVENTS DUE TO UNKNOWN CAUSE (* Likely ingress related)	EVENTS WITHOUT ANY EVIDENT TRIGGER	TOTAL	%
Ekurhuleni (%)	36	69	61	**0**	**166**	
%	**21.7**	**41.6**	**36.7**	**0**		**100**



Graph 17. Overall causes recorded of events in Ekurhuleni.

4.5 SIZE AND DEPTH DISTRIBUTION

Sinkhole size is a very important parameter as land use and design decisions are made according to the size event expected. The size distribution was analyzed according to the size categories proposed (Buttrick and Van Schalkwyk, 1995) in Table 11; however it was necessary to be more specific in terms of defining the start and end of each category when assigning occurrences to a specific size category. The following categories were used in terms of diameter to avoid overlap in categories (Table 24). Depth categories were previously defined by Schőning 1990 (Table 9), however a modification of Schőning's depth categories and Buttricks diameter categories was used (Table 25).

Table 24. Sinkhole and subsidence size categories.

Sinkhole and subsidence diameter categories.			
Small	Medium	large	Very large
≤2m	>2m-≤5m	>5m-≤15m	>15m

The following broad categories were used for sinkhole and subsidence depths.

Table 25. Sinkhole and subsidence depth categories.

Sinkhole and subsidence depth categories.			
≤1m	>1m-≤5m	>5m-≤15m	>15m

4.5.1 Sinkhole Diameters

An estimated 2131 events have been recorded as *sinkholes* across Gauteng, but only in 1005 (47.2%) have diameter information been established. Considering the available data across the entire dolomite area in Gauteng (Table 26);

- 18.51% of the sinkhole events are less than or equal to 2m diameter,
- 26.37 % are between greater than 2m and less than or equal to 5m diameter,
- 32.24% are between greater than 5m and less than or equal to 15m diameter and
- 22.89 % are larger than 15m diameter.

The dominant size is between 5m and 15m diameter overall. In general, based on the overall available data, 77% of sinkholes are less than or equal to 15m diameter across Gauteng.

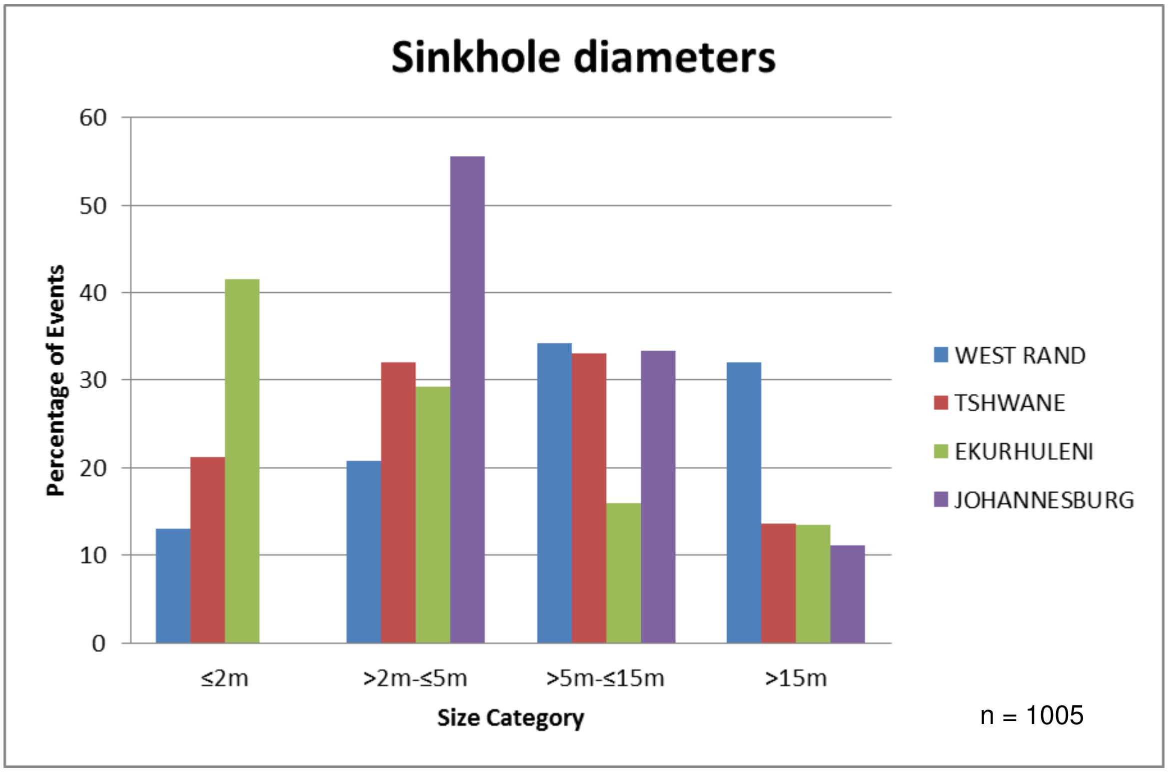
With respect to sinkhole diameter only limited information for each municipality has been recorded (Table 26 & Graph 18);

- West Rand; out of the estimated 1195 *sinkhole* events, 509 (42.6%) have diameter information and from that available data the largest percentage of sinkholes in the West Rand (>60%) are large to very large (i.e. greater than 5m to greater than 15m diameter). Because events post 1984 was mostly used (due to more detailed records), there may still be an underestimation in the very large events category. Prior to 1984 very large sinkhole events which formed as a result of dewatering were notorious on the West Rand.
- City of Tshwane; out of the estimated 824 *sinkhole* events only 405 (49%) have diameter information. From the available data the largest percentage of sinkholes in Tshwane (>60%) are medium to large (i.e. greater than 2m to less than or equal to 15m diameter).
- Ekurhuleni; out of the estimated 96 *sinkholes* events, 82 (85%) have diameter information and the largest percentage (>70%) of events are small to medium (i.e. less than 2m to less than or equal to 5m diameter).

This may be some indication of the development space that can be expected in each area; the West Rand is notorious for very large sinkholes and generally the depth to dolomite bedrock can reach very great depths. The depth to bedrock in the Tshwane region is typically intermediate to great and areas in Ekurhuleni are known for shallow dolomite bedrock (except in places covered by thick Karoo, where dewatering led to very large events). More large to very large sinkholes, medium to large sinkholes and small to medium sinkholes may in general be expected for each area respectively. This does not discount the possibly of other size events occurring however.

Table 26. Sinkhole diameter distribution for Gauteng.

SINKHOLE DIAMETERS						
	≤2m	>2m-≤5m	>5m-≤15m	>15m	TOTAL	%
WEST RAND (%)	66 (13.0)	106 (20.8)	174 (34.2)	163 (32.0)	**509**	**50.65**
TSHWANE (%)	86 (21.2)	130 (32.1)	134 (33.1)	55 (13.6)	**405**	**40.3**
EKURHULENI (%)	34 (41.5)	24 (29.3)	13 (15.9)	11 (13.4)	**82**	**8.16**
JOHANNESBURG (%)	0	5 (55.6)	3 (33.3)	1 (11.1)	**9**	**0.9**
TOTAL	**186**	**265**	**324**	**230**	**1005**	
%	**18.51**	**26.37**	**32.24**	**22.89**		**100**
DATA MISSING	**1126**					



Graph 18. Sinkhole diameter distribution (Gauteng).

4.5.2 Sinkhole Depths

Although an estimated 2131 events have been recorded as *sinkholes* across Gauteng, only 825 (38.7%) have depth information recorded. Considering the available data across the entire dolomite area in Gauteng;

- 17.82 % of the sinkhole events are less than or equal to 1m in depth,
- 56.48 % are between greater than 1m and less than or equal to 5m depth,
- 21.58 % are between greater than 5m and less than or equal to 15m depth and
- 4.22 % are greater than 15m in depth (Table 27).

Sinkhole depth information is very limited and poorly estimated. In general, based on the overall available data, 95.8% of sinkholes are less than or equal to 15m depth.

Only limited information for each municipality has been recorded (Table 28);

- West Rand; out of an estimated 1195 *sinkhole* events 426 (35.6%) have depth information and the largest percentage (>50%) of these recorded are less than 5m deep. This may be an underestimation of deeper sinkholes in the West Rand (where some very deep events have occurred), as mostly data post 1984 was used.

- City of Tshwane, out of an estimated 824 sinkhole events 328 (40%) have depth information, and the largest percentage (>60%) of these recorded are less than 5m deep.
- Ekurhuleni; out of an estimated 96 *sinkhole* events 67 (70%) have depth information and the largest percentage (>50%) of these recorded are less than 5m deep.

This suggests that overall most sinkhole events are less than 5m deep (74.3 %), and 25.7% of events are greater than 5m depth.

Table 27: Sinkhole depth distribution for Gauteng.

SINKHOLE DEPTHS						
	≤1m	>1m-≤5m	>5m-≤15m	>15m	**TOTAL**	**%**
WEST RAND (%)	77 (18.1)	221 (51.9)	105 (24.6)	23 (5.4)	**426**	**51.3**
TSHWANE (%)	54 (16.5)	200 (61.0)	63 (19.2)	11 (3.4)	**328**	**39.5**
EKURHULENI (%)	19 (28.4)	37 (55.2)	10 (14.9)	1 (1.5)	**67**	**8.1**
JOHANNESBURG (%)	0	9 (100)	0	0	**9**	**1.1**
TOTAL	**150**	**467**	**178**	**35**	**830**	
%	**18.07**	**56.27**	**21.45**	**4.22**		**100**
DATA MISSING	**1301**					

4.5.3 Subsidence diameters

Although an estimated 544 events have been recorded as *subsidences* across Gauteng, only 210 (38.6%) have diameter information. Considering the available data across the entire dolomite area in Gauteng (Table 27);

- 25.54 % of the recorded subsidence events are less than or equal to 2m diameter,
- 4.81 % are greater than 2m and less than or equal to 5m diameter,
- 25.93% are greater than 5m and less than or equal to 15m diameter and
- 34.72 % are larger than 15m diameter.

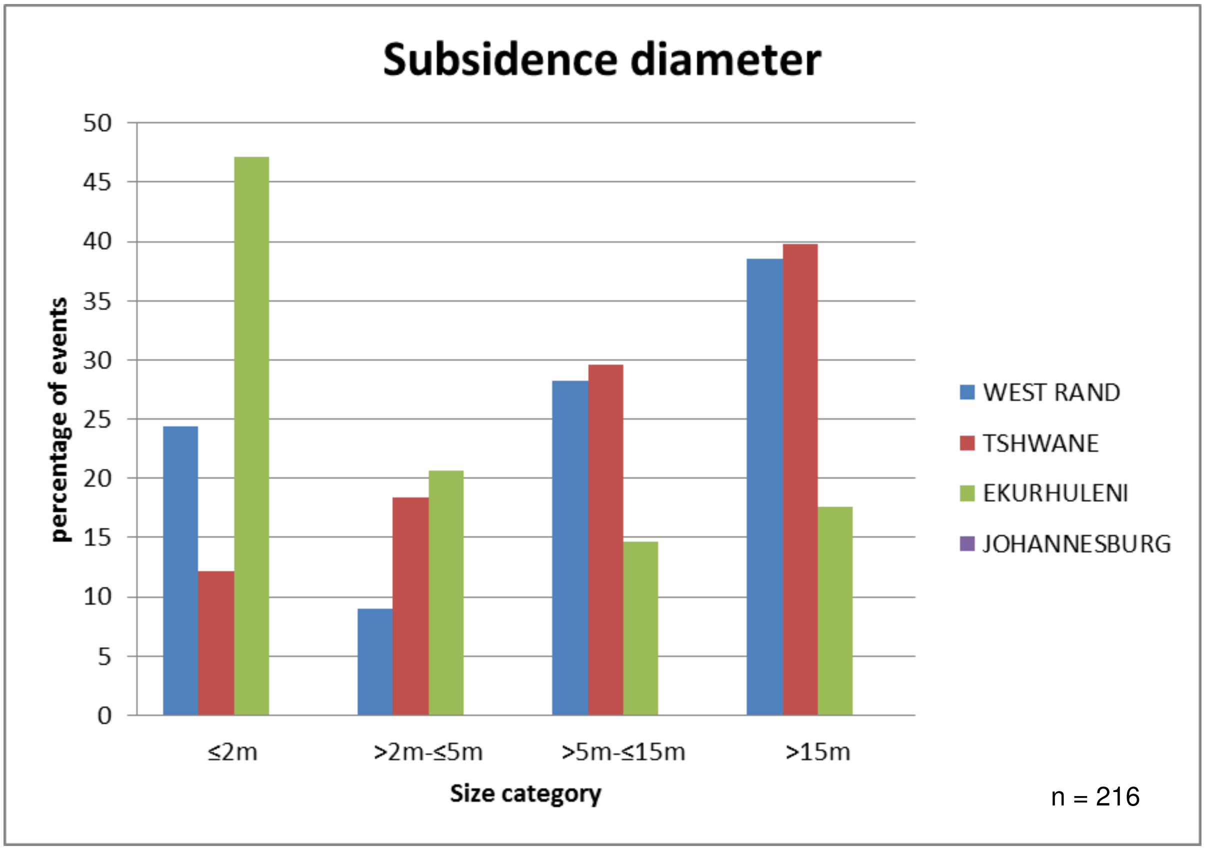
In summary subsidences are generally large to very large (greater than 5m diameter). In total 64.3% of subsidences are less than or equal to 15m diameter across Gauteng.

Only limited information on subsidence diameters for each municipality has been recorded (Table 28 & Graph 19);

- West Rand; out of the estimated 110 *subsidence* events, 78 (70.9%) have diameter information and from those recorded the largest percentage of subsidences in the West Rand (>60%) are large to very large (i.e. greater than 5m to greater than 15m diameter). There may be an underestimation for subsidences because some have, in general, been recorded as sinkholes. Some very noteworthy subsidences have occurred for example Schuttes Depression in 1964.
- City of Tshwane; out of the estimated 398 *subsidence* events only 98 (24.6%) have diameter information. The available data suggest that the largest percentage of subsidences in Tshwane (>60%) are large to very large (i.e. greater than 5m to greater than 15m diameter). There may be an overestimation of subsidence events in Tshwane, as so few have actual data available. Some occurrences may have been noted as a subsidence, rather than a partly developed sinkhole (section 2.5.3).
- Ekurhuleni; out of the estimated 41 *subsidence* events, 34 (82.9%) have diameter information and the largest percentage of events (>60%) are small to medium (i.e. less than or equal to 5m diameter).

Table 28. Subsidence diameter distribution for Gauteng.

SUBSIDENCE DIAMETERS						
	≤2m	>2m-≤5m	>5m-≤15m	>15m	TOTAL	%
WEST RAND (%)	19 (24.4)	7 (9.0)	22 (28.2)	30 (38.5)	**78**	**37.1**
TSHWANE (%)	12 (12.2)	18 (18.4)	29 (29.6)	39 (39.8)	**98**	**46.7**
EKURHULENI (%)	16 (47.1)	7 (20.6)	5 (14.7)	6 (17.6)	34	**16.2**
JOHANNESBURG (%)	0	0	0	0	**0**	**0**
TOTAL	**47**	**32**	**56**	**75**	**210**	
%	**22.38**	**15.24**	**26.67**	**35.71**		**100**
DATA MISSING	**334**					



Graph 19. Subsidence diameter distribution (Gauteng).

4.5.4 Subsidence Depths

An estimated 544 events have been recorded as *subsidences* across Gauteng, but only 118 (21.69%) have depth information recorded. When looking at the available data across the entire dolomite area in Gauteng;

- 74.58 % of the subsidence events are less than or equal to 1m in depth,
- 19.49 % are greater than 1m and less than or equal to 5m depth and,
- 5.9% are greater than 5m and less than or equal to 15m depth (Table 29).

Based on the overall available data, 94% of subsidences are less than or equal to 5m depth.

In respect of subsidence depths only limited information for each municipality has been recorded (Table 29);

- West Rand; out of an estimated 110 *subsidence* events 64 (58.2%) have depth information and most (>80%) are less than or equal to 1m depth.
- City of Tshwane; out of an estimated 398 *subsidence* events 28 (7.03%) have depth information, and most (50%) are less than or equal to 1m depth.

- Ekurhuleni; out of an estimated 41 *subsidence* events 30 (73.1%) have depth information and most (80%) are less than or equal to 1m depth.

Table 29. Sinkhole depth distribution for Gauteng.

SUBSIDENCE DEPTHS						
	≤1m	>1m-≤5m	>5m-≤15m	>15m	**TOTAL**	**%**
WEST RAND (%)	53 (82.8)	8 (12.5)	3 (4.7)	0	**64**	**52.5**
TSHWANE (%)	14 (50.0)	10 (35.7)	4 (14.3)	0	**28**	**23.0**
EKURHULENI (%)	24 (80)	5 (16.7)	1 (3.3)	0	**30**	**24.6**
JOHANNESBURG (%)	0	0	0	0	**0**	**0**
TOTAL	**91**	**23**	**8**	**0**	**122**	
%	**74.59**	**18.85**	**6.56**	**0**		**100**
DATA MISSING	**422**					

4.6 SIZE AND DEPTH DISTRIBUTION ON THE DIFFERENT FORMATIONS

4.6.1 Sinkhole diameter and depth

In respect of sinkhole size categories on the different dolomite formations across Gauteng, and for both ingress and dewatering scenarios, only limited data is available (Table 30);

The size category information regarding sinkholes is shown graphically on Graph 20 and 21. It is difficult to assess size trends as a large portion of the data is missing for sinkhole diameter (52.8% missing) and for depth (61% missing). Based on the available data:

- All the dolomite Formations show the largest percentage (30%-40%) of sinkholes in the large size category (i.e. between 5m and 15m diameter). Sinkholes under ‘other’ formations are mostly very large (greater than 15m diameter). This can be expected as the depth to bedrock and therefore the development space may be greater.
- Only slightly lower percentages are shown in the medium size category (i.e. 2m to 5m diameter) for the dolomite Formations, except for the Oaktree Formation, which shows more very large events than medium events. The Oaktree Formation data comes primarily from the West Rand and a degree of error as discussed in Section 4.3.1 may exist.

There appears not to be a dominant size on a specific Formation, except in the case of ‘other’ formations, where sizes tend to be very large.

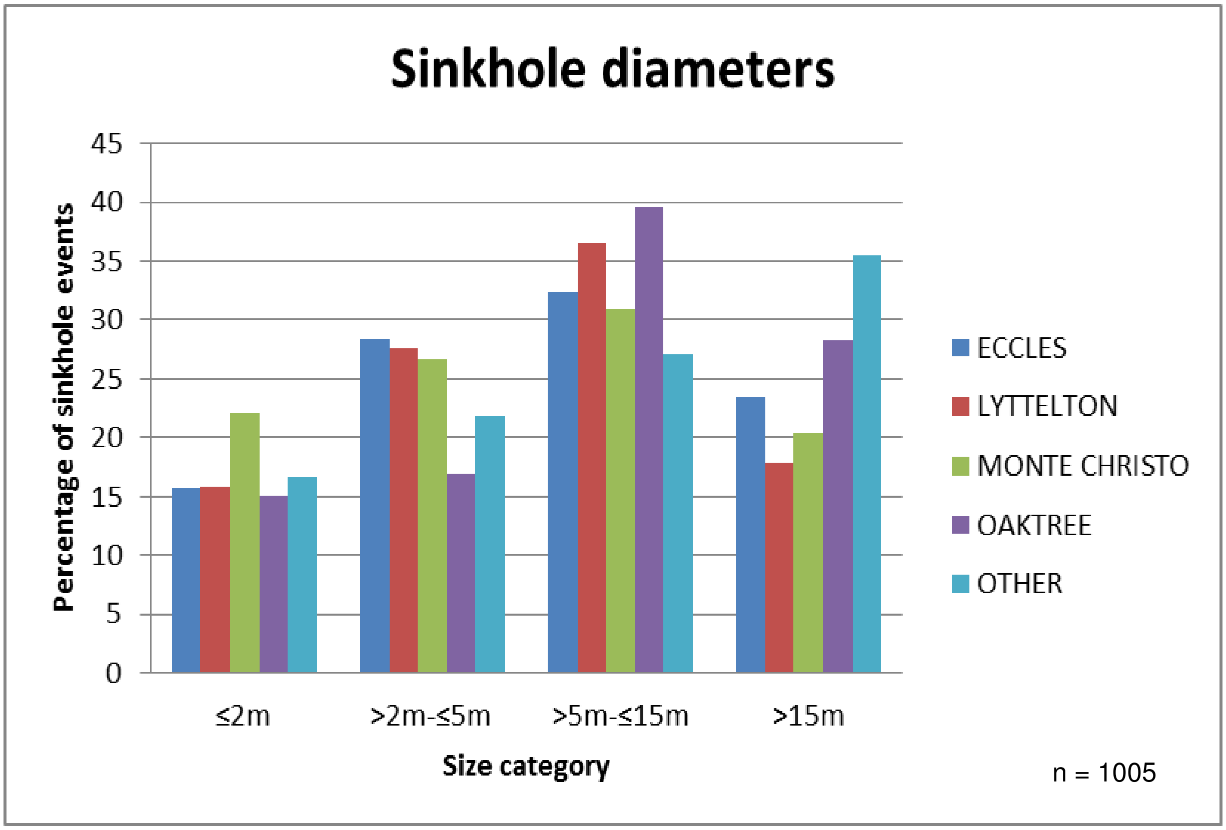
- On all the dolomite Formations the majority of sinkholes are less than 5m deep. Some very deep (>50m) sinkholes have however occurred, especially on the Far West Rand. Sinkholes on 'other' Formations show similar percentage in the less than 5m and less than 15m depth categories.

There appears not to be a dominant depth associated with a specific Formation.

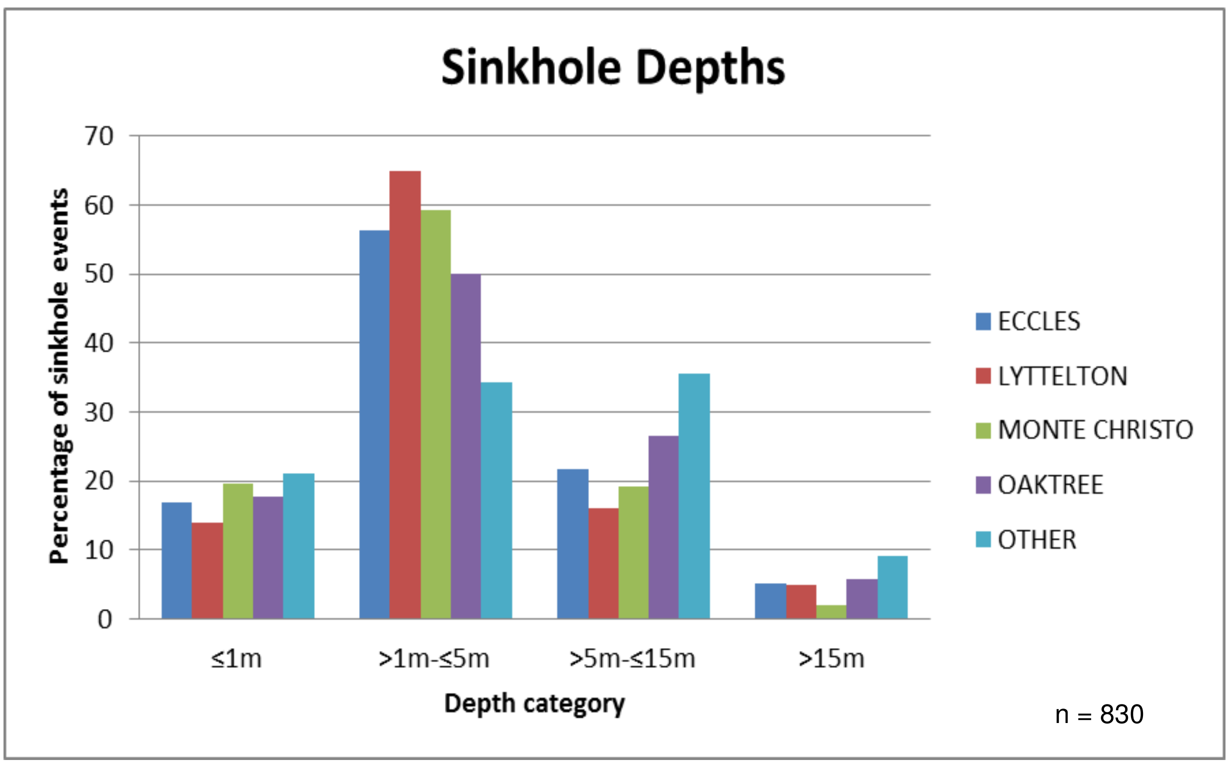
Event diameters (where available) are shown symbolically on maps A2- D2 in Appendix A.

Table 30. Sinkhole diameters and depths for the different Formations.

	SINKHOLE DIAMETER						SINKHOLE DEPTHS					
	small	medium	large	Very large								
	≤2m	>2m-≤5m	>5m-≤15m	>15m	TOTAL	%	≤1m	>1m-≤5m	>5m-≤15m	>15m	TOTAL	%
ECCLES (%)	51 (15.74)	92 (28.40)	105 (32.41)	76 (23.46)	**324 (100)**	**32.24**	47 (16.97)	156 (56.32)	60 (21.66)	14 (5.05)	**277 (100)**	**33.37**
LYTTELTON (%)	24 (15.91)	37 (27.61)	49 (36.57)	24 (17.91)	**134 (100)**	**13.33**	14 (14.00)	65 (65.00)	16 (16.00)	5 (5.00)	**100 (100)**	**12.05**
MONTE CHRISTO (%)	88 (22.11)	106 (26.63)	123 (30.90)	81 (20.35)	**398 (100)**	**39.60**	67 (19.53)	203 (59.18)	66 (19.24)	7 (2.04)	**343 (100)**	**41.33**
OAKTREE (%)	8 (15.09)	9 (16.98)	21 (39.62)	15 (28.30)	**53 (100)**	**5.27**	6 (17.65)	17 (50.00)	9 (26.47)	2 (5.88)	**34 (100)**	**4.10**
OTHER (%)	15 (16.63)	21 (21.89)	26 (27.08)	34 (35.42)	**96 (100)**	**9.56**	16 (21.05)	26 (34.21)	27 (35.53)	7 (9.21)	**76 (100)**	**9.15**
TOTAL	**186**	**265**	**324**	**230**	**1005**		**150**	**467**	**178**	**35**	**830**	
%	**18.51**	**26.37**	**32.24**	**22.89**		**100**	**18.07**	**56.27**	**21.45**	**4.22**		**100**
DATA MISSING	**1126**						**1301**					



Graph 20 : Sinkhole diameter distribution across the size categories per dolomite Formation.



Graph 21: Depth variation with Formation for various depth categories.

4.6.2 Subsidence diameter and depth

Only limited data about subsidence diameter and depth on the different dolomite Formations across Gauteng is available in both ingress and dewatering scenarios (Table 31);

The size category information regarding subsidences is shown graphically on Graphs 22 & 23. It is however difficult to assess size trends as a large portion of the data is missing for subsidence diameter (61.4% missing) and for depth (77.6% missing). Based on the available data:

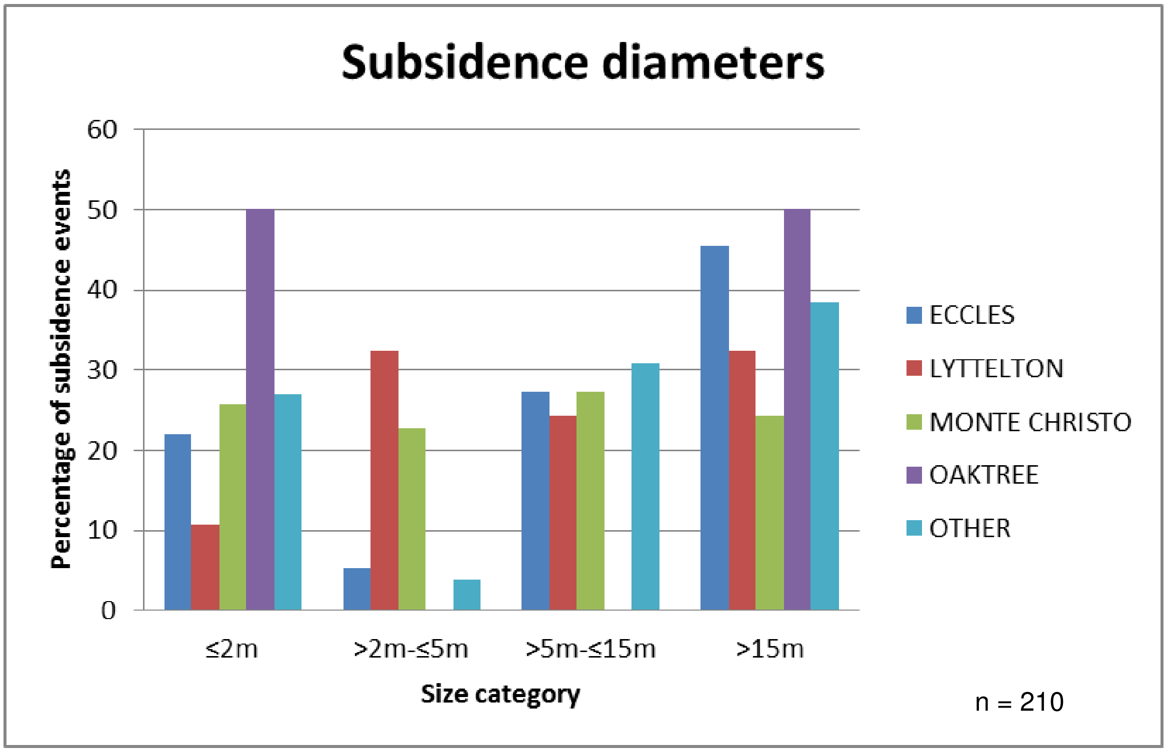
- The size categories for the different Formations vary. The Eccles, Lyttelton, Oaktree and 'Other' Formations show the largest percentage (30-50%) of very large size (greater than 15m diameter) subsidence events, while the Monte Christo has more large size (i.e. between 5m and 15m diameter) subsidence events. The Lyttelton has also recorded the same percentage of medium size (i.e. between 2m and 5m diameter) subsidence events as very large events. The Oaktree has also recorded the same percentage of small size (i.e. less than or equal to 2m diameter) subsidence events as very large events.

Therefore there appears not to be a dominant size on a specific Formation.

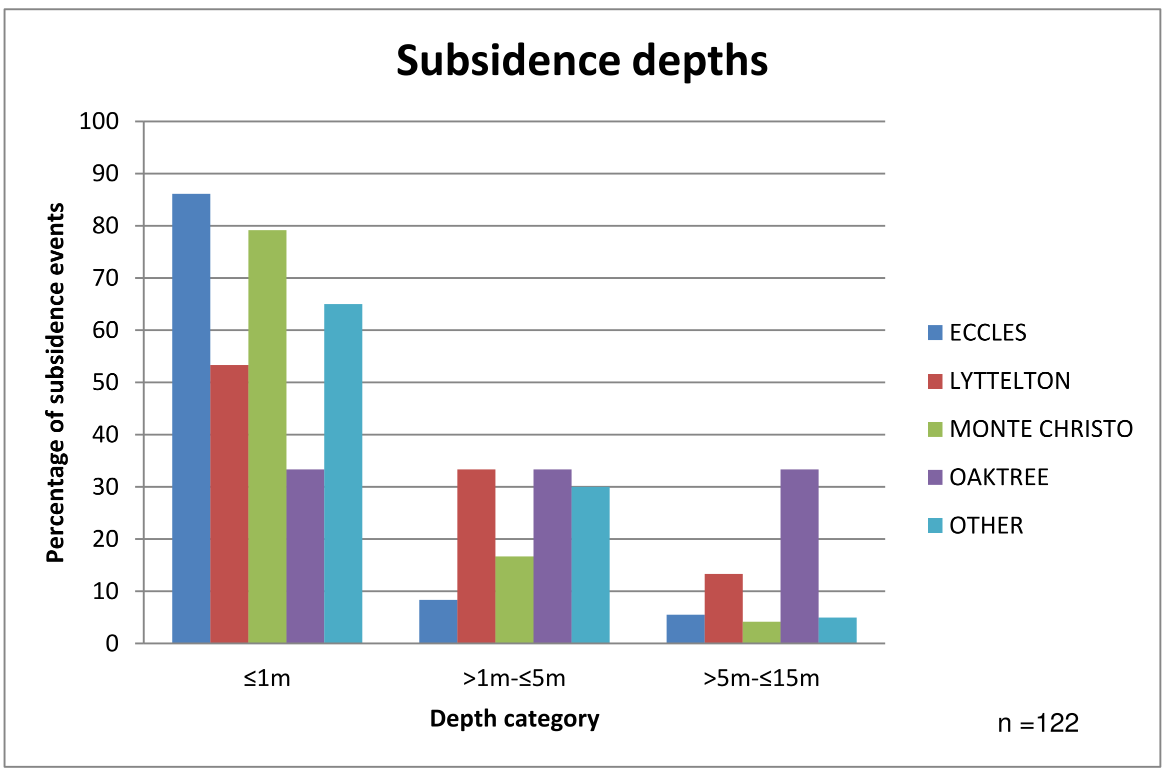
- All the Formations show the largest percentage of subsidences are less than or equal to 1m deep.

Table 31. Subsidence diameters and depths for the different formations.

	SUBSIDENCE DIAMETER						SUBSIDENCE DEPTHS				
	≤2m	>2m-≤5m	>5m-≤15m	>15m	TOTAL	%	≤1m	>1m-≤5m	>5m-≤15m	TOTAL	%
ECCLES (%)	17 (22.08)	4 (5.19)	21 (27.27)	35 (45.45)	**77 (100)**	**36.67**	31 (86.11)	3 (8.33)	2 (5.56)	**36 (100)**	**29.51**
LYTTELTON (%)	4 (10.81)	12 (32.43)	9 (24.32)	12 (32.43)	**37 (100)**	**17.62**	8 (53.33)	5 (33.33)	2 (13.33)	**15 (100)**	**12.30**
MONTE CHRISTO (%)	17 (25.76)	15 (22.73)	18 (27.27)	16 (24.24)	**66 (100)**	**31.43**	38 (79.17)	8 (16.67)	2 (4.17)	**48 (100)**	**39.34**
OAKTREE (%)	2 (50.00)	0 (0)	0 (0)	2 (50.00)	**4 (100)**	**1.90**	1 (33.33)	1 (33.33)	1 (33.33)	**3 (100)**	**2.46**
OTHER (%)	7 (26.92)	1 (3.85)	8 (30.76)	10 (38.46)	**26 (100)**	**12.3**	13 (65.00)	6 (30.00)	1 (5.00)	**20 (100)**	**16.39**
TOTAL	**47**	**32**	**56**	**75**	**210**		**91**	**23**	**8**	**122**	
%	**22.38**	**15.24**	**26.67**	**35.71**		**100**	**74.59**	**18.85**	**6.56**		**100**
DATA MISSING	**334**						**422**				



Graph 22**:** Subsidence diameter size distribution across the size categories per dolomite Formation.



Graph 23: Depth variation with Formation for various depth categories.

4.7 EVENT DENSITY

An event density is calculated by counting all the events (sinkhole, subsidence or cracks) within an area (in this case per 1: 10 000 scale orthophoto sheet) and dividing by the area (km^2). Areas are shown on maps A1-D1, Appendix A, data tables in Appendix B. Only orthophoto sheets with at least 10 events were considered i.e. sheets with less than 10 events are 'outliers'. The rate at which new sinkholes occur according to Waltham & Fookes (2003) is derived using the following formula: (NSH) = events per km^2 per year as described in section 2.7.

4.7.1 West Rand District Municipality

A study area consisting of 19, 1: 10 000 scale orthophoto sheets along the southern limb of the dolomite on the West Rand were used, totaling an area of approximately 493 km^2 of dolomitic land.

- In the non-dewatered areas (approximately 108km^2 of dolomitic land), between 0.4 and 4.17 events per km^2 (average of 2.5) was calculated.
- In the dewatered areas (approximately 385km^2 of dolomitic land), between 0.4 and 7.3 events per km^2 (average of 2.8) was calculated.

The event date information prior to 1984 on the West Rand is largely missing. This makes it difficult to calculate the rate of new sinkhole development for the West Rand using the entire time period. As it's indicated by Wolmarans that 102 events occurred before dewatering, but it's not indicated in which compartment or what year the events occurred, so the time period prior to 1984 cannot be accurately determined. The following results were derived from using events from 1984 -2011, which have more accurate year information (Table 20);

- Non-dewatered areas: Sinkholes /km^2 /year = 183 /108.08 km^2 / 27 years = 0.06,
- Dewatered areas: Sinkholes /km^2 /year = 555 /384.92 km^2 / 27 years = 0.05.
- Overall: Sinkholes /km^2 /year = 738 /493 km^2 / 27 years = 0.055.

The results show that the non-dewatered and dewatered areas have a similar rate of formation, with non-dewatered areas slightly higher after 1984, however before 1984 we would assume the dewatered areas would have been higher. It should also be noted that different areas are used in the calculation.

West Rand would classify as 'mature' karst according to Waltham & Fookes (2003), Table 14. Using the overall NSH, in the 465km^2 study area one could expect approximately 25.5 events per annum, which is similar to the average (25.4 events per annum) established in 4.1.1.

4.7.2 City of Tshwane

A study area consisting of 9, 1: 10 000 Scale orthophoto sheets was used, totaling an area of approximately 202.82 km^2 of dolomitic land.

- In the study area south of Pretoria (approximately 202.82 km^2 of dolomitic land), between 0.36 and 15.61 events per km^2 (average of 7.58) was calculated.

The rate of new sinkhole development for Tshwane overall;

- Sinkholes /km^2 /year = 1365 /202.83km^2 /51 years = 0.13,

The average frequency per km^2 is much higher than for the West Rand (Table 32), however sinkhole occurrences are spread over a much larger area in the West Rand. Events in Tshwane are mainly concentrated in highly developed areas. Tshwane would classify as 'mature' karst according to Waltham & Fookes (2003), Table 14. Using the NSH, in the 202.83km^2 study area one could expect 27 events per annum, which is the same as the average (approximately 27 events per annum) established in section 4.1.2.

4.7.3 Ekurhuleni Metropolitan Municipality

A study area consisting of 7, 1: 10 000 Scale orthophoto sheets was used, totaling an area of approximately 160.57 km^2 of dolomitic land.

- In the non-dewatered areas (approximately 123.73 km^2 of dolomitic land), between 0.36 and 1.5 events per km^2 (average of 0.88) was calculated.
- In the dewatered areas (approximately 36.84 km^2 of dolomitic land), between 0.47 and 1.63 events per km^2 (average of 1.05) was calculated.

The rate of new sinkhole formation for Ekurhuleni;

- Non-dewatered areas: Sinkholes /km^2 /year =104 /123.73km^2/30 years = 0.03
- Dewatered areas: Sinkholes /km^2 /year = 28 /36.84km^2/11 years= 0.07
- Overall: Sinkholes /km^2 /year = 132 /160.57 km^2 / 30years = 0.03.

Ekurhuleni would classify as 'youthful' to 'mature' karst according to Waltham & Fookes (2003), Table 14. Using the NSH, in the 160.57 km^2 study area one could expect approximately 4.8 events per annum, which is similar to the average established in 4.1.3, of 5.53 events per annum.

Table 32. Summary of event frequency's per km^2 and rate of new sinkhole formation.

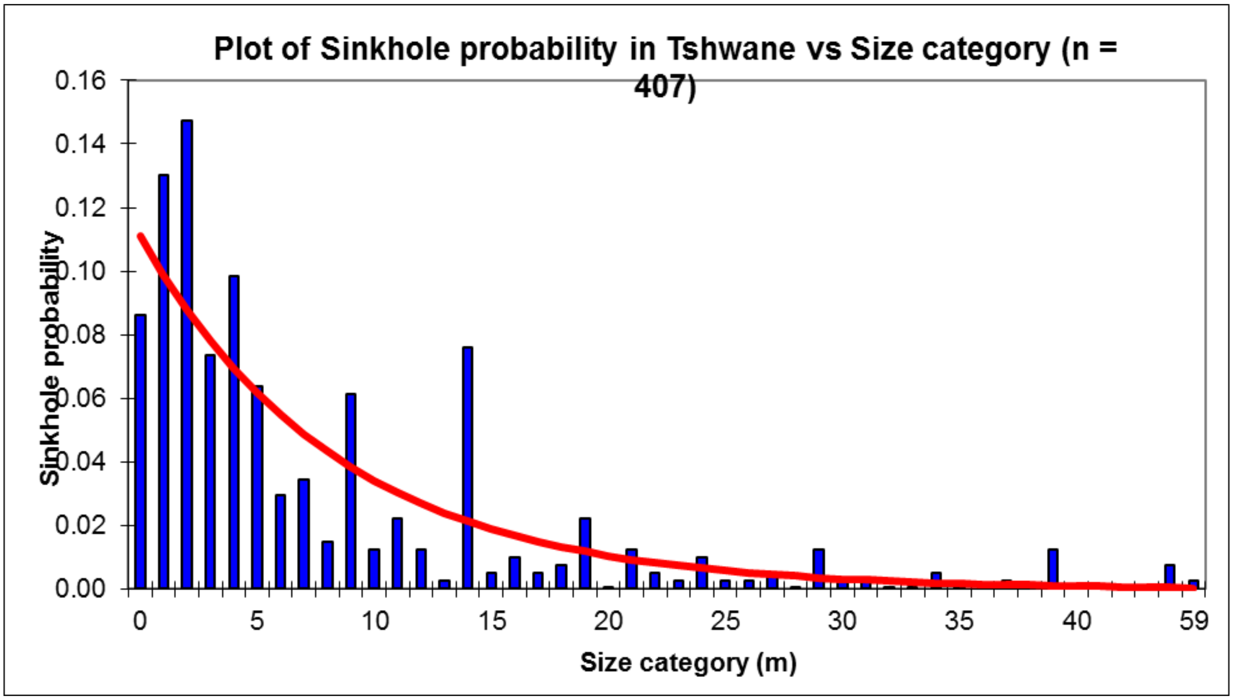
MUNICIPALITY	AREA OF DOLOMITE (KM2)	DEWATERED AREA AVERAGE FREQUENCY (/KM2) #NSH	NON-DEWATERED AREA AVERAGE FREQUENCY (/KM2) #NSH	Classification according to Waltham and Fookes (2003) Table 14.
WEST RAND	493	2.8 #0.05	2.5 #0.06	Mature
TSHWANE	202.82		7.58 # 0.13	Mature
EKURHULENI	160.57	1.05 #0.07	0.88 #0.03	Youthful to Mature

4.8 PROBABILITY DISTRIBUTIONS AND INHERENT HAZARD

As discussed in 2.6.2.6, sinkholes were considered one of the biggest hazards to the Gautrain rapid rail infrastructure, and a study of the frequency of sinkhole occurrence in the area south of Pretoria was undertaken. For Gautrain, exponential probability density functions (PDFs) that best represented the data for sinkhole dimensions and depth were assigned, and simulated using a Monte Carlo approach.

A Monte Carlo approach was not used in the following analysis; rather probability plots were produced by converting sinkhole events in size categories, to probabilities by dividing the percentage of each category by 100. The probability was plotted against the size category and the maximum likelihood (average) was used to fit the exponential distribution to the data (Table, Appendix B). This was done for data for City of Tshwane and 407 data points were used. An average diameter of 8.48 m (determined from the data) was used to fit the exponential distribution (Graph 24).

Cumulative percentages indicate 86.48 % of the 407 sinkholes to be less than or equal to 15m diameter, however a larger database of events and a different approach was used to that of Sartain *et al.*, (2011). Also very large events (>20m diameter) were regarded as overestimated by Sartain.



Graph 24. Probablity plot of Tshwane sinkholes.

While 15m diameter design size was considered appropriate for the Gautrain, a major infrastructure development, this is not always feasible for other development types. The results in 4.5.1 indicate most sinkholes (>60%) in Tshwane are in the range of medium to large size (i.e. greater than 2m and up to 15m in diameter). The average diameter established for the probability distribution here is approximately 8.5m, which is within this range, and suggests a design size to cater for an average sinkhole in Tshwane.

One also need to consider that the industry evaluates dolomite ground based on the 'Method of Scenario Supposition' (Buttrick *et al*., 2001), rather than the method used in Sartain *et al.* 2011. The "Method of Scenario Supposition' defines sinkhole size categories, and therefore the sinkhole size to be expected and catered for in the design. This is easy to determine for the high hazards IHC 5 to 8 because it's definitive, i.e. IHC 6 is a high hazard for up to a 5m diameter sinkhole, hence at least a 5m design size should be used. However it's more difficult to determine the appropriate design for the medium hazard classes 3 & 4. These cannot be more conservative than IHC 6; however the design size needs to prevent catastrophic collapse. At present, a 5m design size is recommended in by SANS 10400-H.

CHAPTER 5 – CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In the past, data on sinkhole and subsidence occurrence has been compiled separately in papers, research theses and databases held by various consultants, and state authorities. Sinkhole statistics were not available before the work by Wolmarans (1984) and Schőning (1990). Although Heath and Oosthuizen (2008) have indicated in excess of 2400 instability events in a preliminary overview of the sinkhole record for South Africa.

In Gauteng "dolomitic land", covers an area of approximately 4005 km^2 (24% of Gauteng's surface area), which is vulnerable to sinkhole and subsidence formation. This study's main objective was to compile historical and current event data for Gauteng, develop an inventory to be used in statistical analysis to investigate the relationship between the formation of sinkholes and subsidences and geological formations as well as other external influences.

Data originates from numerous sources and compiling a comprehensive database presented many challenges, most importantly the large percentage of missing data that could not be retrieved and the fact that format and quality of data varies.

Only karst related events prior to 31 December 2011 were considered in this study. The data compiled is only an estimation of the number of events that has occurred in Gauteng.

Once all the available event data was collected and compiled, data was organised into multiwave frequency tables and various aspects were analyzed.

Results indicate:

1) Approximately 3048 events (Sinkholes, subsidences and ground cracks) have occurred within the study areas over the last 60 years.

2) Sinkholes and subsidences are still regularly occurring on areas underlain by dolomite in Gauteng, however based on available data, events in the West Rand and Tshwane appear to be decreasing on average in the last decade.

3) When comparing the number of events vs. annual and cumulative monthly rainfall for the Tshwane region. It was generally found that more events occur in high rainfall months or years (due to increased ingress water entering the ground profile), and the two variables tend to increase together, but bearing in mind rainfall doesn't necessarily allow prediction of the number of sinkholes that can be expected.

4) The available data shows 69.9% of occurrences were recorded as sinkholes, 17.9% as subsidences, 5.2% as cracks and 7.0 % of events were undefined. A large percentage of the type of events had to be determined from historical maps, which may have generalized the events and some degree of error may be present. Therefore the following is proposed as probably more accurate: 60% sinkholes, 30% subsidences, and 10% as cracks.

5) Overall the largest percentage of the events (36%) have occurred on the chert-rich Monte Christo Formation, followed by the chert-rich Eccles Formation (31 %) and then the chert - poor Lyttelton Formation (17%). The Oaktree Formation has only a recorded 7% of events, while 'Other' formations underlain by dolomite at depth have 9% of the events.

6) When considering causes of instability events; on the West Rand most occurrences prior to 1984 were due to dewatering while post 1984 most are attributed to ingress. Overall in the West Rand, 47% (46% positively + 1% probably) of events can be attributed to ingress, 53% (38% positively + 15% probably) of events as a result of dewatering. The largest percentage of events has occurred in the Oberholzer Groundwater Compartment.

   In Tshwane, 98% of the instability events can be attributed to anthropogenic causes (11 % to a leaking pipe or sewer, 15 % to poor stormwater management or ponding the remaining 72% is likely caused by human induced ingress) and only 2 % to natural causes without any evident man-made trigger.

   In Ekurhuleni, 78% can be attributed to ingress (26 % leaking pipe/sewer, 15 % poor stormwater management or ponding and the remaining 37 % were probably due to human induced ingress) and 22% were identified as due to dewatering.

7) In considering sinkhole and subsidence size and depth distributions; size categories modified from Schőning (1990) and Buttrick *et al.*(2001) were used. Based on the available sinkhole diameter data:
   - West Rand: the largest percentage of sinkholes in the West Rand (>60%) are large to very large (i.e. greater than 5m to greater than 15m diameter).

- City of Tshwane: the largest percentage of sinkholes in Tshwane (>60%) are medium to large (i.e. greater than 2m to less than or equal to 15m diameter).
- Ekurhuleni: the largest percentage of events (>70%) are small to medium (i.e. less than 2m to less than or equal to 5m diameter).
- For Gauteng, overall, 18.5% of the sinkhole events are less than or equal to 2m diameter, 26.4 % are between greater than 2m and less than or equal to 5m diameter, 32.2% are between greater than 5m and less than or equal to 15m diameter and 22.9 % are larger than 15m diameter.

Based on the available sinkhole depth data; 17.8 % of the sinkhole events are less than or equal to 1m deep, 56.5 % are between greater than 1m and less than or equal to 5m deep, 21.6% are between greater than 5m and less than or equal to 15m deep and 4.1 % are greater than 15m in depth.

Based on available subsidence diameter data; 25.54 % of the subsidence events are less than or equal to 2m diameter, 14.81 % are between greater than 2m and less than or equal to 5m diameter, 25.93% are between greater than 5m and less than or equal to 15m diameter and 34.72% are larger than 15m diameter.

Based on available subsidence depth data across the entire dolomite area in Gauteng: 74.58 % of the subsidence events are less than or equal to 1m in deep, 19.49 % are greater than 1m and less than or equal to 5m deep and 5.9 % are greater than 5m and less than or equal to 15m deep.

8) When considering size distribution on the different formations, it was not possible to determine if certain sizes were more prevalent for specific formations. A large portion of the data (50 % – 80 %) is missing for sinkhole diameter and for depth (61%). Based on the available data:
    - All the dolomite formations show the largest percentage (30%-40%) of sinkholes in the large size category (i.e. between 5m and 15m diameter). Sinkholes under 'other' formations are mostly very large (greater than 15m diameter), which is to be expected as the depth to bedrock and therefore the development space may be greater. Although only slightly lower percentages are shown in the medium size category (i.e. 2m to 5m diameter) for the dolomite formations. In general, based on the overall available data, 77% of sinkholes are less than or equal to 15m diameter across Gauteng.

- All the dolomite formations show the majority of sinkholes are less than 5m deep. Some very deep (>50m) sinkholes have however occurred, especially on the Far West Rand. In general, based on the overall available data, 95.8% of sinkholes are less than or equal to 15m deep.
- For subsidences the dominant size categories for the different Formations vary. The Eccles, Lyttelton, Oaktree and 'Other' Formations show the largest percentage of very large size (greater than 15m diameter) subsidence events, while the Monte Christo has more large size (i.e. between 5m and 15m diameter) subsidence events. The Lyttelton has also recorded the same percentage of medium size (i.e. between 2m and 5m diameter) subsidence events as very large events. The Oaktree has also recorded the same percentage of small size (i.e. less than or equal to 2m diameter) subsidence events as very large events. In general, based on the overall available data, 64.3% of subsidences are less than or equal to 15m diameter across Gauteng.
- All the Formations show the largest percentage of subsidences are less than or equal to 1m deep and based on the overall available data, 93.4% of subsidences are less than or equal to 5m deep.

9) When considering event density and rate of new sinkhole formation; for the West Rand, between 0.4 and 4.17 events per km^2 (average of 2.5) was calculated for the non-dewatered areas and between 0.4 and 7.3 events per km^2 (average of 2.8) was calculated for the dewatered areas. The rate of new sinkhole formation for West Rand overall is, 0.055.

   Within Tshwane, between 0.36 and 15.61 events per km^2 (average of 7.58) was calculated. The rate of new sinkhole formation for Tshwane is 0.13. The average frequency per km^2 is much higher than for the West Rand, however sinkhole occurrences are spread over a much larger area in the West Rand. Events in Tshwane are mainly concentrated in highly developed areas.

   For Ekurhuleni, between 0.36 and 1.5 events per km^2 (average of 0.88) was calculated for the non- dewatered areas and an between 0.47 and 1.63 events per km^2 (average of 1.05) for the dewatered areas. The overall rate of new sinkhole formation for Ekurhuleni is 0.03.

10) A probability plot was produced from Tshwane data, by converting sinkhole occurrences in size categories, to probabilities. The probability was plotted against the size category and the maximum likelihood (average) was used to fit the exponential distribution to the data.

The average diameter of 8.48 m was used to fit the exponential distribution. Cumulative percentages indicate 86.48 % of events to be less than or equal to 15m diameter. A larger database of events and a different approach was used than that of Sartain *et al.*, (2011). While a 15m diameter design size was considered appropriate for the Gautrain, a major infrastructure development, this is not always feasible for other development types.

5.2 RECOMMENDATIONS & FUTURE CONCERNS

A sinkhole database is ongoing, continuously updated, therefore results of analysis may change fairly rapidly depending on the current sinkhole database information.

It is imperative to have as complete a database as possible. Large percentages of data were missing from the current inventory, which could not be retrieved and therefore available data may not be truly representative. Moving forward, it is important that accurate and thorough inventorisation is undertaken. It should also become mandatory for reporting of such events to a centralized organization.

Sinkhole and subsidence data is crucial for the future assessment of sinkhole hazards and decision making. The sinkhole record and especially the potential size of events needs to be considered for founding designs.

Only a few aspects were analyzed during this study, many more can possibly be investigated, or more accurately investigated with more complete data. For example, service information could also be overlain. The density of services and their proximity with events could be investigated.

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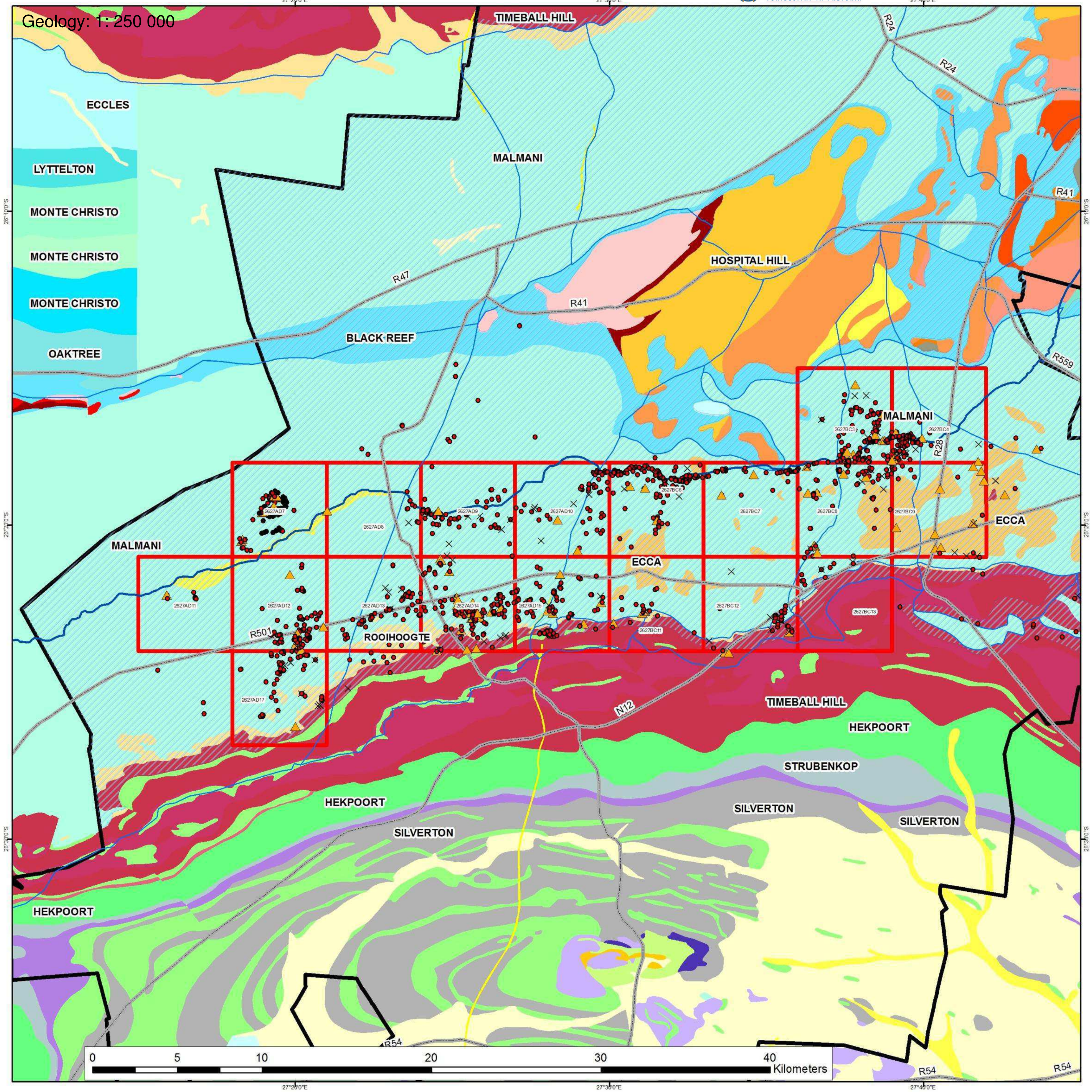
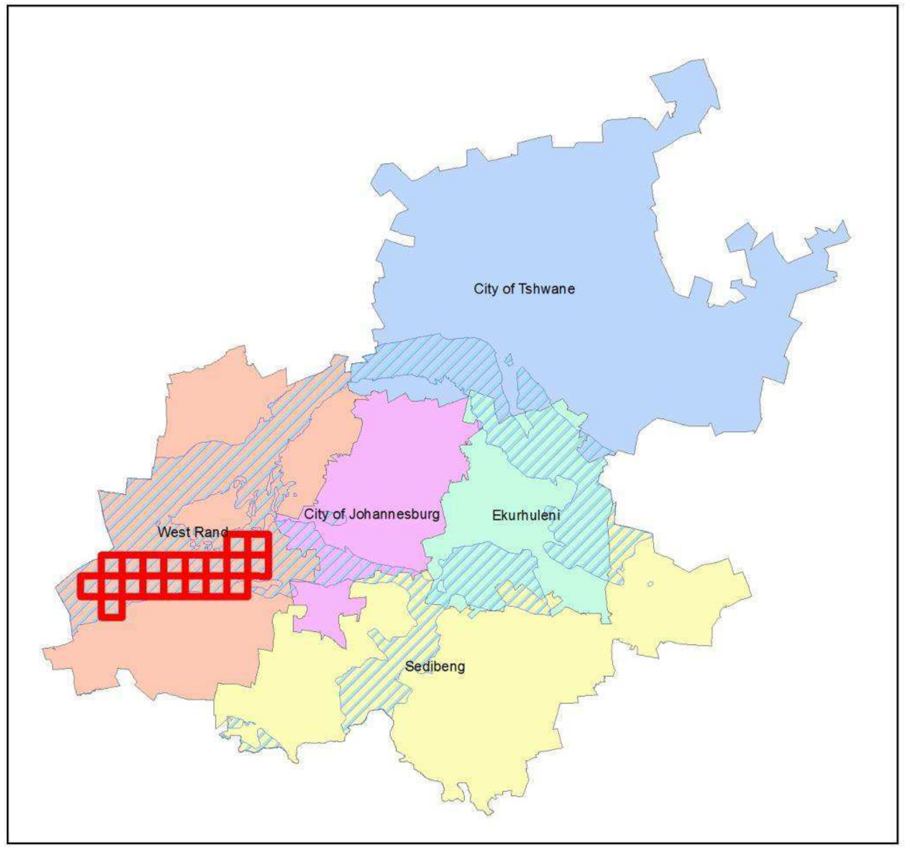
Appendix A: Maps

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA





Legend

- Cracks
- Sinkhole
- Subsidence
- Undefined
- Main road
- Wonderfonteinspruit
- Groundwater Compartments
- 1: 10 000
- Dolomitic land
- Municipalities

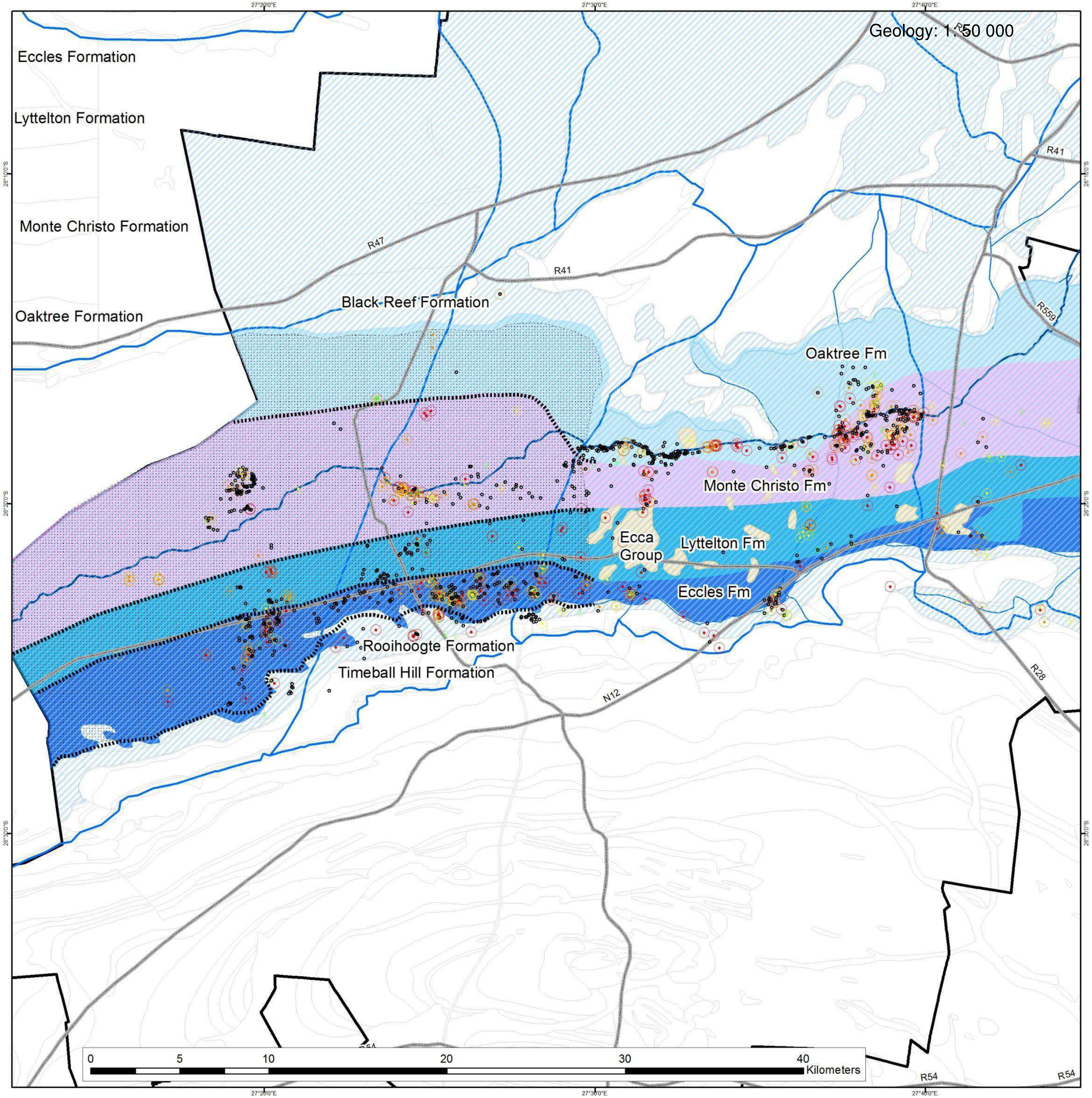
MAP A1: WEST RAND SINKHOLES, SUBSIDENCE & CRACKS

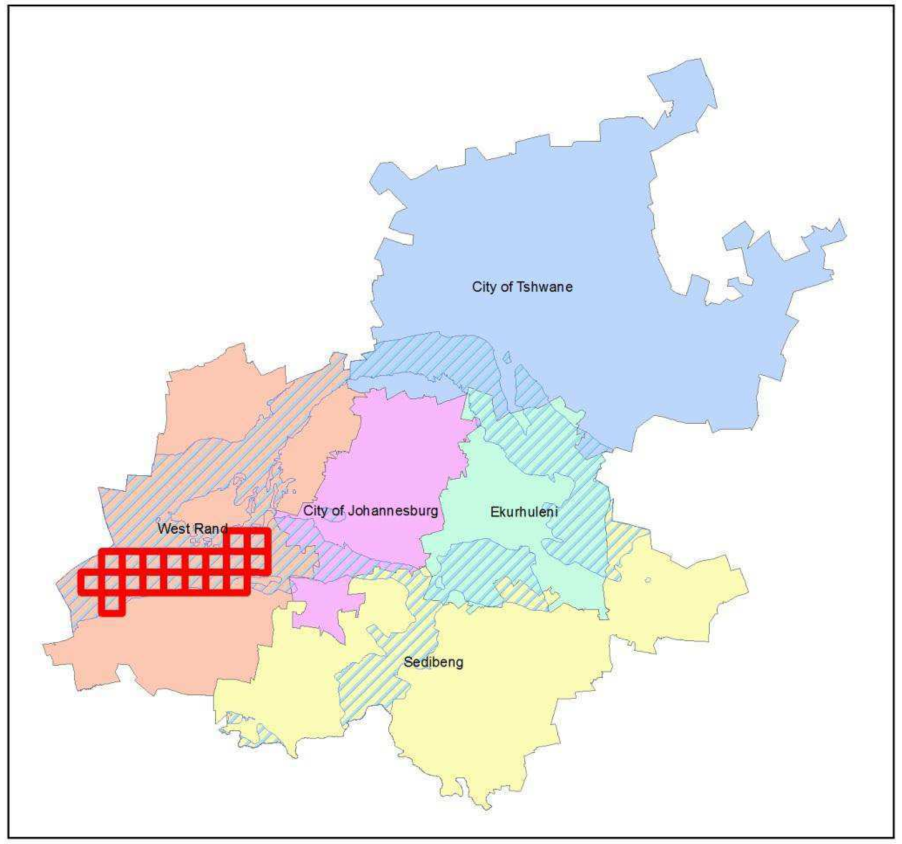
Types of Instabilty events

Geology: Council for Geoscience (CGS)
Groundwater Compartments: Department of Water Affairs (DWA)

July 2013 GCS_WGS_1984

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA





Legend

Size_Cat

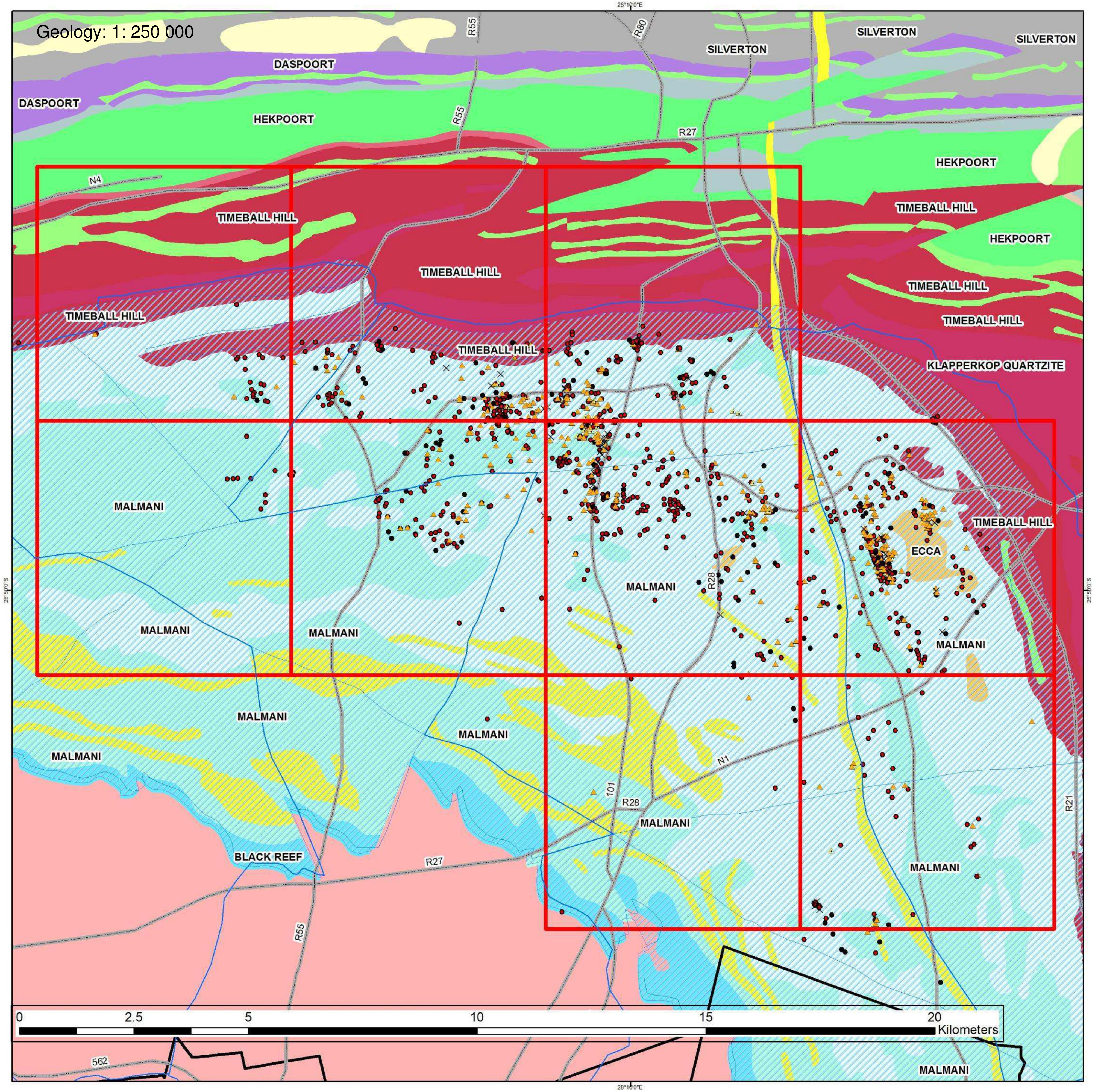
- Unknown
- <=2m
- >2m-<=5m
- >5m-<=15m
- >15m
- Municipalities
- Main road
- Dolomitic land
- Ecca Group
- Eccles Formation
- Lyttelton Formation
- Monte Christo Formation
- Oaktree Formation
- Inferred contact according to Wolmarans 1984 map.
- Inferred geology
- Groundwater Compartments
- Wonderfonteinspruit

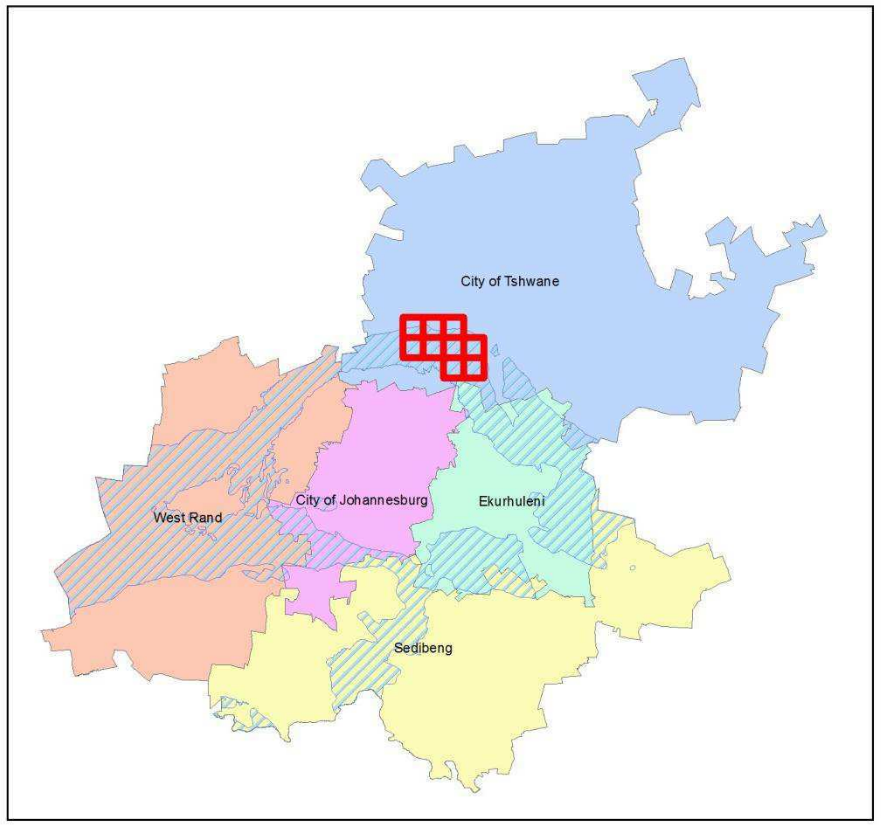
MAP A2: WEST RAND SINKHOLES, SUBSIDENCE & CRACKS

Size categories (diameters) on the dolomite formations

Geology (unpubl.): Council for Geoscience (CGS)
Groundwater Compartments: Department of Water Affairs (DWA)

July 2013 GCS_WGS_1984





Legend

- Groundwater Compartments
- 1: 10 000

Tshwane sinkholes

- Cracks
- Sinkhole
- Subsidence
- Subsidence & Sinkhole
- Undefined
- Main road
- Municipalities
- Dolomitic land

MAP B1: TSHWANE SINKHOLES, SUBSIDENCE & CRACKS

Types of Instabilty events

Geology: Council for Geoscience (CGS)

Groundwater Compartments: Department of Water Affairs (DWA)

W E S

July 2013 GCS_WGS_1984

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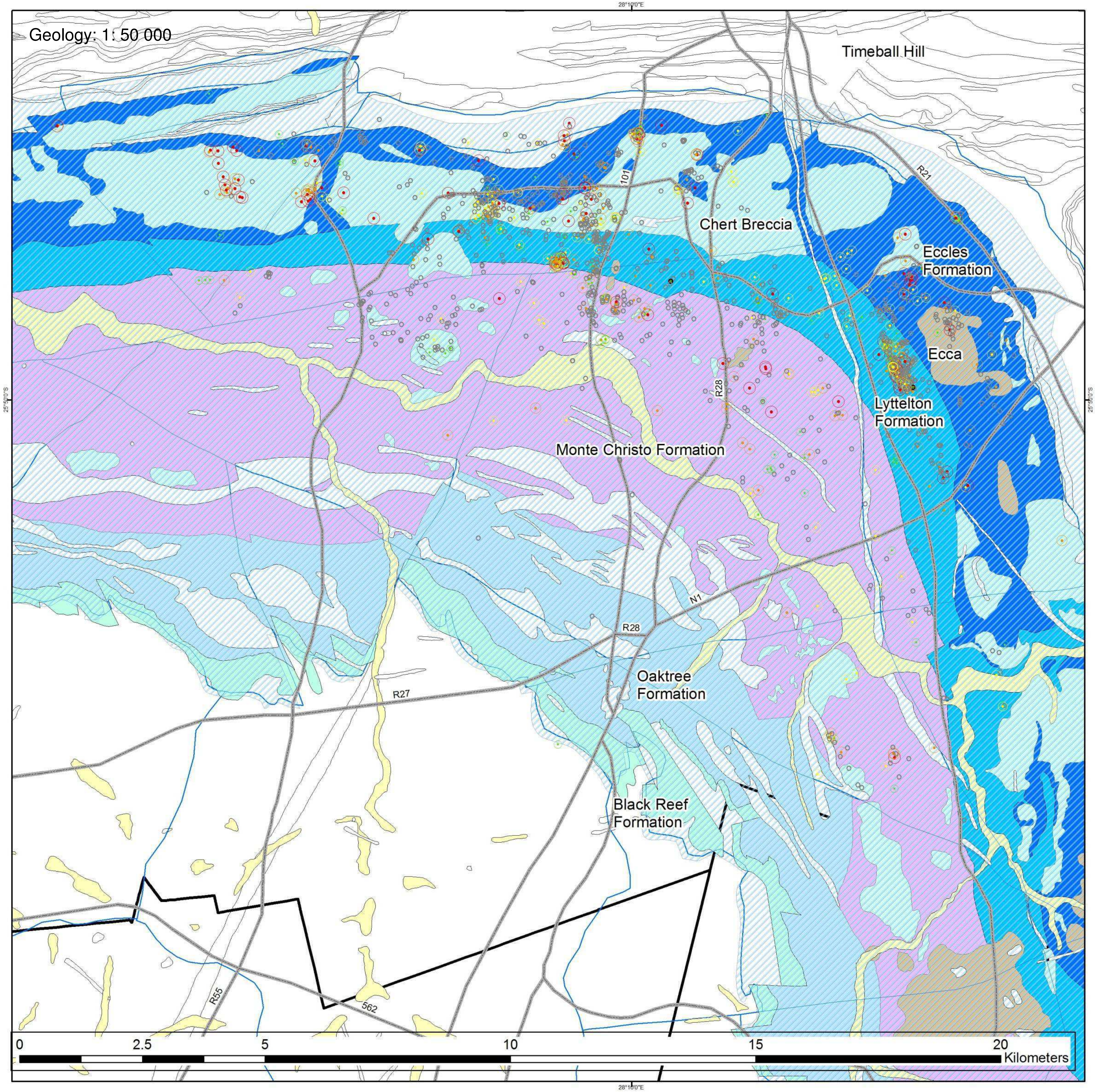
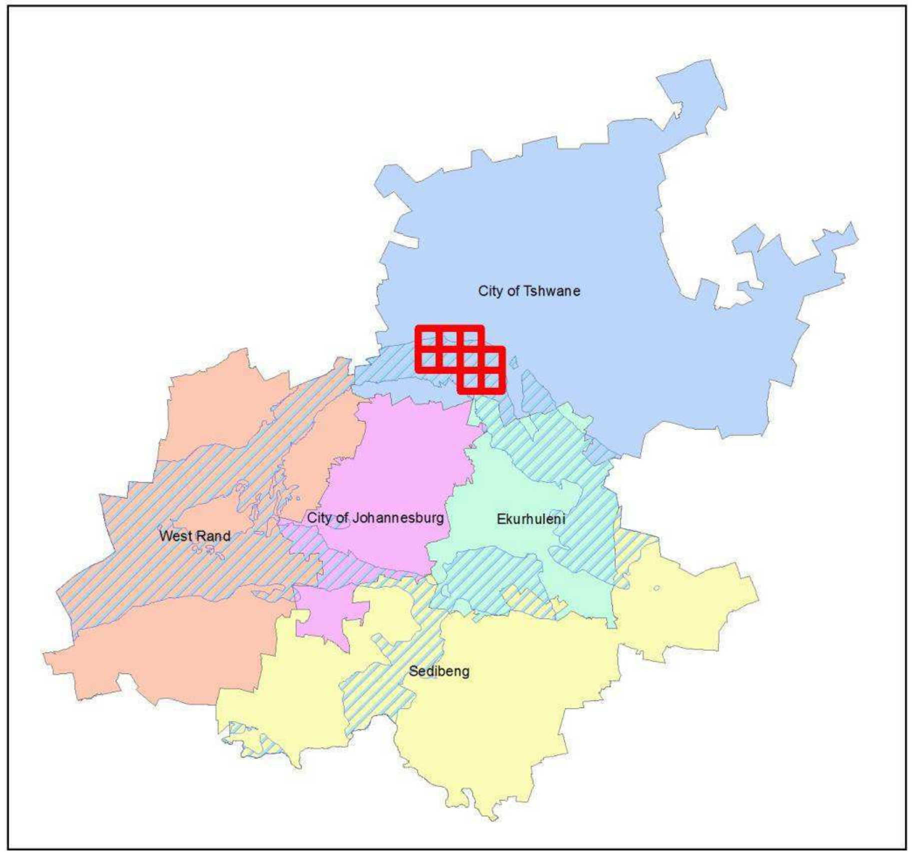




Legend

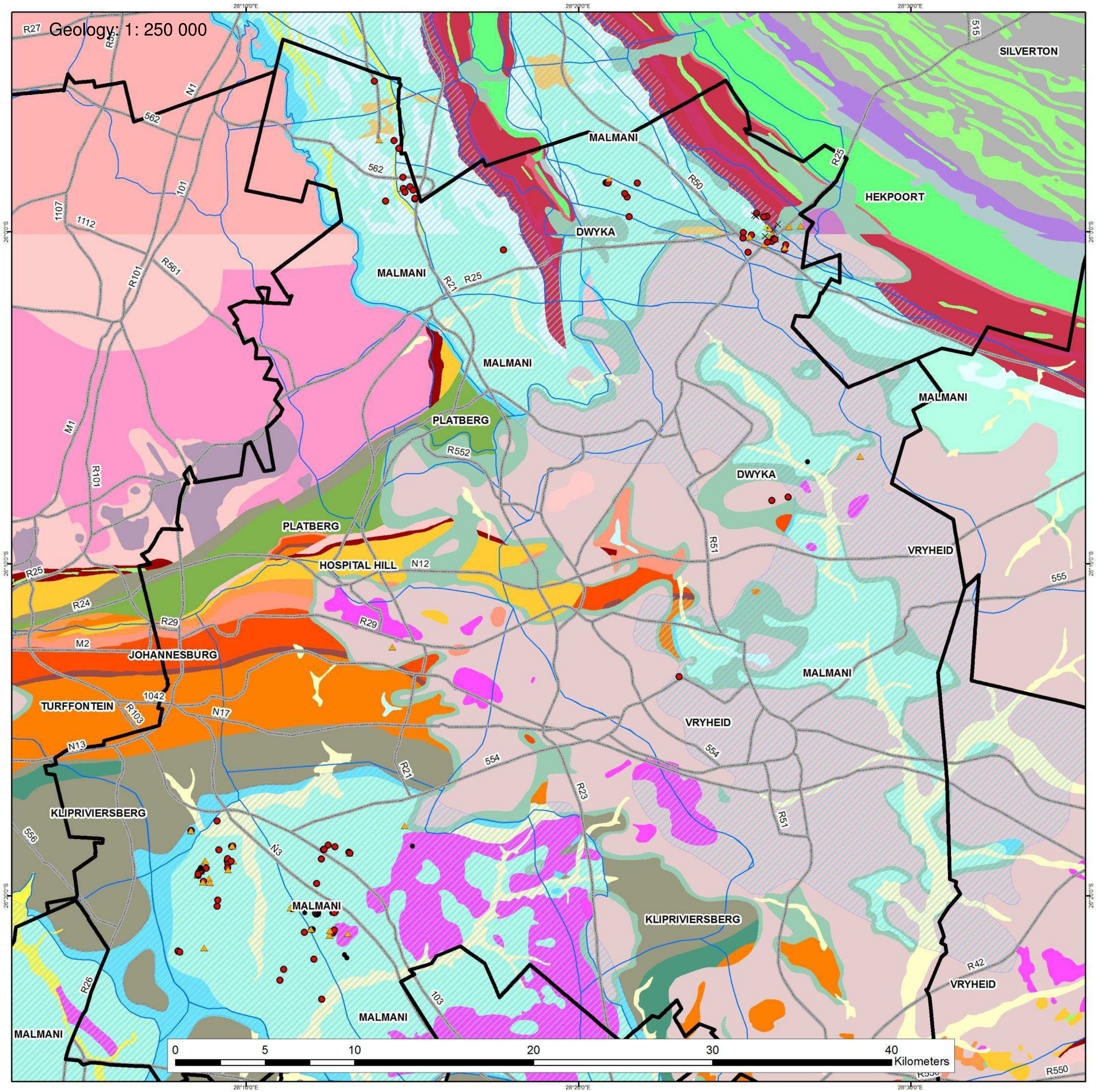
- Unknown
- <=2m
- >2m-<=5m
- >5m-<=15m
- >15m
- Municipalities
- Main road
- Groundwater compartments
- Dolomitic land
- Eccles Fm
- Chert Breccia
- Lyttelton Fm
- Monte Christo Fm
- Oaktree Fm
- Black Reef Fm
- Vryheid Fm
- Quaternary

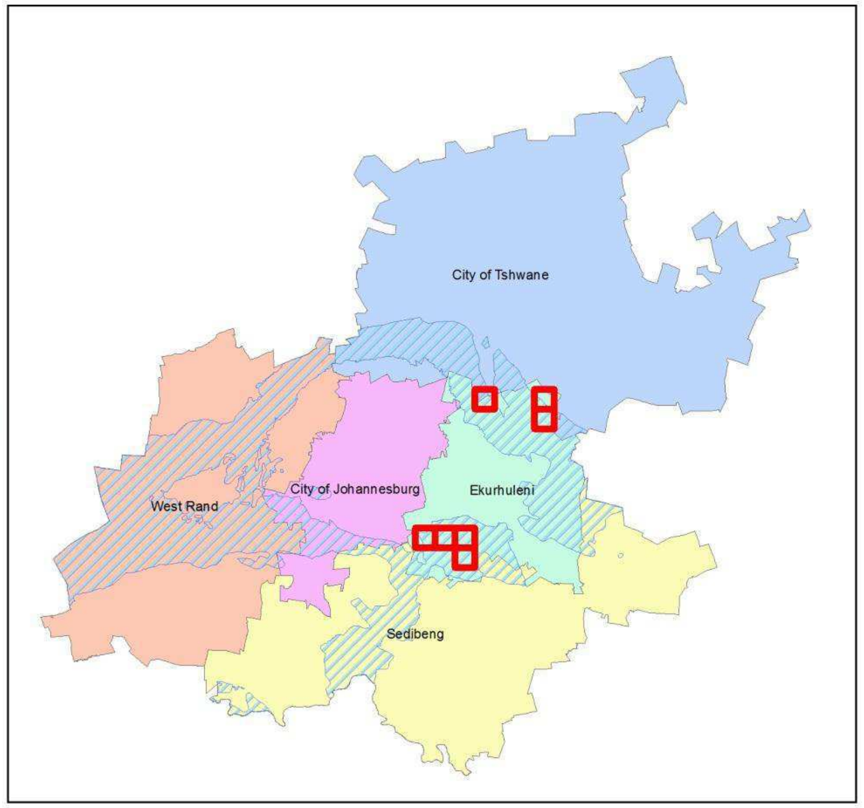
MAP B2: TSHWANE SINKHOLES, SUBSIDENCES & CRACKS

Size categories (diameters) on the dolomite formations

Geology (unpubl.): Council for Geoscience
Groundwater Compartments: department of Water Affairs (DWA)

July 2013 GCS_WGS_1984





Legend

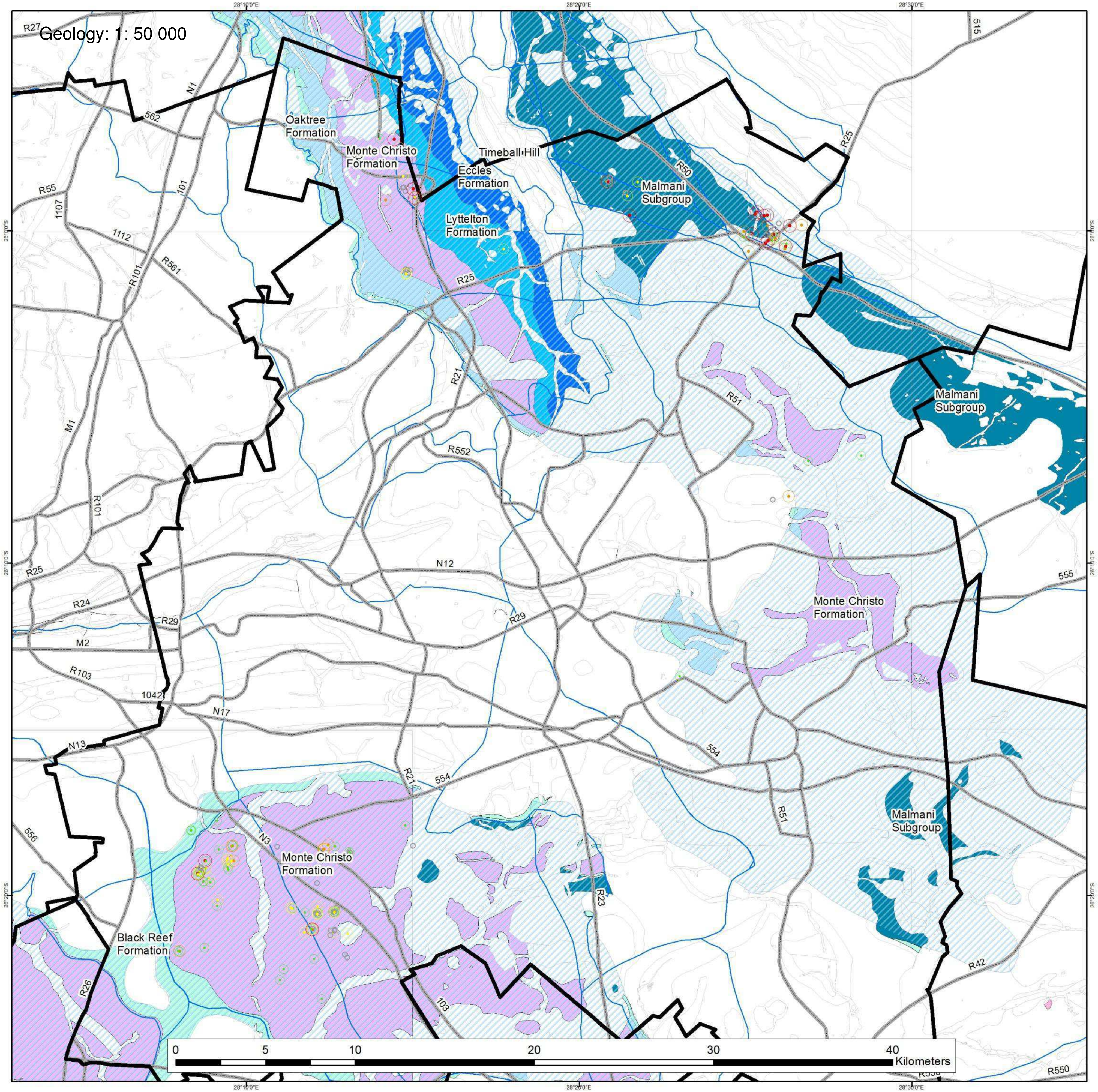
- × Cracks
- Sinkhole
- Subsidence
- Subsidence & Sinkhole
- Undefined
- Municipalities
- Main road
- Groundwater Compartments
- Dolomitic land

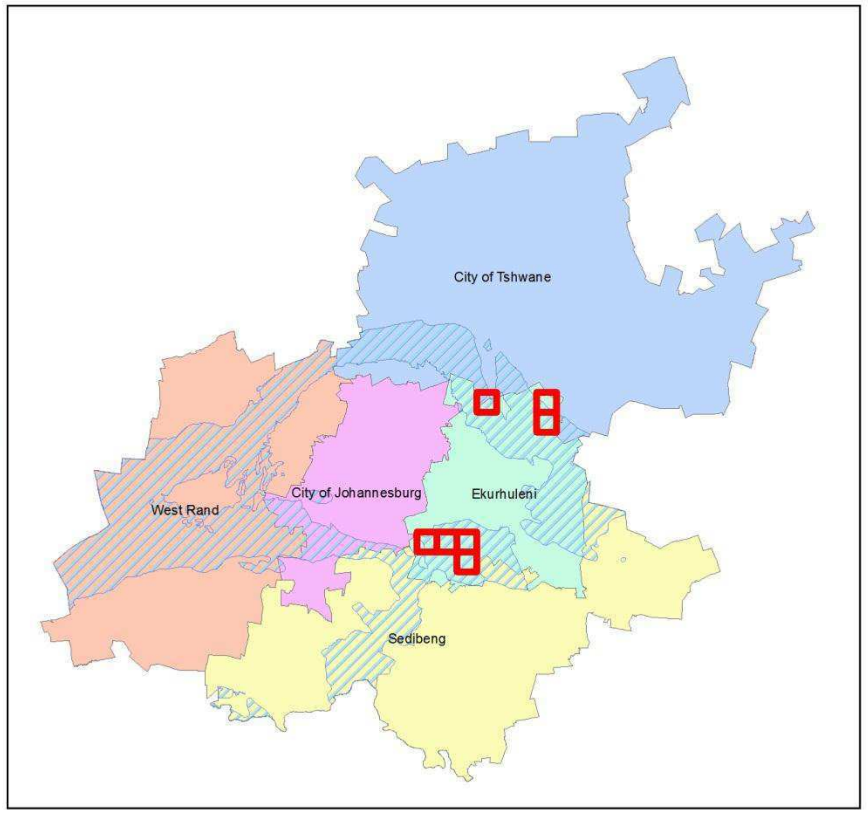
MAP C1: EKURHULENI SINKHOLES, SUBSIDENCES & CRACKS

Types of instability events

Geology: Council for Geoscience
Groundwater Compartments: Department of Water Affairs

July 2013 GCS_WGS_1984





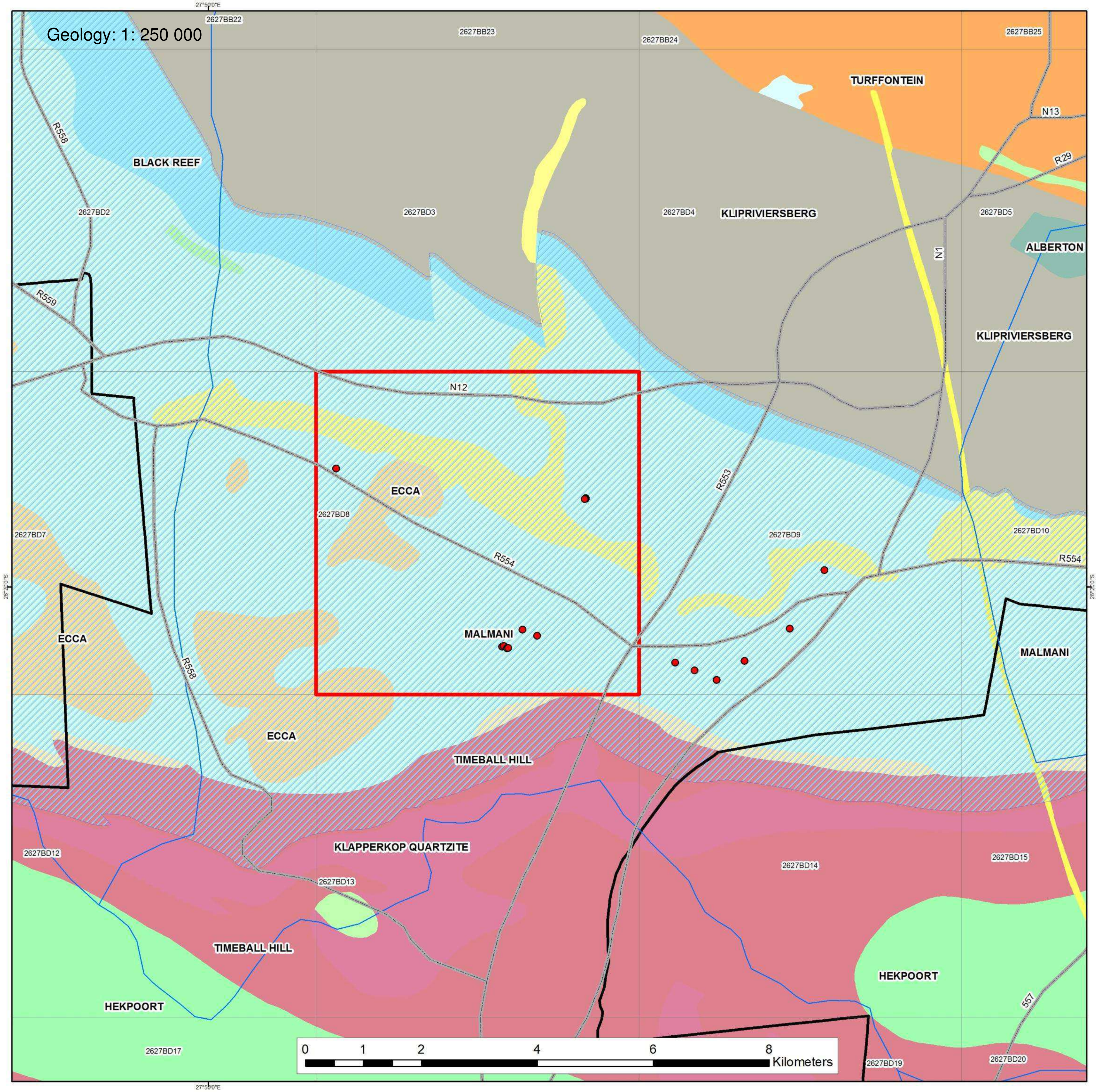
MAP C2: EKURHULENI SINKHOLES AND SUBSIDENCES

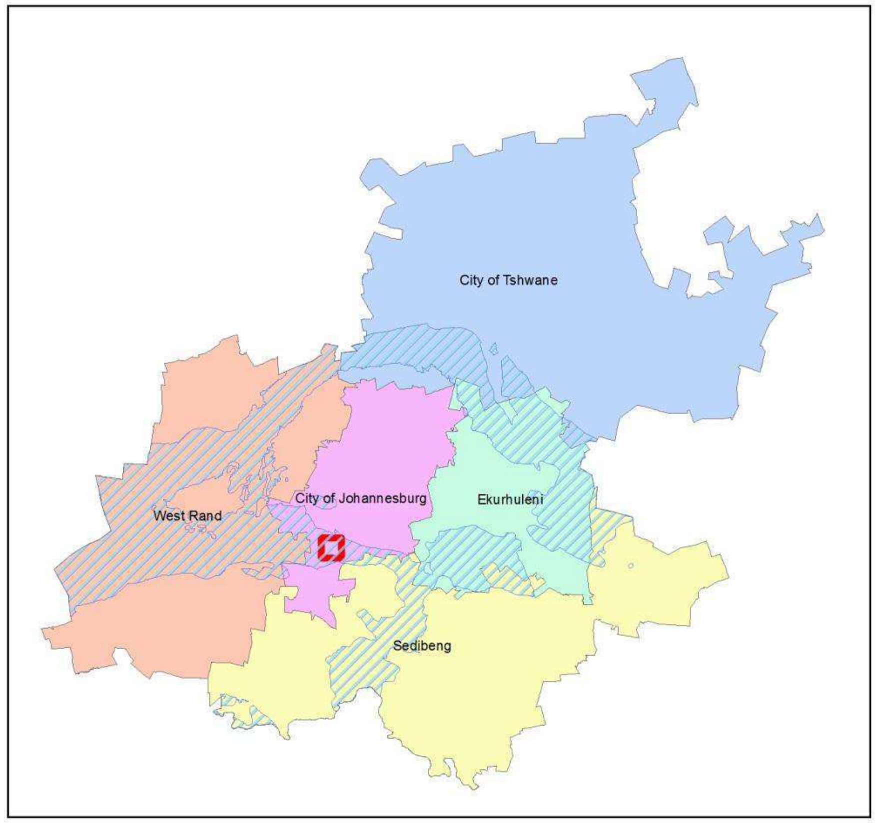
Size categories (diameters) on the dolomite formations

Geology (unpubl.): Council for Geoscience
Groundwater Compartments: Department of Water Affairs

July 2013 GCS_WGS_1984

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA





Legend

- Dolomitic land
- Sinkhole
- Municipalities
- Groundwater Compartments
- Main road
- 1: 10 000

MAP D1: JOHANNESBURG SINKHOLES

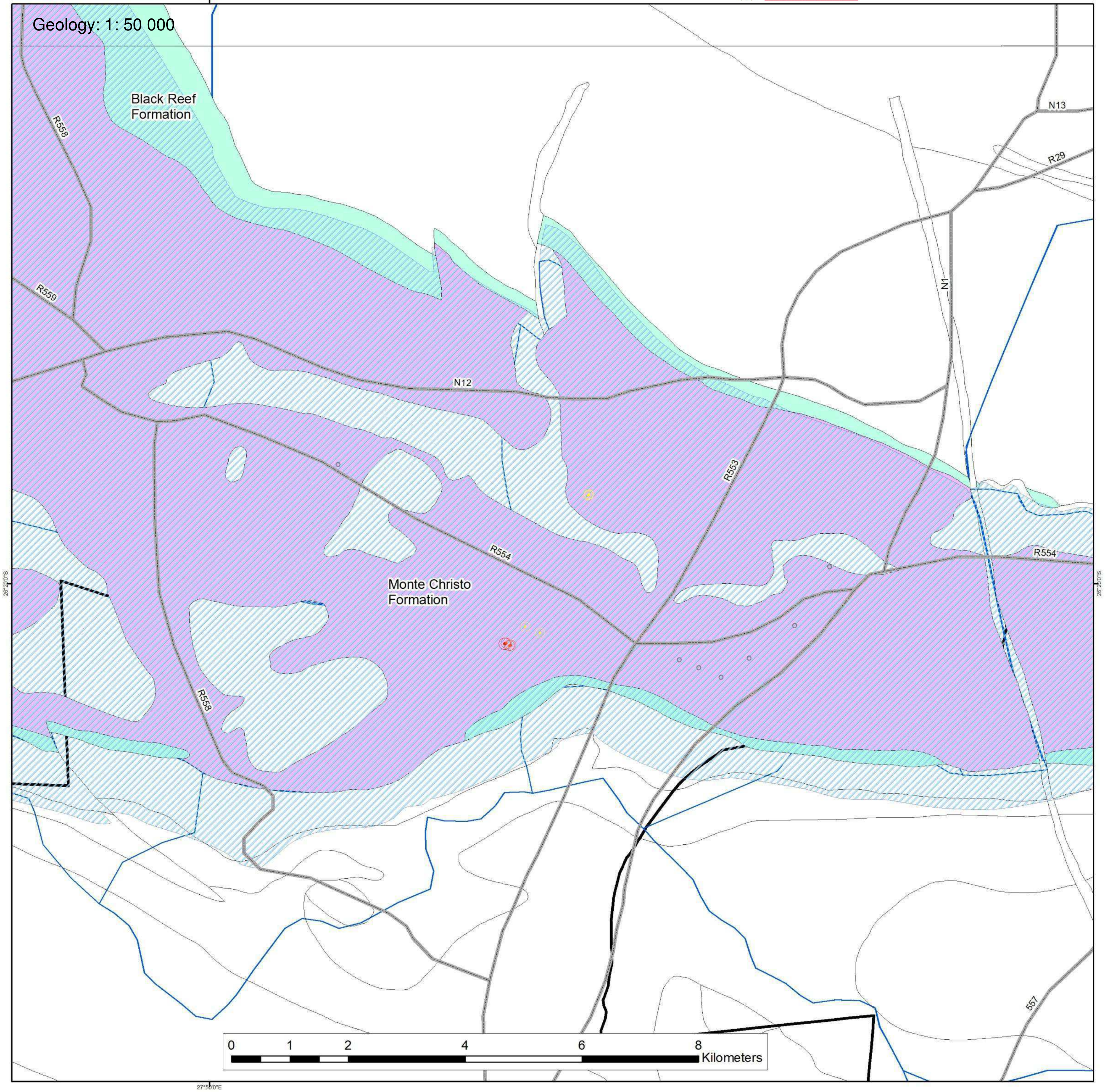
Types of Instabilty events

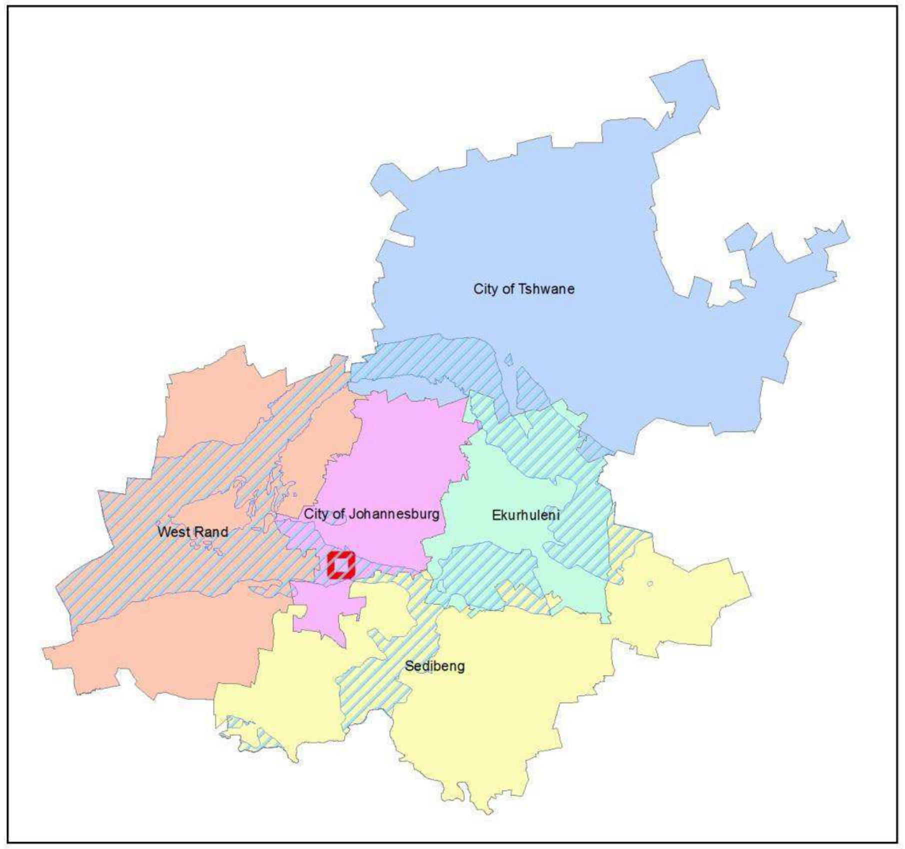
Geology: Council for Geoscience (CGS)
Groundwater Compartments: Department of Water Affairs (DWA)

N E S W

July 2013 GCS_WGS_1984

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA





Legend

Johannesburg sinkholes

Size category

- Unknown
- >2m - <=5m
- >5m - <=15m
- >15m

- Dolomitic land
- Monte Christo Fm
- Black Reef Fm

- Municipalities
- Main road
- Groundwater Compartment

MAP D2: JOHANNESBURG SINKHOLES

Size categories (diameters) on the dolomite formations

Geology (unpubl.): Council for Geoscience (CGS)
Groundwater Comaprtments:Department of Water Affairs (DWA)

N W E S

July 2013 GCS_WGS_1984

Appendix B: Raw data and Newspaper articles

The FREQ Procedure

Table of V7 by V1

V7(Year : V7) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
1910	0	0	0	1	1
	0	0	0	1	
	0.0757	0.412	0.0027	0.4721	
	0.00	0.00	0.00	0.07	0.07
	0.00	0.00	0.00	100.00	
	0.00	0.00	0.00	0.13	
1959	0	0	0	1	1
	0	0	0	1	
	0.0757	0.412	0.0027	0.4721	
	0.00	0.00	0.00	0.07	0.07
	0.00	0.00	0.00	100.00	
	0.00	0.00	0.00	0.13	
1962	0	1	0	1	2
	0	1	0	1	
	0.1514	0.0376	0.0055	0.0004	
	0.00	0.07	0.00	0.07	0.14
	0.00	50.00	0.00	50.00	
	0.00	0.17	0.00	0.13	
1963	0	0	0	3	3
	0	1	0	2	
	0.2271	1.236	0.0082	1.4162	
	0.00	0.00	0.00	0.20	0.20
	0.00	0.00	0.00	100.00	
	0.00	0.00	0.00	0.40	
1964	0	15	4	1	20
	2	8	0	10	
	1.5143	5.5456	285.25	8.2891	
	0.00	1.02	0.27	0.07	1.36
	0.00	75.00	20.00	5.00	
	0.00	2.48	100.00	0.13	
Total	111	604	4	747	1466
	7.57	41.20	0.27	50.95	100.00

(Continued)

The FREQ Procedure

Table of V7 by V1

V7(Year : V7) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
1965	0	7	0	0	7
	1	3	0	4	
	0.53	5.8741	0.0191	3.5668	
	0.00	0.48	0.00	0.00	0.48
	0.00	100.00	0.00	0.00	
	0.00	1.16	0.00	0.00	
1966	0	1	0	0	1
	0	0	0	1	
	0.0757	0.8392	0.0027	0.5095	
	0.00	0.07	0.00	0.00	0.07
	0.00	100.00	0.00	0.00	
	0.00	0.17	0.00	0.00	
1967	0	1	0	1	2
	0	1	0	1	
	0.1514	0.0376	0.0055	0.0004	
	0.00	0.07	0.00	0.07	0.14
	0.00	50.00	0.00	50.00	
	0.00	0.17	0.00	0.13	
1968	0	1	0	4	5
	0	2	0	3	
	0.3786	0.5455	0.0136	0.8278	
	0.00	0.07	0.00	0.27	0.34
	0.00	20.00	0.00	80.00	
	0.00	0.17	0.00	0.54	
1969	0	0	0	7	7
	1	3	0	4	
	0.53	2.884	0.0191	3.3045	
	0.00	0.00	0.00	0.48	0.48
	0.00	0.00	0.00	100.00	
	0.00	0.00	0.00	0.94	
Total	111	604	4	747	1466
	7.57	41.20	0.27	50.95	100.00

(Continued)

(R01-R6) : n-Way PROC FREQ of varbs (V6 V7 NV11)*V1 from data set SINK

The FREQ Procedure

Table of V7 by V1

V7(Year : V7) V1(Data : V1)

Frequency Expected Cell Chi-Square Percent Row Pct Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
1970	0 0 0.0757 0.00 0.00 0.00	0 0 0.412 0.00 0.00 0.00	0 0 0.0027 0.00 0.00 0.00	1 1 0.4721 0.07 100.00 0.13	1 0.07
1971	0 1 0.53 0.00 0.00 0.00	0 3 2.884 0.00 0.00 0.00	0 0 0.0191 0.00 0.00 0.00	7 4 3.3045 0.48 100.00 0.94	7 0.48
1972	0 0 0.4543 0.00 0.00 0.00	0 2 2.472 0.00 0.00 0.00	0 0 0.0164 0.00 0.00 0.00	6 3 2.8324 0.41 100.00 0.80	6 0.41
1973	0 2 1.9686 0.00 0.00 0.00	0 11 10.712 0.00 0.00 0.00	0 0 0.0709 0.00 0.00 0.00	26 13 12.274 1.77 100.00 3.48	26 1.77
1974	0 1 0.6057 0.00 0.00 0.00	0 3 3.296 0.00 0.00 0.00	0 0 0.0218 0.00 0.00 0.00	8 4 3.7765 0.55 100.00 1.07	8 0.55
Total	111 7.57	604 41.20	4 0.27	747 50.95	1466 100.00

(Continued)

The FREQ Procedure

Table of V7 by V1

V7(Year : V7) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
1975	0	1	0	19	20
	2	8	0	10	
	1.5143	6.3615	0.0546	7.6144	
	0.00	0.07	0.00	1.30	1.36
	0.00	5.00	0.00	95.00	
	0.00	0.17	0.00	2.54	
1976	0	0	0	14	14
	1	6	0	7	
	1.06	5.7681	0.0382	6.6089	
	0.00	0.00	0.00	0.95	0.95
	0.00	0.00	0.00	100.00	
	0.00	0.00	0.00	1.87	
1977	0	0	0	14	14
	1	6	0	7	
	1.06	5.7681	0.0382	6.6089	
	0.00	0.00	0.00	0.95	0.95
	0.00	0.00	0.00	100.00	
	0.00	0.00	0.00	1.87	
1978	0	0	0	42	42
	3	17	0	21	
	3.1801	17.304	0.1146	19.827	
	0.00	0.00	0.00	2.86	2.86
	0.00	0.00	0.00	100.00	
	0.00	0.00	0.00	5.62	
1979	0	0	0	26	26
	2	11	0	13	
	1.9686	10.712	0.0709	12.274	
	0.00	0.00	0.00	1.77	1.77
	0.00	0.00	0.00	100.00	
	0.00	0.00	0.00	3.48	
Total	111	604	4	747	1466
	7.57	41.20	0.27	50.95	100.00

(Continued)

(R01-R6) : n-Way PROC FREQ of varbs (V6 V7 NV11)*V1 from data set SINK

The FREQ Procedure

Table of V7 by V1

V7(Year : V7) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
1980	1	0	0	27	28
	2	12	0	14	
	0.5917	11.536	0.0764	11.363	
	0.07	0.00	0.00	1.84	1.91
	3.57	0.00	0.00	96.43	
	0.90	0.00	0.00	3.61	
1981	0	0	0	19	19
	1	8	0	10	
	1.4386	7.8281	0.0518	8.9693	
	0.00	0.00	0.00	1.30	1.30
	0.00	0.00	0.00	100.00	
	0.00	0.00	0.00	2.54	
1982	0	0	0	7	7
	1	3	0	4	
	0.53	2.884	0.0191	3.3045	
	0.00	0.00	0.00	0.48	0.48
	0.00	0.00	0.00	100.00	
	0.00	0.00	0.00	0.94	
1983	0	5	0	7	12
	1	5	0	6	
	0.9086	0.0006	0.0327	0.1282	
	0.00	0.34	0.00	0.48	0.82
	0.00	41.67	0.00	58.33	
	0.00	0.83	0.00	0.94	
1984	0	17	0	16	33
	2	14	0	17	
	2.4986	0.8522	0.09	0.0395	
	0.00	1.16	0.00	1.09	2.25
	0.00	51.52	0.00	48.48	
	0.00	2.81	0.00	2.14	
Total	111	604	4	747	1466
	7.57	41.20	0.27	50.95	100.00

(Continued)

(R01-R6) : n-Way PROC FREQ of varbs (V6 V7 NV11)*V1 from data set SINK

The FREQ Procedure

Table of V7 by V1

V7(Year : V7) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
1985	1	8	0	8	17
	1	7	0	9	
	0.0641	0.1416	0.0464	0.0506	
	0.07	0.55	0.00	0.55	1.16
	5.88	47.06	0.00	47.06	
	0.90	1.32	0.00	1.07	
1986	0	20	0	11	31
	2	13	0	16	
	2.3472	4.0903	0.0846	1.4562	
	0.00	1.36	0.00	0.75	2.11
	0.00	64.52	0.00	35.48	
	0.00	3.31	0.00	1.47	
1987	0	34	0	15	49
	4	20	0	25	
	3.7101	9.4492	0.1337	3.9795	
	0.00	2.32	0.00	1.02	3.34
	0.00	69.39	0.00	30.61	
	0.00	5.63	0.00	2.01	
1988	0	38	0	26	64
	5	26	0	33	
	4.8458	5.131	0.1746	1.3403	
	0.00	2.59	0.00	1.77	4.37
	0.00	59.38	0.00	40.63	
	0.00	6.29	0.00	3.48	
1989	0	28	0	6	34
	3	14	0	17	
	2.5744	13.975	0.0928	7.4027	
	0.00	1.91	0.00	0.41	2.32
	0.00	82.35	0.00	17.65	
	0.00	4.64	0.00	0.80	
Total	111	604	4	747	1466
	7.57	41.20	0.27	50.95	100.00

(Continued)

The FREQ Procedure

Table of V7 by V1

V7(Year : V7) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
1990	1	22	0	18	41
	3	17	0	21	
	1.4265	1.5445	0.1119	0.4002	
	0.07	1.50	0.00	1.23	2.80
	2.44	53.66	0.00	43.90	
	0.90	3.64	0.00	2.41	
1991	0	24	0	16	40
	3	16	0	20	
	3.0286	3.4312	0.1091	0.9421	
	0.00	1.64	0.00	1.09	2.73
	0.00	60.00	0.00	40.00	
	0.00	3.97	0.00	2.14	
1992	0	29	0	9	38
	3	16	0	19	
	2.8772	11.373	0.1037	5.5462	
	0.00	1.98	0.00	0.61	2.59
	0.00	76.32	0.00	23.68	
	0.00	4.80	0.00	1.20	
1993	0	28	0	10	38
	3	16	0	19	
	2.8772	9.7322	0.1037	4.5274	
	0.00	1.91	0.00	0.68	2.59
	0.00	73.68	0.00	26.32	
	0.00	4.64	0.00	1.34	
1994	0	12	0	23	35
	3	14	0	18	
	2.6501	0.4062	0.0955	1.4963	
	0.00	0.82	0.00	1.57	2.39
	0.00	34.29	0.00	65.71	
	0.00	1.99	0.00	3.08	
Total	111	604	4	747	1466
	7.57	41.20	0.27	50.95	100.00

(Continued)

The FREQ Procedure

Table of V7 by V1

V7(Year : V7) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
1995	1	18	0	30	49
	4	20	0	25	
	1.9796	0.2372	0.1337	1.0142	
	0.07	1.23	0.00	2.05	3.34
	2.04	36.73	0.00	61.22	
	0.90	2.98	0.00	4.02	
1996	0	36	0	74	110
	8	45	0	56	
	8.3288	1.9169	0.3001	5.7481	
	0.00	2.46	0.00	5.05	7.50
	0.00	32.73	0.00	67.27	
	0.00	5.96	0.00	9.91	
1997	3	47	0	36	86
	7	35	0	44	
	1.8937	3.7764	0.2347	1.396	
	0.20	3.21	0.00	2.46	5.87
	3.49	54.65	0.00	41.86	
	2.70	7.78	0.00	4.82	
1998	0	43	0	38	81
	6	33	0	41	
	6.133	2.7774	0.221	0.2596	
	0.00	2.93	0.00	2.59	5.53
	0.00	53.09	0.00	46.91	
	0.00	7.12	0.00	5.09	
1999	0	8	0	29	37
	3	15	0	19	
	2.8015	3.4425	0.101	5.4608	
	0.00	0.55	0.00	1.98	2.52
	0.00	21.62	0.00	78.38	
	0.00	1.32	0.00	3.88	
Total	111	604	4	747	1466
	7.57	41.20	0.27	50.95	100.00

(Continued)

The FREQ Procedure

Table of V7 by V1

V7(Year : V7) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
2000	1	13	0	4	18
	1	7	0	9	
	0.0966	4.2044	0.0491	2.9164	
	0.07	0.89	0.00	0.27	1.23
	5.56	72.22	0.00	22.22	
	0.90	2.15	0.00	0.54	
2001	0	10	0	12	22
	2	9	0	11	
	1.6658	0.0966	0.06	0.0557	
	0.00	0.68	0.00	0.82	1.50
	0.00	45.45	0.00	54.55	
	0.00	1.66	0.00	1.61	
2002	0	17	0	15	32
	2	13	0	16	
	2.4229	1.1044	0.0873	0.1045	
	0.00	1.16	0.00	1.02	2.18
	0.00	53.13	0.00	46.88	
	0.00	2.81	0.00	2.01	
2003	3	2	0	11	16
	1	7	0	8	
	2.6405	3.1989	0.0437	0.9943	
	0.20	0.14	0.00	0.75	1.09
	18.75	12.50	0.00	68.75	
	2.70	0.33	0.00	1.47	
2004	4	6	0	19	29
	2	12	0	15	
	1.4825	2.9612	0.0791	1.2069	
	0.27	0.41	0.00	1.30	1.98
	13.79	20.69	0.00	65.52	
	3.60	0.99	0.00	2.54	
Total	111	604	4	747	1466
	7.57	41.20	0.27	50.95	100.00

(Continued)

(R01-R6) : n-Way PROC FREQ of varbs (V6 V7 NV11)*V1 from data set SINK

The FREQ Procedure

Table of V7 by V1

V7(Year : V7) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
2005	11	27	0	22	60
	5	25	0	31	
	9.1775	0.2102	0.1637	2.404	
	0.75	1.84	0.00	1.50	4.09
	18.33	45.00	0.00	36.67	
	9.91	4.47	0.00	2.95	
2006	11	23	0	15	49
	4	20	0	25	
	14.324	0.3916	0.1337	3.9795	
	0.75	1.57	0.00	1.02	3.34
	22.45	46.94	0.00	30.61	
	9.91	3.81	0.00	2.01	
2007	31	6	0	3	40
	3	16	0	20	
	258.33	6.6647	0.1091	14.824	
	2.11	0.41	0.00	0.20	2.73
	77.50	15.00	0.00	7.50	
	27.93	0.99	0.00	0.40	
2008	11	2	0	11	24
	2	10	0	12	
	46.404	6.2927	0.0655	0.1236	
	0.75	0.14	0.00	0.75	1.64
	45.83	8.33	0.00	45.83	
	9.91	0.33	0.00	1.47	
2009	24	12	0	3	39
	3	16	0	20	
	150.01	1.03	0.1064	14.325	
	1.64	0.82	0.00	0.20	2.66
	61.54	30.77	0.00	7.69	
	21.62	1.99	0.00	0.40	
Total	111	604	4	747	1466
	7.57	41.20	0.27	50.95	100.00

(Continued)

The FREQ Procedure

Table of V7 by V1

V7(Year : V7) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
2010	8	33	0	13	54
	4	22	0	28	
	3.7417	5.1959	0.1473	7.6576	
	0.55	2.25	0.00	0.89	3.68
	14.81	61.11	0.00	24.07	
	7.21	5.46	0.00	1.74	
2011	0	9	0	12	21
	2	9	0	11	
	1.59	0.014	0.0573	0.1578	
	0.00	0.61	0.00	0.82	1.43
	0.00	42.86	0.00	57.14	
	0.00	1.49	0.00	1.61	
Total	111	604	4	747	1466
	7.57	41.20	0.27	50.95	100.00

Frequency Missing = 1582

Statistics for Table of V7 by V1

Statistic	DF	Value	Prob
Chi-Square	153	1268.1516	<.0001
Likelihood Ratio Chi-Square	153	881.9124	<.0001
Mantel-Haenszel Chi-Square	1	150.7017	<.0001
Phi Coefficient		0.9301	
Contingency Coefficient		0.6810	
Cramer's V		0.5370	

WARNING: 63% of the cells have expected counts less than 5. Chi-Square may not be a valid test.

Effective Sample Size = 1466
Frequency Missing = 1582

WARNING: 52% of the data are missing.

The FREQ Procedure

Table of V6 by V1

V6(Month : V6) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
April	5	38	0	41	84
	7	42	0	36	
	0.4508	0.3171	.	0.8116	
	0.44	3.32	0.00	3.58	7.33
	5.95	45.24	0.00	48.81	
	5.43	6.69	.	8.44	
April/May	0	0	0	1	1
	0	0	0	0	
	0.0803	0.4956	.	0.7821	
	0.00	0.00	0.00	0.09	0.09
	0.00	0.00	0.00	100.00	
	0.00	0.00	.	0.21	
August	4	47	0	34	85
	7	42	0	36	
	1.1685	0.5632	.	0.1163	
	0.35	4.10	0.00	2.97	7.42
	4.71	55.29	0.00	40.00	
	4.35	8.27	.	7.00	
December	3	77	0	33	113
	9	56	0	48	
	4.0637	7.8688	.	4.6461	
	0.26	6.72	0.00	2.88	9.86
	2.65	68.14	0.00	29.20	
	3.26	13.56	.	6.79	
February	11	43	0	99	153
	12	76	0	65	
	0.134	14.215	.	17.937	
	0.96	3.75	0.00	8.64	13.35
	7.19	28.10	0.00	64.71	
	11.96	7.57	.	20.37	
Total	92	568	0	486	1146
	8.03	49.56	0.00	42.41	100.00

(Continued)

(R01-R6) : n-Way PROC FREQ of varbs (V6 V7 NV11)*V1 from data set SINK

The FREQ Procedure

Table of V6 by V1

V6(Month : V6) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
January	19	62	0	81	162
	13	80	0	69	
	2.7633	4.1677	.	2.2016	
	1.66	5.41	0.00	7.07	14.14
	11.73	38.27	0.00	50.00	
	20.65	10.92	.	16.67	
July	4	37	0	20	61
	5	30	0	26	
	0.1643	1.5142	.	1.3316	
	0.35	3.23	0.00	1.75	5.32
	6.56	60.66	0.00	32.79	
	4.35	6.51	.	4.12	
June	6	22	0	26	54
	4	27	0	23	
	0.6394	0.8481	.	0.4195	
	0.52	1.92	0.00	2.27	4.71
	11.11	40.74	0.00	48.15	
	6.52	3.87	.	5.35	
March	14	54	0	39	107
	9	53	0	45	
	3.4074	0.0176	.	0.8962	
	1.22	4.71	0.00	3.40	9.34
	13.08	50.47	0.00	36.45	
	15.22	9.51	.	8.02	
May	2	34	0	25	61
	5	30	0	26	
	1.7139	0.4691	.	0.0292	
	0.17	2.97	0.00	2.18	5.32
	3.28	55.74	0.00	40.98	
	2.17	5.99	.	5.14	
Total	92	568	0	486	1146
	8.03	49.56	0.00	42.41	100.00

(Continued)

The FREQ Procedure

Table of V6 by V1

V6(Month : V6) V1(Data : V1)

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Ekurhuleni	Far West Rand	Johannesburg	Tshwane	Total
November	7	65	0	36	108
	9	54	0	46	
	0.3217	2.4583	.	2.0973	
	0.61	5.67	0.00	3.14	9.42
	6.48	60.19	0.00	33.33	
	7.61	11.44	.	7.41	
October	12	61	0	26	99
	8	49	0	42	
	2.0662	2.9015	.	6.0856	
	1.05	5.32	0.00	2.27	8.64
	12.12	61.62	0.00	26.26	
	13.04	10.74	.	5.35	
September	5	28	0	25	58
	5	29	0	25	
	0.0254	0.0194	.	0.0066	
	0.44	2.44	0.00	2.18	5.06
	8.62	48.28	0.00	43.10	
	5.43	4.93	.	5.14	
Total	92	568	0	486	1146
	8.03	49.56	0.00	42.41	100.00

Frequency Missing = 1902

The FREQ Procedure

Type : V11

V11	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Cracks	159	5.22	159	5.22
Sinkhole	2131	69.91	2290	75.13
Sinkhole & subsidence	7	0.23	2297	75.36
Subsidence	513	16.83	2810	92.19
Subsidence & Sinkhole	24	0.79	2834	92.98
Undefined	214	7.02	3048	100.00

VV11	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Sinkhole	2131	79.66	2131	79.66
Subsidence	544	20.34	2675	100.00

Frequency Missing = 373

NV11	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Cracks	159	5.22	159	5.22
Sinkhole	2131	69.91	2290	75.13
Subsidence	544	17.85	2834	92.98
Undefined	214	7.02	3048	100.00

The FREQ Procedure

Table of V15 by NV11

V15(Formation : V15) NV11

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Cracks	Sinkhole	Subsidence	Undefined	Total
Dwyka	1 1 0.1528 0.03 7.69 0.63	8 9 0.1305 0.26 61.54 0.38	4 2 1.2161 0.13 30.77 0.74	0 1 0.9127 0.00 0.00 0.00	13 0.43
Ecca	0 1 0.5738 0.00 0.00 0.00	9 8 0.2229 0.30 81.82 0.42	2 2 0.0007 0.07 18.18 0.37	0 1 0.7723 0.00 0.00 0.00	11 0.36
Eccles	34 49 4.5832 1.12 3.62 21.38	663 656 0.0644 21.75 70.61 31.11	201 168 6.6602 6.59 21.41 36.95	41 66 9.425 1.35 4.37 19.16	939 30.81
Karoo	5 1 20.787 0.16 31.25 3.14	6 11 2.4046 0.20 37.50 0.28	5 3 1.6102 0.16 31.25 0.92	0 1 1.1234 0.00 0.00 0.00	16 0.52
Total	159 5.22	2131 69.91	544 17.85	214 7.02	3048 100.00

(Continued)

The FREQ Procedure

Table of V15 by NV11

V15(Formation : V15) NV11

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	Cracks	Sinkhole	Subsidence	Undefined	Total
Lyttelton	34	309	150	34	527
	27	368	94	37	
	1.5411	9.5925	33.272	0.2433	
	1.12	10.14	4.92	1.12	17.29
	6.45	58.63	28.46	6.45	
	21.38	14.50	27.57	15.89	
Malmani	3	10	1	0	14
	1	10	2	1	
	7.0538	0.0046	0.8989	0.9829	
	0.10	0.33	0.03	0.00	0.46
	21.43	71.43	7.14	0.00	
	1.89	0.47	0.18	0.00	
Monte Christo	50	775	135	133	1093
	57	764	195	77	
	0.8635	0.1536	18.501	41.247	
	1.64	25.43	4.43	4.36	35.86
	4.57	70.91	12.35	12.17	
	31.45	36.37	24.82	62.15	
Oaktree	8	212	5	0	225
	12	157	40	16	
	1.19	19.015	30.78	15.797	
	0.26	6.96	0.16	0.00	7.38
	3.56	94.22	2.22	0.00	
	5.03	9.95	0.92	0.00	
Total	159	2131	544	214	3048
	5.22	69.91	17.85	7.02	100.00

(Continued)

(R01-R5) : n-Way PROC FREQ of varbs V15*NV11 from data set SINK

The FREQ Procedure

Table of V15 by NV11

V15(Formation : V15) NV11

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct		Cracks	Sinkhole	Subsidence	Undefined	Total
Rooihoogte	Frequency	13	54	3	1	71
	Expected	4	50	13	5	
	Cell Chi-Square	23.333	0.3831	7.3821	3.1855	
	Percent	0.43	1.77	0.10	0.03	2.33
	Row Pct	18.31	76.06	4.23	1.41	
	Col Pct	8.18	2.53	0.55	0.47	
Timeball Hill	Frequency	9	70	16	2	97
	Expected	5	68	17	7	
	Cell Chi-Square	3.0678	0.0703	0.0995	3.3977	
	Percent	0.30	2.30	0.52	0.07	3.18
	Row Pct	9.28	72.16	16.49	2.06	
	Col Pct	5.66	3.28	2.94	0.93	
Vryheid	Frequency	2	15	22	3	42
	Expected	2	29	7	3	
	Cell Chi-Square	0.0166	7.0266	28.063	0.0009	
	Percent	0.07	0.49	0.72	0.10	1.38
	Row Pct	4.76	35.71	52.38	7.14	
	Col Pct	1.26	0.70	4.04	1.40	
Total	Frequency	159	2131	544	214	3048
	Percent	5.22	69.91	17.85	7.02	100.00

Statistics for Table of V15 by NV11

Statistic	DF	Value	Prob
Chi-Square	30	307.8035	<.0001
Likelihood Ratio Chi-Square	30	310.7755	<.0001
Mantel-Haenszel Chi-Square	1	3.9138	0.0479
Phi Coefficient		0.3178	
Contingency Coefficient		0.3029	
Cramer's V		0.1835	

WARNING: 36% of the cells have expected counts less than 5. Chi-Square may not be a valid test.

Sample Size = 3048

(R01-R8R) : n-Way PROC FREQ of varbs V15*(CATSIZE NCATSIZE NVV12) for NV11 = SINKHOLE from data set SINK

The FREQ Procedure

Table of V15 by CATSIZE

V15(Formation : V15) Frequency Expected Cell Chi-Square Percent Row Pct Col Pct	CATSIZE <= 2m	> 2m to <= 5m	> 5m to <= 15m	> 15m	Total
Dwyka	3 1 1.5592 0.30 37.50 1.61	0 2 2.1095 0.00 0.00 0.00	3 3 0.0687 0.30 37.50 0.93	2 2 0.0156 0.20 25.00 0.87	8 0.80
Ecca	0 1 0.9254 0.00 0.00 0.00	1 1 0.0769 0.10 20.00 0.38	0 2 1.6119 0.00 0.00 0.00	4 1 7.1269 0.40 80.00 1.74	5 0.50
Eccles	51 60 1.3401 5.07 15.74 27.42	92 85 0.5048 9.15 28.40 34.72	105 104 0.0029 10.45 32.41 32.41	76 74 0.0462 7.56 23.46 33.04	324 32.24
Karoo	0 1 1.1104 0.00 0.00 0.00	3 2 1.2708 0.30 50.00 1.13	2 2 0.0022 0.20 33.33 0.62	1 1 0.1014 0.10 16.67 0.43	6 0.60
Total	186 18.51	265 26.37	324 32.24	230 22.89	1005 100.00

(Continued)

(R01-R8R) : n-Way PROC FREQ of varbs V15*(CATSIZE NCATSIZE NVV12) for NV11 = SINKHOLE from data set SINK

The FREQ Procedure

Table of V15 by CATSIZE

V15(Formation : V15) / CATSIZE Frequency Expected Cell Chi-Square Percent Row Pct Col Pct	<= 2m	> 2m to <= 5m	> 5m to <= 15m	> 15m	Total
Lyttelton	24 25 0.0258 2.39 17.91 12.90	37 35 0.0786 3.68 27.61 13.96	49 43 0.7787 4.88 36.57 15.12	24 31 1.4493 2.39 17.91 10.43	134 13.33
Malmani	1 1 0.156 0.10 12.50 0.54	2 2 0.0057 0.20 25.00 0.75	1 3 0.9668 0.10 12.50 0.31	4 2 2.57 0.40 50.00 1.74	8 0.80
Monte Christo	88 74 2.7918 8.76 22.11 47.31	106 105 0.0106 10.55 26.63 40.00	123 128 0.2198 12.24 30.90 37.96	81 91 1.1165 8.06 20.35 35.22	398 39.60
Oaktree	8 10 0.3336 0.80 15.09 4.30	9 14 1.7711 0.90 16.98 3.40	21 17 0.8963 2.09 39.62 6.48	15 12 0.6794 1.49 28.30 6.52	53 5.27
Total	186 18.51	265 26.37	324 32.24	230 22.89	1005 100.00

(Continued)

(R01-R8R) : n-Way PROC FREQ of varbs V15*(CATSIZE NCATSIZE NVV12) for NV11 = SINKHOLE from data set SINK

The FREQ Procedure

Table of V15 by CATSIZE

V15(Formation : V15) / CATSIZE Frequency Expected Cell Chi-Square Percent Row Pct Col Pct	<= 2m	> 2m to <= 5m	> 5m to <= 15m	> 15m	Total
Rooihoogte	4	8	9	14	35
	6	9	11	8	
	0.9477	0.1636	0.4622	4.4795	
	0.40	0.80	0.90	1.39	3.48
	11.43	22.86	25.71	40.00	
	2.15	3.02	2.78	6.09	
Timeball Hill	5	7	8	9	29
	5	8	9	7	
	0.0251	0.0547	0.1947	0.8415	
	0.50	0.70	0.80	0.90	2.89
	17.24	24.14	27.59	31.03	
	2.69	2.64	2.47	3.91	
Vryheid	2	0	3	0	5
	1	1	2	1	
	1.248	1.3184	1.1953	1.1443	
	0.20	0.00	0.30	0.00	0.50
	40.00	0.00	60.00	0.00	
	1.08	0.00	0.93	0.00	
Total	186	265	324	230	1005
	18.51	26.37	32.24	22.89	100.00

Frequency Missing = 1126

The FREQ Procedure

Statistics for Table of V15 by CATSIZE

Statistic	DF	Value	Prob
Chi-Square	30	43.7978	0.0497
Likelihood Ratio Chi-Square	30	47.1711	0.0239
Mantel-Haenszel Chi-Square	1	0.1280	0.7205
Phi Coefficient		0.2088	
Contingency Coefficient		0.2044	
Cramer's V		0.1205	

WARNING: 45% of the cells have expected counts less than 5. Chi-Square may not be a valid test.

Effective Sample Size = 1005
Frequency Missing = 1126

WARNING: 53% of the data are missing.

(R01-R8R) : n-Way PROC FREQ of varbs V15*(CATSIZE NCATSIZE NVV12) for NV11 = SINKHOLE from data set SINK

The FREQ Procedure

Table of V15 by NVV12

V15(Formation : V15) / NVV12 Frequency Expected Cell Chi-Square Percent Row Pct Col Pct	<= 1m	> 1m to <= 5m	> 5m to <= 15m	> 15m	Total
Dwyka	2 1 0.427 0.24 28.57 1.33	2 4 0.9542 0.24 28.57 0.43	3 2 1.4964 0.36 42.86 1.69	0 0 0.2952 0.00 0.00 0.00	7 0.84
Ecca	0 0 0.3614 0.00 0.00 0.00	2 1 0.6799 0.24 100.00 0.43	0 0 0.4289 0.00 0.00 0.00	0 0 0.0843 0.00 0.00 0.00	2 0.24
Eccles	47 50 0.1871 5.66 16.97 31.33	156 156 0.0001 18.80 56.32 33.40	60 59 0.006 7.23 21.66 33.71	14 12 0.4605 1.69 5.05 40.00	277 33.37
Karoo	0 1 1.0843 0.00 0.00 0.00	4 3 0.1154 0.48 66.67 0.86	2 1 0.3954 0.24 33.33 1.12	0 0 0.253 0.00 0.00 0.00	6 0.72
Total	150 18.07	467 56.27	178 21.45	35 4.22	830 100.00

(Continued)

(R01-R8R) : n-Way PROC FREQ of varbs V15*(CATSIZE NCATSIZE NVV12) for NV11 = SINKHOLE from data set SINK

The FREQ Procedure

Table of V15 by NVV12

V15(Formation : V15) / Frequency, Expected, Cell Chi-Square, Percent, Row Pct, Col Pct	NVV12: <= 1m	> 1m to <= 5m	> 5m to <= 15m	> 15m	Total
Lyttelton	14	65	16	5	100
	18	56	21	4	
	0.9176	1.3561	1.3829	0.1454	
	1.69	7.83	1.93	0.60	12.05
	14.00	65.00	16.00	5.00	
	9.33	13.92	8.99	14.29	
Malmani	0	1	3	1	5
	1	3	1	0	
	0.9036	1.1687	3.4655	2.9537	
	0.00	0.12	0.36	0.12	0.60
	0.00	20.00	60.00	20.00	
	0.00	0.21	1.69	2.86	
Monte Christo	67	203	66	7	343
	62	193	74	14	
	0.4053	0.5193	0.7768	3.8516	
	8.07	24.46	7.95	0.84	41.33
	19.53	59.18	19.24	2.04	
	44.67	43.47	37.08	20.00	
Oaktree	6	17	9	2	34
	6	19	7	1	
	0.0034	0.2372	0.4003	0.2237	
	0.72	2.05	1.08	0.24	4.10
	17.65	50.00	26.47	5.88	
	4.00	3.64	5.06	5.71	
Total	150	467	178	35	830
	18.07	56.27	21.45	4.22	100.00

(Continued)

The FREQ Procedure

Table of V15 by NVV12

V15(Formation : V15) / NVV12 Frequency Expected Cell Chi-Square Percent Row Pct Col Pct	<= 1m	> 1m to <= 5m	> 5m to <= 15m	> 15m	Total
Rooihoogte	8 5 2.3193 0.96 30.77 5.33	7 15 3.9784 0.84 26.92 1.50	9 6 2.1027 1.08 34.62 5.06	2 1 0.7447 0.24 7.69 5.71	26 3.13
Timeball Hill	3 4 0.4123 0.36 12.50 2.00	8 14 2.2431 0.96 33.33 1.71	9 5 2.8843 1.08 37.50 5.06	4 1 8.8216 0.48 16.67 11.43	24 2.89
Vryheid	3 1 3.3843 0.36 50.00 2.00	2 3 0.5608 0.24 33.33 0.43	1 1 0.0639 0.12 16.67 0.56	0 0 0.253 0.00 0.00 0.00	6 0.72
Total	150 18.07	467 56.27	178 21.45	35 4.22	830 100.00

Frequency Missing = 1301

The FREQ Procedure

Statistics for Table of V15 by NVV12

Statistic	DF	Value	Prob
Chi-Square	30	53.7087	0.0050
Likelihood Ratio Chi-Square	30	50.9739	0.0098
Mantel-Haenszel Chi-Square	1	0.0692	0.7925
Phi Coefficient		0.2544	
Contingency Coefficient		0.2465	
Cramer's V		0.1469	

WARNING: 59% of the cells have expected counts less than 5. Chi-Square may not be a valid test.

Effective Sample Size = 830
Frequency Missing = 1301

WARNING: 61% of the data are missing.

(R01-R9R) : n-Way PROC FREQ of varbs V15*(CATSIZE NCATSIZE NVV12) for NV11 = SUBSIDENCE from data set SINK

The FREQ Procedure

Table of V15 by CATSIZE

V15(Formation : V15) CATSIZE

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	<= 2m	> 2m to <= 5m	> 5m to <= 15m	> 15m	Total
Dwyka	0	0	1	2	3
	1	0	1	1	
	0.6714	0.4571	0.05	0.8048	
	0.00	0.00	0.48	0.95	1.43
	0.00	0.00	33.33	66.67	
	0.00	0.00	1.79	2.67	
Ecca	0	0	1	0	1
	0	0	0	0	
	0.2238	0.1524	2.0167	0.3571	
	0.00	0.00	0.48	0.00	0.48
	0.00	0.00	100.00	0.00	
	0.00	0.00	1.79	0.00	
Eccles	17	4	21	35	77
	17	12	21	28	
	0.0032	5.097	0.0106	2.0455	
	8.10	1.90	10.00	16.67	36.67
	22.08	5.19	27.27	45.45	
	36.17	12.50	37.50	46.67	
Karoo	1	1	1	1	4
	1	1	1	1	
	0.0123	0.2501	0.0042	0.1286	
	0.48	0.48	0.48	0.48	1.90
	25.00	25.00	25.00	25.00	
	2.13	3.13	1.79	1.33	
Total	47	32	56	75	210
	22.38	15.24	26.67	35.71	100.00

(Continued)

(R01-R9R) : n-Way PROC FREQ of varbs V15*(CATSIZE NCATSIZE NVV12) for NV11 = SUBSIDENCE from data set SINK

The FREQ Procedure

Table of V15 by CATSIZE

V15(Formation : V15)	Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	<= 2m	> 2m to <= 5m	> 5m to <= 15m	> 15m	Total
Lyttelton	Frequency	4	12	9	12	37
	Expected	8	6	10	13	
	Cell Chi-Square	2.2131	7.1786	0.0761	0.1116	
	Percent	1.90	5.71	4.29	5.71	17.62
	Row Pct	10.81	32.43	24.32	32.43	
	Col Pct	8.51	37.50	16.07	16.00	
Malmani	Frequency	0	0	0	0	0
	Expected	0	0	0	0	
	Cell Chi-Square	.	.	.	.	
	Percent	0.00	0.00	0.00	0.00	0.00
	Row Pct	.	.	.	.	
	Col Pct	0.00	0.00	0.00	0.00	
Monte Christo	Frequency	17	15	18	16	66
	Expected	15	10	18	24	
	Cell Chi-Square	0.3362	2.4293	0.0091	2.432	
	Percent	8.10	7.14	8.57	7.62	31.43
	Row Pct	25.76	22.73	27.27	24.24	
	Col Pct	36.17	46.88	32.14	21.33	
Oaktree	Frequency	2	0	0	2	4
	Expected	1	1	1	1	
	Cell Chi-Square	1.3633	0.6095	1.0667	0.2286	
	Percent	0.95	0.00	0.00	0.95	1.90
	Row Pct	50.00	0.00	0.00	50.00	
	Col Pct	4.26	0.00	0.00	2.67	
Total	Frequency	47	32	56	75	210
	Percent	22.38	15.24	26.67	35.71	100.00

(Continued)

(R01-R9R) : n-Way PROC FREQ of varbs V15*(CATSIZE NCATSIZE NVV12) for NV11 = SUBSIDENCE from data set SINK

The FREQ Procedure

Table of V15 by CATSIZE

V15(Formation : V15) CATSIZE

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	<= 2m	> 2m to <= 5m	> 5m to <= 15m	> 15m	Total
Rooihoogte	0 1 0.6714 0.00 0.00 0.00	0 0 0.4571 0.00 0.00 0.00	0 1 0.8 0.00 0.00 0.00	3 1 3.4714 1.43 100.00 4.00	3 1.43
Timeball Hill	4 2 1.9575 1.90 44.44 8.51	0 1 1.3714 0.00 0.00 0.00	3 2 0.15 1.43 33.33 5.36	2 3 0.4587 0.95 22.22 2.67	9 4.29
Vryheid	2 1 0.3216 0.95 33.33 4.26	0 1 0.9143 0.00 0.00 0.00	2 2 0.1 0.95 33.33 3.57	2 2 0.0095 0.95 33.33 2.67	6 2.86
Total	47 22.38	32 15.24	56 26.67	75 35.71	210 100.00

Frequency Missing = 334

The FREQ Procedure

Statistics for Table of V15 by CATSIZE

(Rows and Columns with Zero Totals Excluded)

Statistic	DF	Value	Prob
Chi-Square	27	41.0219	0.0410
Likelihood Ratio Chi-Square	27	46.1066	0.0124
Mantel-Haenszel Chi-Square	1	4.4229	0.0355
Phi Coefficient		0.4420	
Contingency Coefficient		0.4043	
Cramer's V		0.2552	

WARNING: 70% of the cells have expected counts less than 5. Chi-Square may not be a valid test.

Effective Sample Size = 210
Frequency Missing = 334

WARNING: 61% of the data are missing.

(R01-R9R) : n-Way PROC FREQ of varbs V15*(CATSIZE NCATSIZE NVV12) for NV11 = SUBSIDENCE from data set SINK

The FREQ Procedure

Table of V15 by NVV12

V15(Formation : V15) / NVV12 Frequency Expected Cell Chi-Square Percent Row Pct Col Pct	<= 1m	> 1m to <= 5m	> 5m to <= 15m	Total
Dwyka	1 2 0.6846 0.82 33.33 1.10	2 1 3.638 1.64 66.67 8.70	0 0 0.1967 0.00 0.00 0.00	3 2.46
Ecca	1 1 0.0866 0.82 100.00 1.10	0 0 0.1885 0.00 0.00 0.00	0 0 0.0656 0.00 0.00 0.00	1 0.82
Eccles	31 27 0.6406 25.41 86.11 34.07	3 7 2.113 2.46 8.33 13.04	2 2 0.0551 1.64 5.56 25.00	36 29.51
Karoo	4 4 0.0196 3.28 80.00 4.40	1 1 0.0035 0.82 20.00 4.35	0 0 0.3279 0.00 0.00 0.00	5 4.10
Total	91 74.59	23 18.85	8 6.56	122 100.00

(Continued)

(R01-R9R) : n-Way PROC FREQ of varbs V15*(CATSIZE NCATSIZE NVV12) for NV11 = SUBSIDENCE from data set SINK

The FREQ Procedure

Table of V15 by NVV12

V15(Formation : V15) NVV12

Frequency / Expected / Cell Chi-Square / Percent / Row Pct / Col Pct	<= 1m	> 1m to <= 5m	> 5m to <= 15m	Total
Lyttelton	8 11 0.9087 6.56 53.33 8.79	5 3 1.6684 4.10 33.33 21.74	2 1 1.0503 1.64 13.33 25.00	15 12.30
Malmani	0 0 . 0.00 . 0.00	0 0 . 0.00 . 0.00	0 0 . 0.00 . 0.00	0 0.00
Monte Christo	38 36 0.1348 31.15 79.17 41.76	8 9 0.1216 6.56 16.67 34.78	2 3 0.4184 1.64 4.17 25.00	48 39.34
Oaktree	1 2 0.6846 0.82 33.33 1.10	1 1 0.3337 0.82 33.33 4.35	1 0 3.2801 0.82 33.33 12.50	3 2.46
Total	91 74.59	23 18.85	8 6.56	122 100.00

(Continued)

The FREQ Procedure

Table of V15 by NVV12

V15(Formation : V15) / NVV12 Frequency Expected Cell Chi-Square Percent Row Pct Col Pct	<= 1m	> 1m to <= 5m	> 5m to <= 15m	Total
Rooihoogte	0 0 . 0.00 . 0.00	0 0 . 0.00 . 0.00	0 0 . 0.00 . 0.00	0 0.00
Timeball Hill	6 7 0.0758 4.92 66.67 6.59	2 2 0.0542 1.64 22.22 8.70	1 1 0.2846 0.82 11.11 12.50	9 7.38
Vryheid	1 1 0.1621 0.82 50.00 1.10	1 0 1.0292 0.82 50.00 4.35	0 0 0.1311 0.00 0.00 0.00	2 1.64
Total	91 74.59	23 18.85	8 6.56	122 100.00

Frequency Missing = 422

(R01-R9R) : n-Way PROC FREQ of varbs V15*(CATSIZE NCATSIZE NVV12) for NV11 = SUBSIDENCE from data set SINK

The FREQ Procedure

Statistics for Table of V15 by NVV12

(Rows and Columns with Zero Totals Excluded)

Statistic	DF	Value	Prob
Chi-Square	16	18.3573	0.3034
Likelihood Ratio Chi-Square	16	16.2567	0.4352
Mantel-Haenszel Chi-Square	1	1.0737	0.3001
Phi Coefficient		0.3879	
Contingency Coefficient		0.3616	
Cramer's V		0.2743	

WARNING: 78% of the cells have expected counts less than 5. Chi-Square may not be a valid test.

Effective Sample Size = 122
Frequency Missing = 422

WARNING: 78% of the data are missing.

(R01-R10) : PROC FREQ of varbs V19*NV11 from data set FV19NV11

Obs	V19	NV11	COUNT	DENSITY
1	Missing	Sinkhole	3	0.04167
2	Missing	Subsidence	1	0.01389
3	2028CC09	Sinkhole	1	0.01389
4	2527AD07	Sinkhole	1	0.01389
5	2527AD14	Sinkhole	1	0.01389
6	2528C04	Subsidence	1	0.01389
7	2528CC01	Sinkhole	1	0.01389
8	2528CC02	Sinkhole	20	0.27778
9	2528CC02	Subsidence	3	0.04167
10	2528CC02	Undefined	1	0.01389
11	2528CC03	Cracks	6	0.08333
12	2528CC03	Sinkhole	115	1.59722
13	2528CC03	Subsidence	51	0.70833
14	2528CC03	Undefined	14	0.19444
15	2528CC04	Cracks	3	0.04167
16	2528CC04	Sinkhole	113	1.56944
17	2528CC04	Subsidence	53	0.73611
18	2528CC04	Undefined	15	0.20833
19	2528CC05	Sinkhole	3	0.04167
20	2528CC05	Subsidence	1	0.01389
21	2528CC07	Sinkhole	10	0.13889
22	2528CC08	Cracks	2	0.02778
23	2528CC08	Sinkhole	79	1.09722
24	2528CC08	Subsidence	40	0.55556
25	2528CC08	Undefined	22	0.30556
26	2528CC09	Cracks	19	0.26389
27	2528CC09	Sinkhole	228	3.16667
28	2528CC09	Subsidence	100	1.38889
29	2528CC09	Undefined	32	0.44444
30	2528CC10	Cracks	13	0.18056
31	2528CC10	Sinkhole	196	2.72222
32	2528CC10	Subsidence	126	1.75000
33	2528CC10	Undefined	31	0.43056
34	2528CC13	Sinkhole	1	0.01389
35	2528CC14	Sinkhole	5	0.06944
36	2528CC14	Subsidence	3	0.04167
37	2528CC14	Undefined	2	0.02778
38	2528CC15	Cracks	3	0.04167
39	2528CC15	Sinkhole	39	0.54167
40	2528CC15	Subsidence	15	0.20833
41	2528CC15	Undefined	4	0.05556
42	2528CC20	Sinkhole	1	0.01389
43	2528CC20	Undefined	5	0.06944
44	2528CD12	Sinkhole	8	0.11111
45	2528CD21	Sinkhole	11	0.15278
46	2528CD21	Subsidence	1	0.01389
47	2528CD21	Undefined	3	0.04167
48	2528CD22	Sinkhole	3	0.04167
49	2528CD22	Subsidence	1	0.01389
50	2528CD23	Sinkhole	4	0.05556
51	2528CD24	Cracks	4	0.05556
52	2528CD24	Sinkhole	5	0.06944
53	2528CD24	Subsidence	5	0.06944
54	258CC03	Undefined	1	0.01389
55	2627AB22	Sinkhole	10	0.13889

(R01-R10) : PROC FREQ of varbs V19*NV11 from data set FV19NV11

Obs	V19	NV11	COUNT	DENSITY
56	2627AB23	Sinkhole	5	0.06944
57	2627AD04	Sinkhole	1	0.01389
58	2627AD05	Sinkhole	2	0.02778
59	2627AD07	Sinkhole	1	0.01389
60	2627AD08	Cracks	1	0.01389
61	2627AD08	Sinkhole	8	0.11111
62	2627AD08	Subsidence	1	0.01389
63	2627AD10	Cracks	5	0.06944
64	2627AD10	Sinkhole	47	0.65278
65	2627AD10	Subsidence	2	0.02778
66	2627AD11	Sinkhole	10	0.13889
67	2627AD11	Subsidence	1	0.01389
68	2627AD12	Cracks	2	0.02778
69	2627AD12	Sinkhole	81	1.12500
70	2627AD12	Subsidence	5	0.06944
71	2627AD13	Cracks	8	0.11111
72	2627AD13	Sinkhole	57	0.79167
73	2627AD13	Subsidence	1	0.01389
74	2627AD14	Cracks	12	0.16667
75	2627AD14	Sinkhole	154	2.13889
76	2627AD14	Subsidence	30	0.41667
77	2627AD14	Undefined	2	0.02778
78	2627AD15	Cracks	5	0.06944
79	2627AD15	Sinkhole	89	1.23611
80	2627AD15	Subsidence	9	0.12500
81	2627AD15	Undefined	1	0.01389
82	2627AD16	Sinkhole	3	0.04167
83	2627AD17	Cracks	8	0.11111
84	2627AD17	Sinkhole	48	0.66667
85	2627AD17	Subsidence	1	0.01389
86	2627AD18	Cracks	1	0.01389
87	2627AD18	Sinkhole	8	0.11111
88	2627AD19	Sinkhole	2	0.02778
89	2627AD19	Subsidence	1	0.01389
90	2627AD7	Cracks	7	0.09722
91	2627AD7	Sinkhole	42	0.58333
92	2627AD7	Subsidence	9	0.12500
93	2627AD7	Undefined	57	0.79167
94	2627AD8	Sinkhole	1	0.01389
95	2627AD9	Cracks	7	0.09722
96	2627AD9	Sinkhole	81	1.12500
97	2627AD9	Subsidence	1	0.01389
98	2627AD9	Undefined	1	0.01389
99	2627BA05	Sinkhole	2	0.02778
100	2627BA22	Cracks	9	0.12500
101	2627BA22	Sinkhole	134	1.86111
102	2627BA22	Subsidence	7	0.09722
103	2627BA23	Cracks	12	0.16667
104	2627BA23	Sinkhole	69	0.95833
105	2627BA23	Subsidence	9	0.12500
106	2627BA24	Sinkhole	4	0.05556
107	2627BA24	Subsidence	1	0.01389
108	2627BC06	Cracks	4	0.05556
109	2627BC06	Sinkhole	17	0.23611
110	2627BC06	Subsidence	1	0.01389

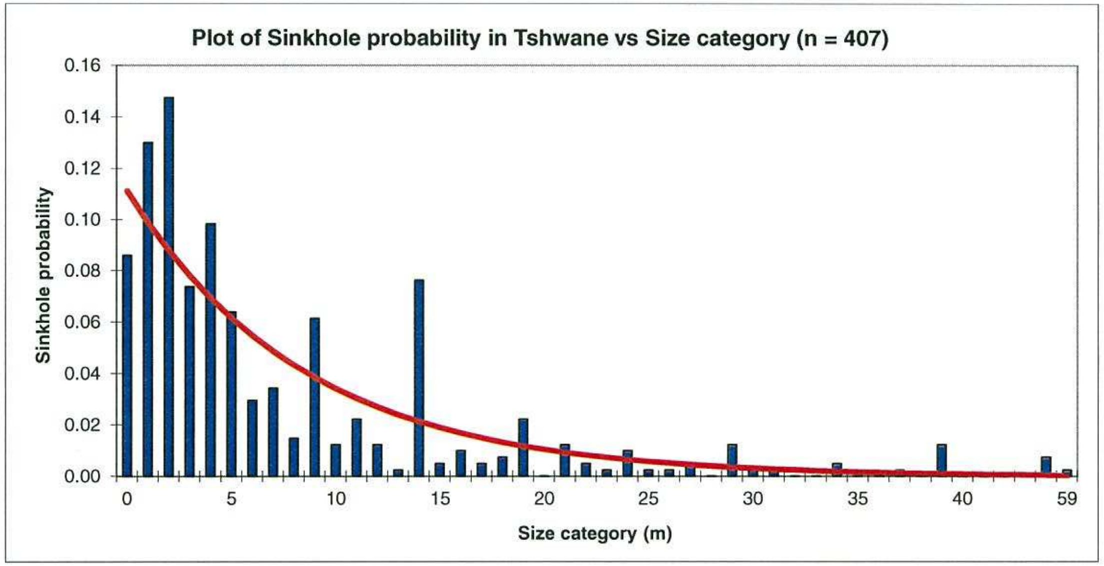
(R01-R10) : PROC FREQ of varbs V19*NV11 from data set FV19NV11

Obs	V19	NV11	COUNT	DENSITY
111	2627BC07	Sinkhole	5	0.06944
112	2627BC07	Subsidence	2	0.02778
113	2627BC08	Cracks	7	0.09722
114	2627BC08	Sinkhole	41	0.56944
115	2627BC08	Subsidence	9	0.12500
116	2627BC09	Cracks	5	0.06944
117	2627BC09	Sinkhole	10	0.13889
118	2627BC09	Subsidence	8	0.11111
119	2627BC10	Cracks	1	0.01389
120	2627BC10	Sinkhole	1	0.01389
121	2627BC10	Subsidence	1	0.01389
122	2627BC11	Cracks	2	0.02778
123	2627BC11	Sinkhole	18	0.25000
124	2627BC11	Subsidence	4	0.05556
125	2627BC12	Cracks	7	0.09722
126	2627BC12	Sinkhole	38	0.52778
127	2627BC12	Subsidence	1	0.01389
128	2627BC13	Cracks	2	0.02778
129	2627BC13	Sinkhole	14	0.19444
130	2627BC13	Undefined	1	0.01389
131	2627BC14	Sinkhole	1	0.01389
132	2627BC15	Cracks	1	0.01389
133	2627BC15	Sinkhole	7	0.09722
134	2627BC17	Subsidence	2	0.02778
135	2627BC6	Sinkhole	116	1.61111
136	2627BC6	Subsidence	2	0.02778
137	2627BC7	Sinkhole	34	0.47222
138	2627BC8	Sinkhole	29	0.40278
139	2627BC8	Subsidence	1	0.01389
140	2627BC9	Sinkhole	3	0.04167
141	2627BC9	Subsidence	1	0.01389
142	2627BD08	Sinkhole	10	0.13889
143	2627BD09	Sinkhole	6	0.08333
144	2628AA05	Undefined	8	0.11111
145	2628AA23	Sinkhole	1	0.01389
146	2628AB04	Sinkhole	1	0.01389
147	2628AB14	Sinkhole	4	0.05556
148	2628AB14	Undefined	1	0.01389
149	2628AB15	Subsidence	1	0.01389
150	2628AB4	Cracks	2	0.02778
151	2628AB4	Sinkhole	6	0.08333
152	2628AB4	Subsidence	5	0.06944
153	2628AC05	Subsidence	1	0.01389
154	2628AC069	Sinkhole	1	0.01389
155	2628AC08	Sinkhole	11	0.15278
156	2628AC08	Subsidence	11	0.15278
157	2628AC08	Undefined	4	0.05556
158	2628AC09	Sinkhole	10	0.13889
159	2628AC09	Subsidence	4	0.05556
160	2628AC09	Undefined	2	0.02778
161	2628AC10	Cracks	1	0.01389
162	2628AC10	Sinkhole	27	0.37500
163	2628AC10	Subsidence	5	0.06944
164	2628AC10	Undefined	4	0.05556
165	2628AC13	Sinkhole	2	0.02778

(R01-R10) : PROC FREQ of varbs V19*NV11 from data set FV19NV11

Obs	V19	NV11	COUNT	DENSITY
166	2628AC13	Subsidence	3	0.04167
167	2628AC14	Sinkhole	3	0.04167
168	2628AC15	Sinkhole	5	0.06944
169	2628AC15	Subsidence	2	0.02778
170	2628AC15	Undefined	3	0.04167
171	2628AC28	Sinkhole	2	0.02778
172	2628AC28	Subsidence	1	0.01389
173	2628AD03	Sinkhole	1	0.01389

Tshwane	001	8.5995	0	0.0859951	0.5	8.4867322	0.111089453
Tshwane	002	13.0221	1	0.1302211	1.5	8.4867322	0.098741446
Tshwane	003	14.742	2	0.1474201	2.5	8.4867322	0.087765966
Tshwane	004	7.371	3	0.0737101	3.5	8.4867322	0.078010451
Tshwane	005	9.828	4	0.0982801	4.5	8.4867322	0.069339299
Tshwane	006	6.3882	5	0.0638821	5.5	8.4867322	0.061631977
Tshwane	007	2.9484	6	0.0294841	6.5	8.4867322	0.054781353
Tshwane	008	3.4398	7	0.0343981	7.5	8.4867322	0.048692201
Tshwane	009	1.4742	8	0.0147421	8.5	8.4867322	0.043279881
Tshwane	010	6.1425	9	0.0614251	9.5	8.4867322	0.038469161
Tshwane	011	1.2285	10	0.0122851	10.5	8.4867322	0.03419317
Tshwane	012	2.2113	11	0.0221131	11.5	8.4867322	0.030392472
Tshwane	013	1.2285	12	0.0122851	12.5	8.4867322	0.027014235
Tshwane	014	0.2457	13	0.0024571	13.5	8.4867322	0.024011502
Tshwane	015	7.6167	14	0.0761671	14.5	8.4867322	0.021342534
Tshwane	016	0.4914	15	0.0049141	15.5	8.4867322	0.018970232
Tshwane	017	0.9828	16	0.0098281	16.5	8.4867322	0.01686162
Tshwane	018	0.4914	17	0.0049141	17.5	8.4867322	0.014987388
Tshwane	019	0.7371	18	0.0073711	18.5	8.4867322	0.013321484
Tshwane	020	2.2113	19	0.0221131	19.5	8.4867322	0.011840751
Tshwane	021	0	20	0.0000001	20.5	8.4867322	0.010524608
Tshwane	022	1.2285	21	0.0122851	21.5	8.4867322	0.009354758
Tshwane	023	0.4914	22	0.0049141	22.5	8.4867322	0.008314942
Tshwane	024	0.2457	23	0.0024571	23.5	8.4867322	0.007390705
Tshwane	025	0.9828	24	0.0098281	24.5	8.4867322	0.006569201
Tshwane	026	0.2457	25	0.0024571	25.5	8.4867322	0.00583901
Tshwane	027	0.2457	26	0.0024571	26.5	8.4867322	0.005189982
Tshwane	028	0.4914	27	0.0049141	27.5	8.4867322	0.004613096
Tshwane	029	0	28	0.0000001	28.5	8.4867322	0.004100333
Tshwane	030	1.2285	29	0.0122851	29.5	8.4867322	0.003644566
Tshwane	031	0.2457	30	0.0024571	30.5	8.4867322	0.003239459
Tshwane	032	0.2457	31	0.0024571	31.5	8.4867322	0.002879381
Tshwane	033	0	32	0.0000001	32.5	8.4867322	0.002559327
Tshwane	034	0	33	0.0000001	33.5	8.4867322	0.002274848
Tshwane	035	0.4914	34	0.0049141	34.5	8.4867322	0.00202199
Tshwane	036	0	35	0.0000001	35.5	8.4867322	0.001797239
Tshwane	037	0	36	0.0000001	36.5	8.4867322	0.001597469
Tshwane	038	0.2457	37	0.0024571	37.5	8.4867322	0.001419904
Tshwane	039	0	38	0.0000001	38.5	8.4867322	0.001262077
Tshwane	040	1.2285	39	0.0122851	39.5	8.4867322	0.001121792
Tshwane	041	0	40	0.0000001	40.5	8.4867322	0.000997101
Tshwane	042	0	41	0.0000001	41.5	8.4867322	0.000886269
Tshwane	043	0	42	0.0000001	42.5	8.4867322	0.000787757
Tshwane	044	0	43	0.0000001	43.5	8.4867322	0.000700195
Tshwane	045	0.7371	44	0.0073711	44.5	8.4867322	0.000622366
Tshwane	060	0.2457	59	0.0024571	59.5	8.4867322	0.000106279



WEST RAND (1960-2011)					
Non- dewatered					
Orthophoto	Occurrences	Area dolomite land (km^2)	events/km^2 dolomite land	Area dolomite land ha	events/ha dolomite land
2627AD11	11	27.66	0.4	2766	0.004
2627AD12	88	27.66	3.18	2766	0.032
2627AD17	57	25.19	2.26	2519	0.023
2627AD7	115	27.57	4.17	2757	0.042
Total (average)	271	108.08	(2.50)	10808	(0.025)
Dewatered					
2627AD10	54	27.67	1.95	2767	0.02
2627AD13	66	27.66	2.39	2766	0.024
2627AD14	198	27.12	7.3	2712	0.073
2627AD15	74	22.61	3.27	2261	0.033
2627AD8	11	27.67	0.4	2767	0.004
2627AD9	90	27.67	3.25	2767	0.033
2627BC11	24	21.66	1.11	2166	0.011
2627BC12	46	26.14	1.76	2614	0.018
2627BC13	17	10.81	1.57	1081	0.016
2627BC3	150	27.6	5.43	2760	0.054
2627BC4	90	27.68	3.25	2768	0.033
2627BC6	140	27.67	5.06	2767	0.051
2627BC7	41	27.61	1.48	2761	0.015
2627BC8	87	27.68	3.14	2768	0.031
2627BC9	27	27.67	0.98	2767	0.01
Total (average)	1115	384.92	(2.82)	38492	(0.028)

CITY OF TSHWANE (1960-2011)					
Non-dewatered					
orthophoto	Occurrences	Area dolomite land (km2)	events/km2 dolomite land	Area dolomite land ha	events/ha dolomite land
2528CC10	366	25.46	14.38	2546	0.144
2528CC14	10	27.76	0.36	2776	0.004
2528CC15	61	27.76	2.2	2776	0.022
2528CC02	24	14.03	1.71	1403	0.017
2528CC03	187	12.63	14.81	1263	0.148
2528CC04	185	11.85	15.61	1185	0.156
2528CC07	10	27.78	0.36	2778	0.004
2528CC08	143	27.78	5.15	2778	0.051
2528CC09	379	27.78	13.64	2778	0.136
Total (average)	1365	202.83	(7.58)	20283	(0.076)

EKURHULENI (1980-2011)					
Non- dewatered areas					
Orthophoto	Occurrences	Area dolomite land (km2)	events/km2 dolomite land	Area dolomite land (ha)	events/ha dolomite land
2528CD21	15	23.41	0.64	2341	0.006
2628AC10	37	27.66	1.34	2766	0.013
2628AC15	10	27.65	0.36	2765	0.004
2628AC08	26	17.35	1.5	1735	0.015
2628AC09	16	27.66	0.58	2766	0.006
Total (average)	104	123.73	(0.88)	12373	(0.009)
Dewatered areas					
2528CD24	15	9.18	1.63	918	0.016
2628AB04	13	27.66	0.47	2766	0.005
Total (average)	28	36.84	(1.05)	3684	(0.011)