THE KARST VADOSE ZONE: INFLUENCE ON RECHARGE, VULNERABILITY AND SURFACE STABILITY

Matthys A Dippenaar, Duan Swart, J Louis Van Rooy, Roger E Diamond

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THE KARST VADOSE ZONE: INFLUENCE ON RECHARGE, VULNERABILITY AND SURFACE STABILITY

Report to the
Water Research Commission

by

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SUMMARY

Project Background

The project emanated from a series of projects focused on the role of the vadose zone in the hydrological and geotechnical behaviour of materials, as well as those exacerbated by anthropogenic change. The karstic tertiary vadose zone remained after completion of the projections on the interstitial primary, and fractured secondary vadose zone, as well as a study on the contaminant transport through the vadose zone with the emphasis on cemeteries and burial sites.

Case Studies and Experimental Work

Experimental and field studies incorporated into this project form part of the vadose zone research projects and are listed chronologically as Vadose Zone Study Areas (VZSAs). Those pertaining to this project include:

- VZSA09: Hydrological and Geochemical Assessment of a Dolomite Mine
- VZSA10: Dolomite Bedrock
- VZSA11: Residual Dolomite and Wad
- VZSA12: Facilitated Karst Dialogues.

Novel Findings

The project rationale and main findings are summarised (based on the contents of this report) in Box 1.

Box 1. **Project Summary.**

BOX 1. Project Summary

(a) Project Background

The project emanated from a series of projects related to vadose zone hydrology applied to engineering geology and hydrogeology.

Karst systems are intrinsically complex. Surface instability in the form of sinkholes and subsidences affects infrastructure, and groundwater is vulnerable in areas where karst features promote quicker and more direct connection to the land surface. Both these processes – resulting in the downward erosion of overburden and/ or the rate of flow between land surface and the phreatic surface – are directly related to the properties of the karst vadose zone.

Very little research is available on the properties and behaviour of the karst vadose zone, especially for older and more dolomitic karst such as those in South Africa. The project aimed to:

- Contribute to a cross-disciplinary nomenclature and terminology to allow for better communication between geological, engineering and hydrological specialists
- Improve cross-disciplinary interaction between dolomite professionals with notable focus on improved understanding of the risks of dolomite land and water use, further exacerbated by anthropogenic impacts.
- Inform policy on optimal investigation for safe development of dolomite land and water resources with notable emphasis on the ingress scenario surface instability events and groundwater vulnerability.

The project followed on the preceding vadose zone projects, implying that fundamental research questions were posed and form part of the rationale of this project.

Case studies were selected, based on (i) literature, (ii) project team knowledge, (iii) outcomes of two dolomite dialogues (one closed dialogue and one open congress), (iv) issues identified during conducting of experimental work, and (v) accessibility of study sites.

Given the heterogeneity and anisotropy of dolomite terrain, the project team opted to investigate very specific aspects of the karstic vadose zone. It was, for instance, decided to (i) focus on Proterozoic dolomite rather than younger rocks or limestones; (b) emphasise the shallow vadose zone impacted by karst geomorphology and the soil-rock interface rather than the deep fractured bedrock and cavity systems; (iii) water ingress and unsaturated flow through residual dolomite into dolomite bedrock; and (iv) hydrostratigraphical models based on isotopes, hydraulic tests, laboratory tests and geochemistry rather than single tracer tests.

Projects included a series of field and laboratory tests focused around fundamental geochemical, hydraulic, mechanical and geotechnical properties of dolomite bedrock from different localities and formations, as well as the residual dolomite soils occurring throughout portions of the outcrop area.

(a) Project Outline and Findings

Questions remaining include, for instance:

- Do we have epikarst with high storage and transmissivity, or do we have low residuum with high storage and low transmissivity?
- Exactly how direct is recharge, and what happens in the intermediate vadose zone with this percolating water?
- Do our simplified box models present every absolute worst-case outcome on a highly zoomed-in scale?
- Do we protect construction works by the no-use approach to groundwater, or could restricted use possibly promote better monitoring and knowledge about the influence of the water in karst terrains?

There are however many external factors that influence sinkhole development such as overburden mechanics and concentrated water ingress due to anthropogenic activities. The age and time of exposure to natural weathering processes may also have resulted in cavity development in all formations, irrespective of their chemistry.

Present-day dissolution rates do not directly dictate the likelihood of sinkholes forming. Present day karst is a product of past dissolution occurring over long periods of time. The likelihood exists that ground movement has already occurred in many instances where no chert is present, and that chert-rich formations have survived failure longer due to the resistance of the chert. This may to some extent explain why sinkhole occurrence at the present moment in time is more prevalent in chert-rich horizons.

Hydraulic parameters were calculated and confirmed to be roughly in the order of 10^{-5} m/s for infiltration, 10^{-4} m/s for deeper percolation in soils, and 10^{-7} m/s for saturated hydraulic conductivities of residual dolomite soils.

Hydraulic behaviour of the karst vadose zone may very likely be governed almost exclusively by the high storage of fractured dolomite (epikarst) and residual dolomite (wad). These have differing hydraulic conductivities, and will also be influenced by the presence of karren features such as grykes. Dolomite systems in South Africa can, therefore, not at all be considered uniform in the vadose zone; even more so than for most other soil-rock systems.

The project informed regarding the properties dictating the hydraulic behaviour of the possible strata making up the hydrostratigraphical model of Southern African dolomite karst systems. This in itself is highly beneficial to engineering geologists, civil engineers, hydrogeologists, and like professionals,

It is recommended to progress yet further with this work into full-scale field studies and to assess the influence of improved parameters for different strata (or hydrostratigraphic units) in models.

READ MORE:
ADAPTED FROM: Dippenaar et al. 2014; Dippenaar et al. 2019; this document

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SECTION A: INTRODUCTION

Matthys A DIPPENAAR

1. ABOUT THE PROJECT

The project emanated from a series of Water Research Commission funded projects related to vadose zone hydrology applied to engineering geology and hydrogeology:

- WRC K8/876 Preliminary Vadose Zone Classification Methodology (2009-2010) report K8/876
- WRC K5/2052 Vadose Zone Hydrology (2011-2014) report TT 583/13
- WRC K5/2326 Fractured Intermediate Vadose Zone (2014-2016) report in print
- WRC K5/2449 State-of-the-Art Cemetery Guidelines (2015-2018) report in print
- WRC K5/2523 Karst Vadose Zone (2016-2019) this report
- WRC K5/2826 Complex and Anthropogenically Altered Vadose Zone (2018-2021) future report.

The research outputs, mostly in the form of rated journal and conference contributions, are summarised in Figure 1-1. The work forming part of this publication fall within the *conceptual models*, *applications/ implications*, and *interdisciplinary paradigms* sections with (9), (11) and (14) focusing on the properties of wad and karst systems in general.

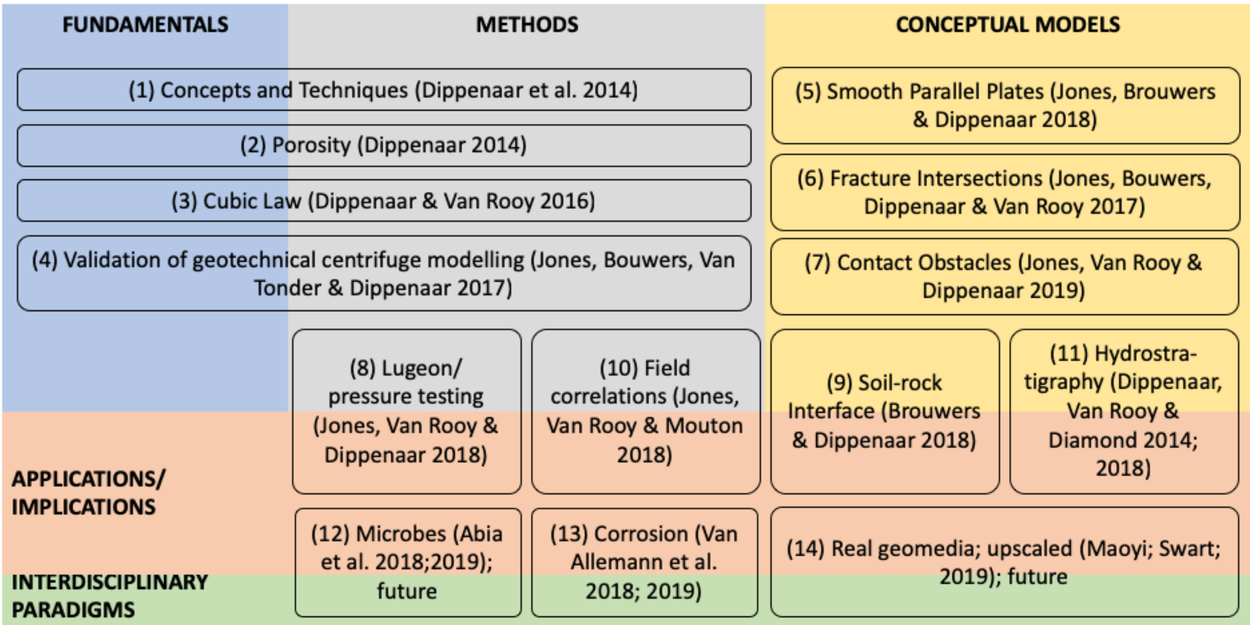

Figure 1-1. **Summarised research outputs contributing to the development of the present research rationale on complexity and anthropogenic influences on the vadose zone.**

1.1. Project Rationale

The development and motivation of this project is taken from Dippenaar et al. (2019).

Large portions of the continental surface area of the Earth are underlain by carbonate rock, with roughly 20-25% of the global population dependent on water supply from these rocks (Ford and Williams 2007). These carbonate rocks include, but are not limited to, limestone (CaCO3) and dolomite ($CaMg(CO3)_2$). In South Africa, large portions of Gauteng – a province housing approximately a third of South Africa's population, generating the bulk of South Africa's gross domestic product, and including the largest city Johannesburg and the capital city Pretoria (City of Tshwane Municipality) – are underlain by dolomites of the Malmani Subgroup (Chuniespoort Group, Transvaal Supergroup). Pretoria itself was supplied exclusively from dolomitic springs for its first 75 years and its water supply is still supplemented with spring water from the Malmani Subgroup to this day (Dippenaar 2013). The lithostratigraphy of the Malmani Subgroup is well documented and, in the more arid northwestern parts of South Africa, is correlated to the Ghaap Group of the Griqualand-West Supergroup (e.g. Brink 1979; CGS and SAIEG 2003; Eriksson et al. 2009).

The increased urbanisation of Gauteng results in denser, higher, and deeper underground developments, exacerbating the risks posed by dolomite bedrock in terms of groundwater quality and surface instability. Given the highly heterogeneous and anisotropic distribution of earth materials in dolomitic karst areas of Gauteng (and many other places of the world), groundwater recharge estimation, addressing aquifer susceptibility to contamination, and risks posed due to surface instability (subsidences, dolines and sinkholes) resulting from regional groundwater lowering and water ingress become increasingly complex.

South Africa's dolomites are well described (e.g. Altermann and Wotherspoon 1995; CGS and SAIEG 2003, Eriksson et al. 1995; Martini and Kavalieris 1976; Martini et al. 1995), and are somewhat exceptional given its exposure to significant geomorphological processes (mechanical weathering in the Ghaap Group and profound chemical dissolution in the Chuniespoort Group) due to:

- Its significant age of almost 3 billion years
- Three periods of karstification post deposition prior to present karst development cycle
- Its long exposure to weathering and erosion following significant geotectonic events such as the intrusion of the Bushveld Igneous Complex, break-up of Gondwana, various continental uplifts and the current neotectonic effects of the East African Rifting

The distinctly different past and present-day climates at the different localities of exposure in the northern and eastern parts of South Africa.

In terms of land use planning, apart from water quality issues and the dependence of urban areas on groundwater for supply, sinkholes and subsidences are occurring due to dewatering or water ingress. The close proximity of the Witwatersrand goldfields adds additional strain on the dolomite hydrogeology through acid mine drainage decant into the carbonate aquifers. An advanced understanding of these karst systems therefore becomes necessary despite the current lack of a unified and cross-disciplinary approach to site characterisation.

Karst systems are intrinsically complex. Surface instability in the form of sinkholes and subsidences affects infrastructure, and groundwater is vulnerable in areas where karst features promote quicker and more direct connection to the land surface. Both these processes – resulting in the downward erosion of overburden and/ or the rate of flow between land surface and the phreatic surface – are directly related to the properties of the karst vadose zone.

Very little research is available on the properties and behaviour of the karst vadose zone, especially for older and more dolomitic karst such as those in South Africa.

1.2. Aims and Objectives

The project aimed to:

- Contribute to a cross-disciplinary nomenclature and terminology to allow for better communication between geological, engineering and hydrological specialists
- Improve cross-disciplinary interaction between dolomite professionals with notable focus on improved understanding of the risks of dolomite land and water use, further exacerbated by anthropogenic impacts.
- Inform policy on optimal investigation for safe development of dolomite land and water resources with notable emphasis on the ingress scenario surface instability events and groundwater vulnerability.

1.3. Research Approach

The project followed on the preceding vadose zone projects, implying that fundamental research questions were posed and form part of the rationale of this project.

Case studies were selected, based on (i) literature, (ii) project team knowledge, (iii) outcomes of two dolomite dialogues (one closed dialogue and one open congress), (iv) issues identified during conducting of experimental work, and (v) accessibility of study sites.

Given the heterogeneity and anisotropy of dolomite terrain, the project team opted to investigate very specific aspects of the karstic vadose zone. It was, for instance, decided to (i) focus on Proterozoic dolomite rather than younger rocks or limestones; (b) emphasise the shallow vadose zone impacted by karst geomorphology and the soil-rock interface rather than the deep fractured bedrock and cavity systems; (iii) water ingress and unsaturated flow through residual dolomite into dolomite bedrock; and (iv) hydrostratigraphical models based on isotopes, hydraulic tests, laboratory tests and geochemistry rather than single tracer tests.

Case studies, listed as Vadose Zone Study Areas (VZSAs) to link to preceding vadose zone projects, are therefore variable and do not necessarily imply a given site with given methods, but rather the scientific solution of an important research question.

SECTION B: KARST AND KARSTIFICATION

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2. KARST

Karst and dolomite are described in Box 2. In South Africa this mostly pertains to Proterozoic dolomites, although much younger and chemically different lithologies such as limestone exist in South Africa and elsewhere in the world. Given the complexity in karst systems, the focus henceforth will be on the Proterozoic dolomitic karst terrains in South Africa, with specific emphasis on the Campbell Rand and Malmani Subgroups of the Ghaap and Chuniespoort Groups of the Griqualand-West and Transvaal Supergroups.

2.1. South African Dolomites and Karst

South African Proterozoic dolomites are discussed extensively in Dippenaar et al. (2019), an include Late Archaean to early Proterozoic rocks of the Transvaal and Griqualand-West Supergroups distributed between three basins on the Kaapvaal Craton: (i) the Transvaal and (ii) Griqualand-West Basins (the latter subdivided into the Ghaap Plateau and Prieska Sub-basins) in South Africa, and (iii) the Kanye Basin in Botswana. The chemical sedimentary parts of the South African Transvaal and Griqualand-West Supergroups are the Chuniespoort (north-eastern portions of South Africa) and Ghaap (north-western portions of South Africa) Groups respectively (e.g. Altermann and Wotherspoon 1995, Eriksson et al. 2009.) as shown in Box 3.

Younger iron-formations of the Asbestos Hill Subgroup overlie the dolomite and limestone of the Schmidtsdrif and Campbell Rand Subgroups (Ghaap Supergroup), whereas the iron-formations of the Penge Formation overlie the chemical sediments of the Malmani Subgroup (Transvaal Supergroup). All these associated chemical sedimentary rocks formed through chemical and organic (algal) precipitation of calcium and magnesium carbonates from inland basins, resulting in remnant stromatolitic structures. Initial deposition is believed to be limestone, with dolomite (through dolomitization) and chert representing secondary replacement of the limestone (Brink 1979)

The formations of the Malmani Subgroup is subdivided based on the presence or absence of stromatolites and chert. The Eccles and Monte Christo Formations have interlayered chert, and the Lyttleton and Oaktree Formations are poorer in chert with more stromatolites (e.g. Eriksson et al. 2009).

Karst is well developed in the Malmani Subgroup and Campbell Group. Surface morphology is not typical of karst due to the high concentration of insoluble impurities in the rock coupled with the semi-arid climate (especially for the Ghaap Group in the more arid western parts of the country). Residuum is mostly chert fragments in a matric of manganiferous and ferruginous oxides following dissolution of dolomite with highly variable thickness (Martini 2009).

Dolomite rocks with a silica content of 1.34-4 wt-% and MgO content of 20.13-20.78 wt-% belong to the Lyttelton Formation and those characterised by a silica content of about 11.6 wt-% and 18.48 wt-% MgO belong to the Eccles Formation. The Monte Christo Formation is characterised by a silica content of 30.7 wt-% with a standard deviation 6.3 and 13.95 wt% MgO with a standard deviation of 1.02 (Page and Du Plessis 1986).

Examples from Southern African and Croatian karst are shown in Box 4 and Box 5.

Box 2. Karst and Dolomite

BOX 2. Karst and Dolomite

(a) Karst

The term ***karst*** refers broadly to a series of distinctive landforms and underground drainage systems forming from the chemical decomposition, dissolution or solutional erosion of soluble rock such as carbonates and evaporites.

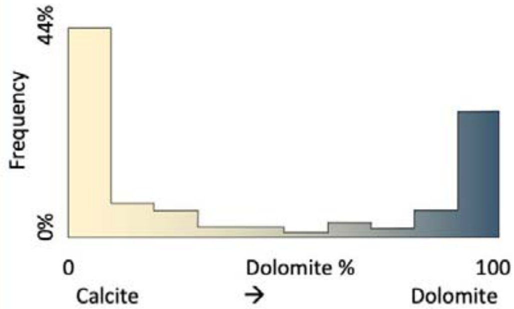
Karst is typically characterised by ***karren***, which is is defined as "channels or furrows, caused by solution on massive bare limestone surfaces", which can "vary in depth from a few millimetres to more than a metre", which is separated by ridges, and in which the "topography is chiefly formed by the dissolving of rock". Karst, and notably dolomite, is well described in South African context by Dippenaar et al. (2019).

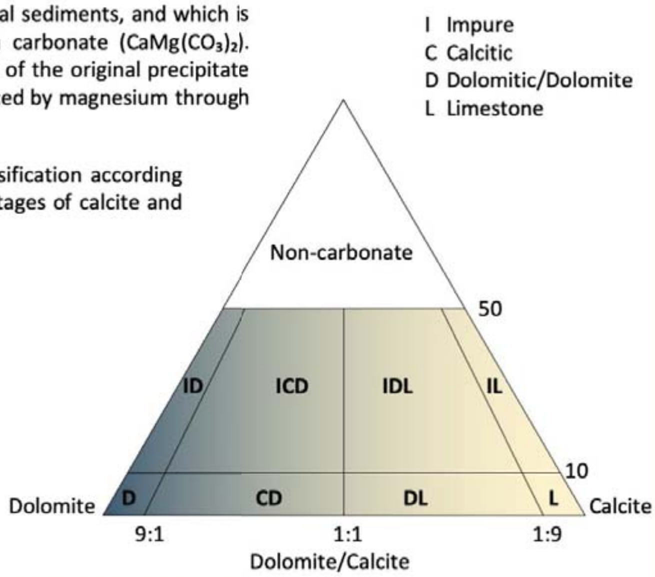
Karstification is the process of dolomite dissolution. Once karstification has occurred, the dissolution causes variably sized cave systems, crevices and voids which are highly permeable areas and have a high water storage capacity

(b) Carbonates

Dolomite is a rock formed from chemical or biochemical sediments, and which is mainly composed of the mineral calcium magnesium carbonate ($CaMg(CO_3)_2$). Dolomite is the product of the secondary replacement of the original precipitate limestone ($CaCO_3$), where some of the calcium is replaced by magnesium through the process of dolomitization.

Dolomite classification: (below) general carbonate classification according to mineralogy of component; (right) computed percentages of calcite and dolomite for 1148 of North American carbonate.





(c) Dolomite

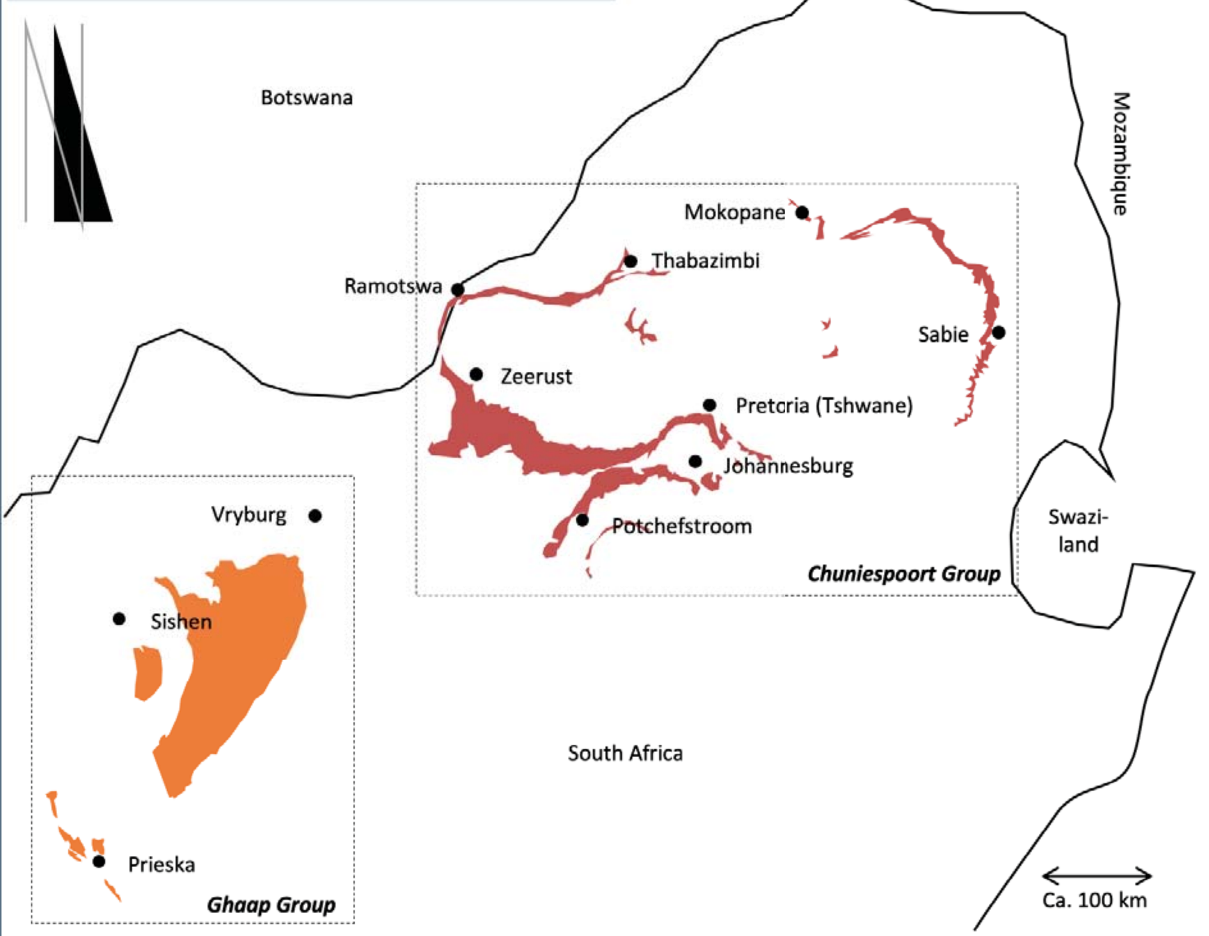
Characteristic weathering surfaces on dolomite from the Zeerust-Dinokana (North-West Province) area. Note the typical blue-grey to red-grey colours, affected by magnesium content and degree of weathering.

READ MORE: ADAPTED FROM: (a) Dippenaar et al. 2019; Buttrick et al. 1993; Ford & Williams 2007; Keary 2001; Lapidus 1990; (b) Warren 2000; (c) photos © Matthys Dippenaar 2018

Box 3. **South African Dolomite Lithostratigraphy.**

BOX 3. South African Dolomite Lithostratigraphy

(a) Distribution of the Chuniespoort and Ghaap Groups



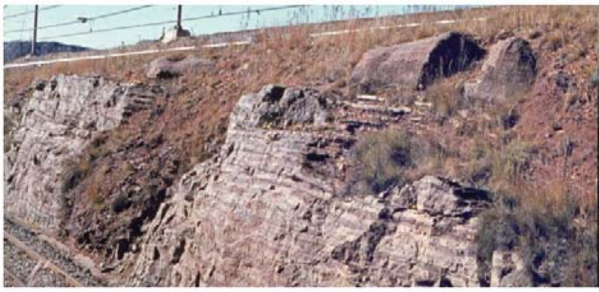
(b) Lithostratigraphy of the Chuniespoort and Ghaap Groups

<table>
<tr><th colspan="4">Griqualand-West Basin</th><th colspan="4">Transvaal Basin</th></tr>
<tr><td rowspan="4">Griqualand-West Supergroup</td><td colspan="3">Postmasburg Group</td><td rowspan="4">Transvaal Supergroup</td><td colspan="3">Pretoria Group</td></tr>
<tr><td rowspan="3">Ghaap Group</td><td colspan="2">Koegas and Asbestos Hills Subgroups</td><td rowspan="3">Chuniespoort Group</td><td colspan="2">Duitschland Formation (carbonate & clastic)
Penge Formation (iron-formation)</td></tr>
<tr><td>Campbell Rand Subgroup</td><td>Various formations (dolomite)</td><td rowspan="2">Malmani Subgroup</td><td rowspan="2">Frisco
Eccles
Lyttleton
Monte Christo &
Oaktree Formations
(dolomite)</td></tr>
<tr><td>Schmidtsdrif Subgroup</td><td>Clearwater & Boomplaas Formations (dolomite)</td></tr>
<tr><td></td><td colspan="3">Vryburg Formation</td><td></td><td colspan="3">Black Reef Formation</td></tr>
</table>

READ MORE:
ADAPTED FROM: Dippenaar et al. 2019; adapted from Eriksson et al. 2009

Box 4. South African Karst: Ground Conditions

BOX 4. South African Karst: Ground Conditions



(a) Pinnacled dolomite in the West Rand (© A van Schalwyk, date unknown).

(b) Pinnacled dolomite in the West Rand (© A van Schalwyk, date unknown).

(c) Pinnacled dolomite in Pretoria (City of Tshwane, © MA Dippenaar 2017).

(d) Mafic intrusive dyke in dolomite (City of Tshwane, © MA Dippenaar 2017).

(e) Removal of pinnacles for foundations (City of Tshwane, © JL van Rooy 2004).

(f) Pier foundation of rail system (City of Tshwane, © MA Dippenaar 2010).

(g) Dolomite and calcrete in the Ghaap Group (Taung, North-West Province, © MA Dippenaar 2008).

(h) Ghaap Group dolomite (near Taung, North-West Province, © MA Dippenaar 2008).

READ MORE:
ADAPTED FROM: Dippenaar et al. 2019

Box 5. Younger Karst from Namibia, Botswana and Croatia

BOX 5. Younger Karst from Namibia, Botswana and Croatia

(a) Etosha (Namibia, © JL van Rooy 2010).

(b) Aha Hills (Botswana, © Matthys Dippenaar 2018).

(c) Gcwihaba Caves: entrance into caves, and roof showing calcite precipitation in vertical joint in cave roof (Botswana 2018).

(d) Karst at Plitvice (Croatia 2017).

(e) Karst in Dubrovnik (Croatia 2017).

READ MORE:
ADAPTED FROM: a: photographs © Louis van Rooy; b-e: photographs © Matthys Dippenaar

2.2. Karst Hydrology and Karstification

Karst is a term used to describe a particular type of landscape which includes caves and far-reaching underground water systems which developed in soluble rocks such as dolomite. Karst topography does not only apply to carbonate rocks, but can be found in quartzites, granite and basalt despite their low solubility (Ford and Williams 2007). The process of karst formation (karstification) is controlled by a number of factors such as quantity and pH of precipitation, p_{CO2}, hydraulic gradient, climate as well as the occurrence of discontinuities.

During karst formation the rock is dissolved in acid, and after billions of years results in a culmination of fully weathered and partially weathered material. The karst topography is generally characterized by bedrock pinnacles and troughs with a blanketing layer of chert gravels and wad or residual dolomite (Avutia 2014).

There were three periods of karstification since the break-up of Gondwanaland, prior to the present cycle. All of the karstification periods coincide with times when weathering was prominent, and deposition was suspended (Martini and Kavalieris 1976). The three periods are the pre-Pretoria Group (1.95Ga), the pre-Waterberg (1.7Ga) and the pre-Karoo with the fourth period ongoing at present.

The phreatic zone in soluble rock environments is thoroughly addressed in international literature. Bakalowicz (2005), for instance, notes in detail that flow in phreatic systems depends on the type of porosity and the type of recharge. Bakalowicz additionally emphasises the hydraulic gradient and direction thereof. In terms of porosity, the author also distinctly notes that aquifers can be fractured and non-karstic or truly karstic with the whole array of intermediary karst development. In non-karstic terrain, recharge is a function almost solely of concentrated infiltration through swallow holes (or palaeo-sinkholes), whereas karstic terrains result in delayed infiltration and associated vadose zone water storage due to the likely presence of an epikarst zone which allows for water movement from the regolith into the fractured soluble rock. The need to first identify whether the landscape is truly karstic rather than fractured is therefore highlighted (Dippenaar et al. 2019).

Further to this, Dubois et al. (2014) extensively detail the chemical decomposition and hydrodynamical erosion processes involved in karstification by total removal and ghost-rock karstification. Ghost-rock features result from the latter and include large weathered features, weathered corridors, ghost-endokarst and weathered galleries.

As elaborated in Dippenaar et al. (2019), the vadose zone (in South Africa) lacks the common fluted pits and key-hole passages of classic karsts, with channels mostly having formed above the water table due to slumping of residual cover into deeper fissures, keeping these fissures filled. Networks of passages in karst itself cross-cuts stratigraphy, suggesting a control by former water tables (Martini 2009). Monroe (1970) defines a flute as synonymous to a scallop, being an "oval hollow having an asymmetrical cross section along its main axis [sic.]" … and "forming patterns on the walls of caves and in streambeds", whereas a key-hole is a "… small passage or opening in a cave…" that is "rounded at the top, constricted in the middle, and rectangular or flared out below [sic.]" in cross-section. Karst morphology in South Africa has been classified as mature, plateau, escarpment or bushveld types by Martini and Kavalieris (1976).

Porosities of some South African dolomites were presented by Castany (1984 in Ford and Williams 2007) to vary from 9% at 60m depth to 5.5% at 75m, 2.6% at 100m, 2% at 125m and 1.3% at 150m. This, however, relates only to interstitial porosity, and subsequently secondary and tertiary porosity may contribute to significantly higher values.

Examples of South African karst springs are shown in Box 6, and some standard published properties of the karst aquifers throughout South Africa are shown in Table 2-1.

Box 6. South African Karst: Springs

BOX 6. South African Karst: Springs

(a) Dinokana Eye, partially supplying water to the greater Dinokana (North-West Province; January 2018)

(b) View of the collection chamber and pumphouse, as well as view inside the collection chamber of Lower Fountain spring partially supplying Pretoria (2017).

(c) View of the collection chamber, as well as view inside the collection chamber of Grootfontein spring partially supplying Pretoria (2017).

(d) Marico Eye (near Groot Marico, North-West Province, 2017).

(e) Maloney's Eye (Gauteng; date unknown)

READ MORE:
ADAPTED FROM: a-d: photographs © Matthys Dippenaar; e: photographs © Martin Holland

Table 2-1. General hydrogeological properties (adapted from DWAF 2006a;b).

	Storage	Transmissivity	Best groundwater potential	Recharge
Far East to Far West Rand (Gauteng)	Variable by orders of magnitude	Variable by orders of magnitude	Chert-rich dolomites (Monte Christo and Eccles Formations)	10-15% of MAP (occasionally 20-50%)
North-West Province	Variable by orders of magnitude	Variable by orders of magnitude	Chert-rich dolomites (Monte Christo and Eccles Formations)	Ca. 10% of MAP
Ghaap Plateau	No information	No information	No information	2.6-10% of MAP (ca. 6%)

The karst aquifers of Gauteng were formed after the erosion of the Ventersdorp Group, which produced the depression known as the Transvaal Basin. The Transvaal Basin became a depository environment known as an epeiric sea, which was the basin or depression in which the dolomites accumulated (Brink 1979). This environment had meteoric and marine water mixed and the saline water became supersaturated in silica and magnesium, and undersaturated in calcite, therefore increasing the dolomitisation and certification processes (Kleinhans 2017).

2.3. Hazards and Risks posed by Dolomite/ Karst

Geotechnical risks pertaining to karst or dolomite land are explained in Box 7. Recent advances in engineering geological research on karst, including the characterisation, stability and subsidence issues, and remedial measures (e.g. Buttrick et al. 1993; Buttrick et al. 2011; Constantinou and Oosthuizen 2014; Constantinou and Van Rooy 2019; Kleinhans and Van Rooy 2016; Momubaghan 2012; Oosthuizen 2013; Oosthuizen and Van Rooy 2015; Richardson 2013; Trollip 2006; Trollip et al. 2008).

The formation and maximum size of sinkholes that can occur depend on (Buttrick et al. 2001):

- The thickness of the blanket layer
- The size or width of the throat (gryke or fissure)
- The estimated 'angle of draw' in the various soil horizons.

The vadose zone is the pathway of water ingress, with the ingress scenario (as opposed to the dewatering scenario) accounting for the majority of sinkholes and subsidence in the urbanised karst areas of South Africa (Constantinou and Van Rooy 2018).

Some recent sinkholes in dolomite terrains associated with the Malmani Subgroup are shown in Box 8 and Box 9.

Box 7. Geotechnical Risks related to Dolomite

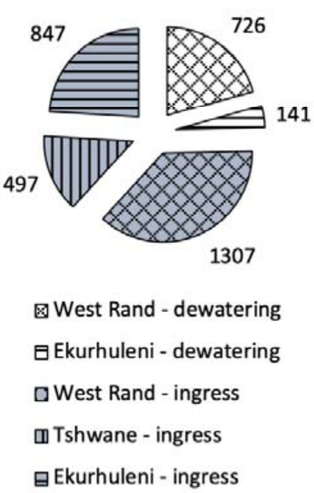
BOX 7. Geotechnical Risks related to Dolomite

(a) Terminology

The South African Bureau of Standards supplies standard definitions related to hazards and risks posed on dolomite land:

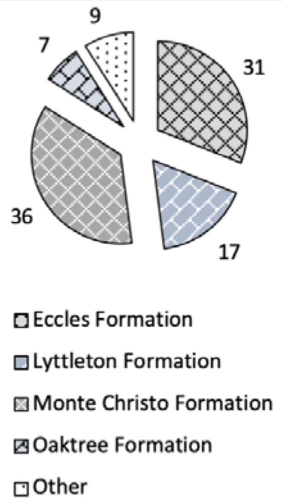
- ***Dolomite land***: "land underlain by dolomite or limestone rock directly or at a shallow depth typically less than
  - (a) 60 m in areas underlain by limestone;
  - (b) 60 m in areas underlain by dolomite where no de-watering has taken place and the local authority has jurisdiction, is monitoring and has control over the groundwater levels over the areas under consideration; or
  - (c) 100 m in areas underlain by dolomite where de-watering has taken place or where the local authority has no jurisdiction or control over groundwater levels" (SANS 1936-1:2012).
- ***Subsidence***: "shallow, enclosed depression" (SANS 1936-1:2012); ***doline*** was historically used to refer to subsidence.
- ***Sinkhole***: "feature that occurs suddenly and manifests itself as a hole in the ground" (SANS 1936-1:2012).
- ***Hazard***: "a source of potential harm" (SANS 1936-1:2012).
- ***Risk***: "effect of uncertainty on objectives" (SANS 1936-1:2012).

(b) Major Controls on the Occurrence of Sinkholes in Gauteng



In South Africa, sinkholes and subsidences do occur, and is mostly ascribed to concentrated ingress of water eroding material into subsurface cavities, or regional groundwater lowering or dewatering resulting in loss of roof support of the cavity.

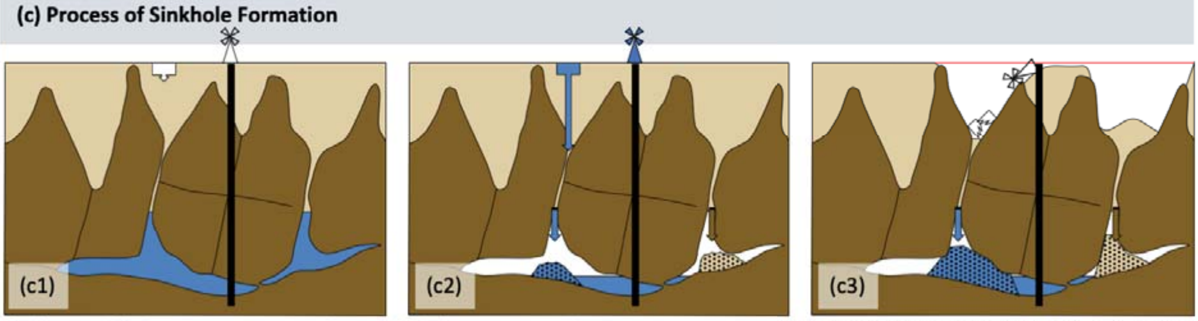
By far the majority of the recorded sinkholes formed due to water ingress in the West Rand, East Rand and City of Tshwane, and approximately 98% have been caused by anthropogenic impacts such as concentrated ingress related to leaking pipelines. Little has yet been done on the exact mechanism of the ingress scenario through which precipitation or leaking pipelines erode overburden downward into deeper cavities (termed receptacles) that accounted for 2651 of the total 3312 sinkholes in Gauteng recorded so far. The presence of chert furthermore also has a direct influence on the probability of sinkhole formation.



ABOVE LEFT: Sinkhole event densities for dewatered (shaded white) and non-dewatered/ ingress (shaded blue) areas in Gauteng; plot indicates number of recorded events.

ABOVE RIGHT: Sinkhole event occurrences by geological formations (grey-shaded – chert-rich; blue-shaded – chert-poor); plot indicates percentage of total recorded events.

(c) Process of Sinkhole Formation



(c1) waterfilled cavities support the roof; (c2) as cavities desaturate, a receptacle develops into which material can erode either by ingress (left; blue) or roof collapse due to groundwater lowering (right; brown); (c3) sinkholes develop on surface.

READ MORE: ADAPTED FROM: Dippenaar et al. 2019, adapted from (a) SABS 2012 (SANS 634; SANS 1936; (b) Constantinou and Oosthuizen 2014

Box 8. South African Karst: Sinkholes

BOX 8. South African Karst: Sinkholes

(a) Damage to house due to sinkhole (left) and to adjacent property (right) in City of Tshwane in 2012

(b) 20 m diameter sinkhole in Bapsfontein (City of Ekurhuleni, 18 July 2007), including close-up on surface cracks indicating further development towards maximum size

(c) Sinkhole in Bapsfontein, further developed over a period of ten years (City of Ekurhuleni, © JL van Rooy 2017).

READ MORE: ADAPTED FROM: a: photographs © Matthys Dippenaar; b: photographs © Ilsé Kleinhans; d: photographs © Louis van Rooy

Box 9. South African Karst: Sinkholes

BOX 9. South African Karst: Sinkholes

(a) Sinkhole in Khutsong, 10 m diameter (24 January 2018).

(b) Khutsong, 10 m increased to 30 m diameter sinkhole, affected two other houses (30 May 2017).

(c) Sinkhole in Khutsong; shallow dolomite with dissolution features, interlayered with chert (3 May 2018).

(d) Highly weathered karst profile > 20m deep, south of Carletonville; interlayered dolomite and chert (29 May 2015).

(e) Dolomite sinkhole in a cemetery in Irene, City of Tshwane (2010).

READ MORE:
ADAPTED FROM: a-d: photographs © Ilsé Kleinhans; e: photographs © Matthys Dippenaar

2.4. Trends in Karst Research in South Africa

The influences of development in karst regions are well understood (e.g. Gutiérrez et al. 2014). In South Africa, some of the earliest work was by Buttrick et al. (1993), clearly stating that subsidences (including sinkholes) and potential for groundwater contamination are some of the major concerns in dolomitic areas.

Karst research in South Africa is mostly centred around issues of:

- Engineering Geology, including the characterisation, stability and subsidence issues, and remedial measures (e.g. Buttrick et al. 2001; Constantinou and Oosthuizen 2014; Kleinhans and Van Rooy 2016; Momubaghan 2012; Richardson 2013; Oosthuizen 2013; Oosthuizen and Van Rooy 2015; Buttrick et al. 2011 Trollip 2006; Trollip et al. 2008;),
- Hydrogeology, including concepts of aquifer vulnerability, recharge and water supply (e.g. Bredenkamp et al. 2007; Bredenkamp 2007; Holland 2007; Holland and Witthüser 2009; Leyland et al. 2006; Leibundgut 1997; Leyland 2008; Leyland and Witthüser 2010; Meyer 2014; Van Rooy and Witthüser 2008), or applied to specialised studies of spring flow and the implications of AMD decant in dolomite terrain (e.g. Abiye 2014; Abiye et al. 2015; Durand 2012; Leketa et al. 2018; Leketa et al. 2019; Naidoo 2014)
- Despite the recent contributions, the collation of these studies is still lacking. Some attempts were made to describe slot development in shallow dolomite (Trollip et al. 2008; Wagener 1982) and the role of groundwater tables (Kleywegt 1981; Warrick 1987), but the focus was purely from an engineering and stability point of view, and did not aim to address the karst vadose zone per se.

3. THE KARST VADOSE ZONE

3.1. The Vadose Zone

The vadose zone and the distribution of water in the Earth's crust is well described in literature, notably by Dippenaar et al. (2014) and as shown in Figure 3-1.

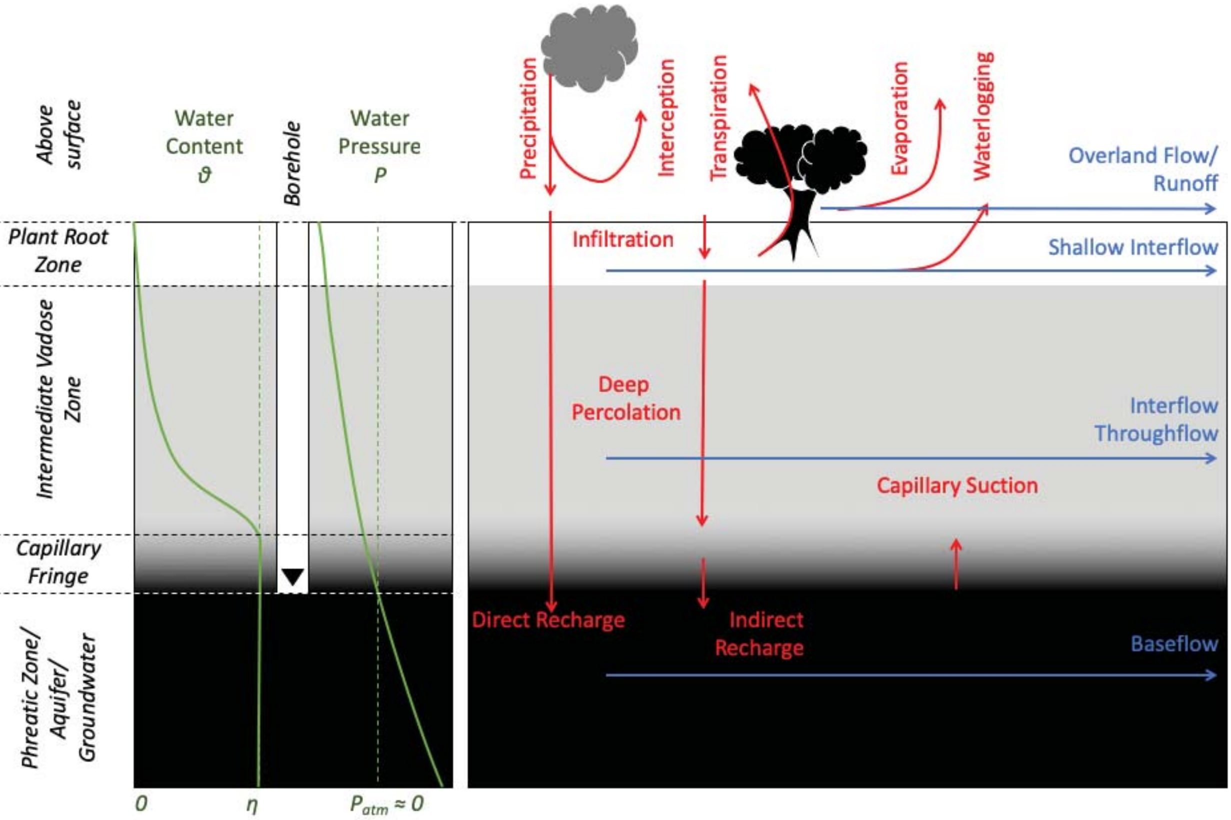


Figure 3-1. **The distribution of water in the crust and the associated flow pats (adapted from Dippenaar et al. 2014).**

Vadose zone hydrology is becoming increasingly important in South Africa and worldwide. Apart from the important applications to the fields of hydrology and soil science, notably with respect to hillslope and landscape scale flow modelling and plant water availability, the field of vadose zone hydrology has expanded to the geological and engineering domains.

Recent advances in quantifying partially saturated subsurface flow are published extensively for intergranular systems (e.g. Dippenaar 2014a,2014b,2014c; Dippenaar and Van Rooy 2014,2015; Dippenaar et al. 2014) and subsequently also for fractured systems (e.g. Brouwers and Dippenaar 2018; Dippenaar and Van Rooy 2016; Jones et al. 2017a,2017b). What has been highlighted through the culmination of a series of field studies, laboratory analyses, geotechnical centrifuge models and numerical models include:

- Flow regimes (turbulent versus laminar) govern the applicability of existing empirical approaches to estimating unsaturated hydraulic parameters (e.g. grading-based methods; cubic law)
- Flow mechanisms depend on the balance between gravitational flow and imbibition, resulting in unsaturated seepage occupying very limited void space and being dependent on pore or discontinuity heterogeneity rather than solely size and orientation
- Flow needs to be quantified at very localised scale (e.g. single fracture) and need to be upscaled to hillslope scale.

The knowledge gaps addressed in these recent publications emanate from well-established international knowledge gaps emphasised by, for instance, Berkowitz (2002) and Neumann (2005).

3.2. Role of the Karst Vadose Zone

Karstic overburden is typically absent in karst assessments (e.g. Deere and Patton 1971; Novosel et al. 1980 (in Pollak et al. 2013). The interface between soil and rock governs water storage and movement (e.g. Gunn 1986; Williams 2008; White 1969), and is often due to a thin epikarst horizon that contributes to gradual percolation and increased water storage. Epikarst can broadly be defined as the portion of the karst vadose zone between regolith and solid rock (Aley and Kirkland 2012). More thoroughly, it refers to a “recharge” zone as diffuse infiltration water concentrates in this near-surface weathered and/ or fractured zone, resulting in a perched water system (Klimchouk 2004; Mangin 1973,1975; Williams 1983) and have been in part conceptualised by for instance Aquilina et al. (2006) and Immenhauser and Rameil (2011).

The vadose zone plays an exceedingly important role in karst terrains. Water movement between land surface and the phreatic (saturated) zone occurs within this vadose zone, and it is therefore directly related to (i) advection rates of contaminants from surface, (ii) recharge rates of precipitation, (iii) downward erosion of residual and transported soils into cavities under increased unit weight when wet, and (iv) aquifer vulnerability in general. The relationship between subsurface waters and the geomechanical properties of subsurface materials therefore has obvious implications on both development of infrastructure and development of groundwater resources (Dippenaar et al. 2019).

The influences of development in karst regions are well understood (e.g. Gutiérrez et al. 2014). In South Africa, dewatering of the dolomite compartments on the Far West Rand gold mining area started during the early 1960’s and a number of catastrophic events lead to some of the more recent research by, for instance, Brink and Partridge (1965), Donaldson (1963), Kleywegt and Enslin (1973) and Wolmerans (1984). Urban expansion onto dolomite land around the major metropolitan areas such as Pretoria and Johannesburg also caused surface instability mainly due to leaking water bearing services and more recent research on this issue includes contributions by Buttrick et al. (1993). Findings show that surface instability (including subsidences and sinkholes) and potential for groundwater contamination are some of the major concerns more specifically in urban dolomitic areas.

The karstic vadose zone plays two fundamental roles. Firstly, the vadose zone serves as protection to the phreatic zone in karst aquifers from contamination, subsequently protecting the very vulnerable groundwater which is used widely as municipal and domestic water supply. Secondly, the vadose zone is the pathway of water ingress, with the ingress scenario (as opposed to the dewatering scenario) accounting for majority of the sinkholes and subsidence in the urbanised karst areas of South Africa.

Through the aquifer vulnerability approach, the influence of the vadose zone is qualified as an index method to anticipate the level of protection it will likely offer with respect to the protection of the aquifer. Very little – if any – quantification forms part of a typical aquifer vulnerability assessment, but yet the information is vital as the databases are typically ranking-based, insinuating that vadose zone thicknesses, hydraulic conductivities and other parameters can be deduced from the resulting maps. The VUKA method, developed by Leyland and Witthüser (2010), is based on the COP method (Vías et al. 2003) to specifically better account for the vulnerability of karst aquifers in semi-arid southern Africa.

Regarding engineering geology and surface stability of dolomites, the Gauteng region has been addressed in extensive detail. What is still absent remains the exact mechanism of the ingress scenario through which precipitation or leaking pipelines erode overburden downward into deeper cavities (termed receptacles) which accounted for 2651 of the total 3312 sinkholes in Gauteng recorded so far (Constantinou and Oosthuizen 2014).

Development in karst terrains is governed by the South African National Standards series SANS 1936:2012 (SABS 2012a, 2012b). All geotechnical investigations have to comply with these standards, linking the site data to inherent hazard classes based on water ingress and groundwater dewatering scenarios. The data are based on standard borehole and soil profile description guidelines published in SANS 633:2012 (SABS 2012c) and are available to some extent in the Council for Geoscience's dolomite database.

However, following these pre-development investigations, little contributions to knowledge of the karst vadose zone exist. Mostly the hazard is based on the likelihood of the overburden (which implies the vadose zone) to mobilise into a subsurface receptacle. The influences of residual dolomite (termed wad in South Africa) and epikarst on these mechanisms of sinkhole and subsidence formation are poorly understood. Site investigation of the vadose zone (overburden) for geotechnical purposes is primarily based on intrusive drilling methods, often leading to mixed material retrieval, increasing uncertainty in the conceptual model.

Numerous authors have conceptualised the South African karst vadose zone (e.g. Colvin et al. 2003; Leyland et al. 2008; Vegter 1995). All these conceptual models essentially depict a highly variable bedrock interface comprising pinnacles and grykes, dissolution cavities at depth, and fracture networks (joint; fissure [sic]. networks) generating some secondary and tertiary porosity in the systems. Saprolite, within the grykes and above the pinnacles, comprises chert rubble, residual dolomite, residuum of younger caprock, or transported soils. Sinkholes, swallow holes or caves are commonly indicated where subsurface cavities or receptacles are open to land surface, the nomenclature depending on context. These are, however, still dissolution-dominant and, although very representative of the South African vadose zone, require associated hydrological behaviour.

The lack of incorporation of the karstic overburden in classical karst assessments is noted by, for instance, Deere and Patton (1971) and Novosel et al. (1980) (in Pollak et al. 2013). International literature, notably those published in speleological, carbonate and evaporite sedimentary, and biodiversity research, view the interface between soil and regolith as a governing zone of water storage or movement (e.g. Gunn 1986; White 1968; Williams 2008). A thin epikarst horizon is often present which contributes to gradual percolation and increased water storage. Epikarst can broadly be defined as the portion of the karst vadose zone between regolith and solid rock (Aley and Kirkland 2012). More thoroughly, it refers to a "recharge" zone as diffuse infiltration water concentrates in this near-surface weathered zone, resulting in a perched water system (Mangin 1973, 1975; Williams 1983 in Klimchouk 2004) and have been in part conceptualised by for instance Aquilina et al. (2006) and Immenhauser and Rameil (2011).

Residual soils in other lithologies are typically packed into a higher dry density (e.g. Hencher 2012), or profiles are clogged by secondary pedogenic processes or weathering products such as pedocretes and clay minerals. Residuum and completely weathered bedrock do not commonly behave with increased hydraulic conductivity and storage, as suggested for the karstic networks and epikarst zone, and subsequently the properties of the intermediate vadose zone are likely fundamentally different between karst and non-karst systems. Further to this, non-karst profiles rely on horizons with differing hydraulic properties to induce illuviation into the residuum and, very likely, interflow or some degree of waterlogging of shallower horizons. Recharge, in other words, become more preferential and localised, and less diffuse, as water entry is from soil through lower porosity residual soils into fractured bedrock. Karst profiles, on the other hand, rely on flow through soil possibly comprising very low hydraulic conductivity (although likely very porous and very low density) residual dolomite, possibly via a highly transmissive epikarst zone, into bedrock with large conduits (dissolutioned joint sets) or grykes. A detailed review of the role of weathering in bedrock permeability is presented by Worthington et al. (2016), commenting specifically that carbonate rock permeability is very improved due to weathering associated with underground water.

Further to this, non-karst profiles rely on horizons with differing hydraulic properties to induce illuviation into the residuum and, very likely, interflow or some degree of waterlogging of shallower horizons. Recharge, in other words, become more preferential and localised, and less diffuse, as water entry is from soil through lower porosity residual soils into fractures in bedrock. Karst profiles, on the other hand, rely on flow through soil possibly comprising very low hydraulic conductivity (although likely very porous and very low density) residual dolomite, possibly via a highly transmissive epikarst zone, into bedrock with large conduits (dissolutioned fractures) or grykes (Table 3-1). A detailed review of the role of weathering in bedrock permeability is presented by Worthington et al. (2016), commenting specifically that carbonate rock permeability is higher due to weathering associated with subsurface water.

Table 3-1. Properties of the ground profile overlying bedrock with negligible interstitial porosity (K – hydraulic conductivity; S – storage) (from Dippenaar et al. 2019; * adapted).

	Fractured Rock	Shallow Karst	Deep Karst
Example	Basement Granite gneiss	Ghaap Group Dolomite	Chuniespoort Group Dolomite
Residuum	High density Low porosity Low vertical K Variable S	Horizon very thin or absent	Low density Low to high porosity Low (to moderate*) vertical K Very high S
Completely Weathered	Lower density Higher porosity Higher K but decreasing with depth	Horizon likely absent as complete dissolution cannot maintain mass properties	Horizon likely absent as complete dissolution cannot maintain mass properties
Weathered, fractured bedrock	K, S dependent on extent of fracture network, generally low K & S	If epikarst: very high porosity, K and S K, S possibly dependent on extent of fracture network	If epikarst: very high porosity, K and S (* mostly absent) K, S dependent on extent of dissolution, generally very high K
Fresh bedrock	Low porosity Low vertical K Low S	Low porosity Low vertical K Low S	Low porosity Low vertical K Low S

These generalisations have been confirmed during most of the work making up this report, where storage is fairly high in soils (such as the residuum) and low density and high porosity is associated with moderate to fairly low hydraulic conductivities.

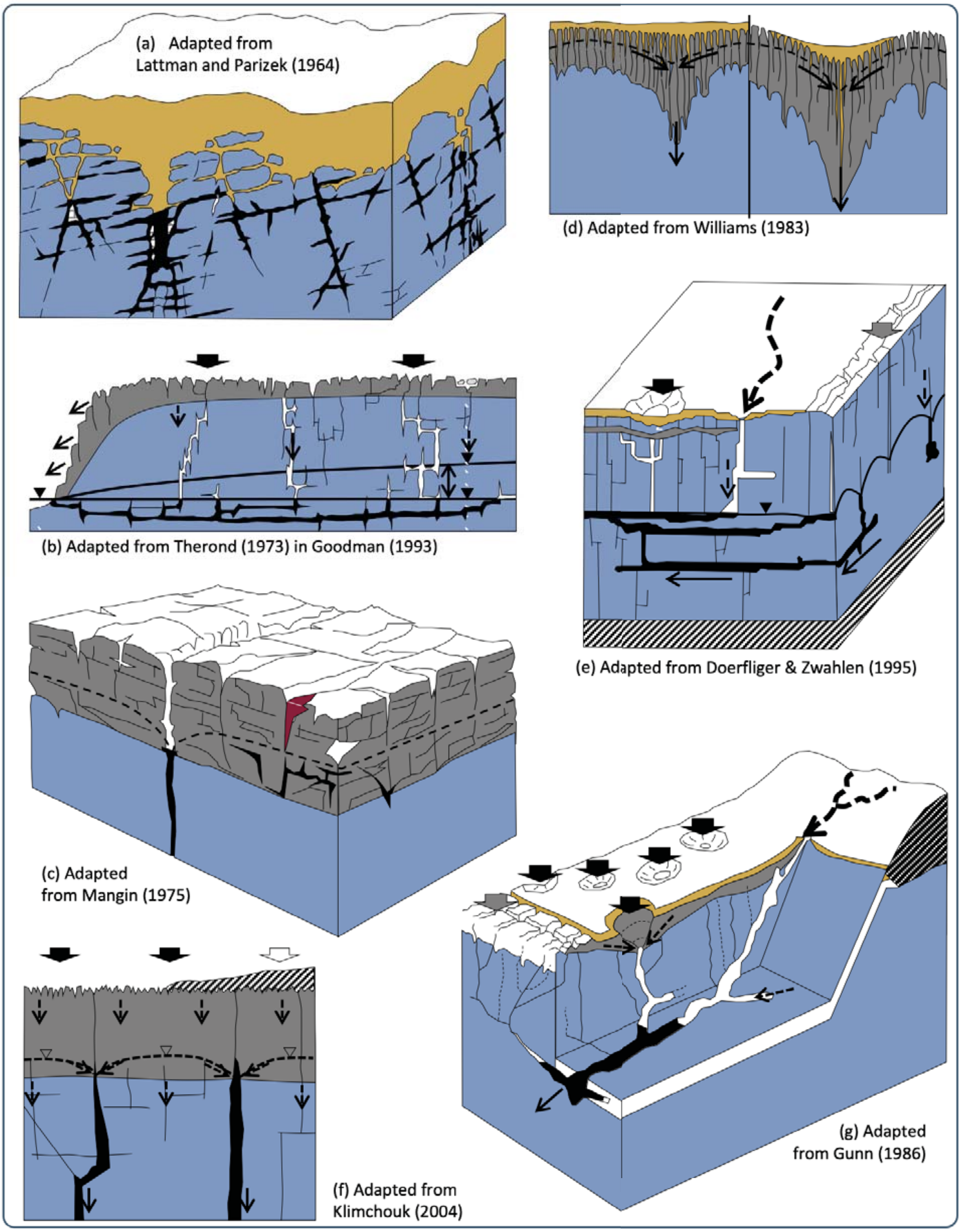
The age of the epikarst and other associated weathering products in areas of soluble rock govern whether water will infiltrate or run off; whether water will percolate or move as interflow; and how water will be stored in the vadose zone. Anthropogenic changes to the shallow subsurface, notably with urban development and commercialisation, result in increased risks of surface instability and aquifer pollution as water ingress into the subsurface is promoted through poor land use planning, leaking services and concentrated water infiltration. Recent reports estimate almost a third of municipal water losses are ascribed to leakages (e.g. McKenzie 2014), further emphasising the importance of understanding shallow subsurface flowpaths in karst regions together with influence of leaking pipes. Contaminant transport through the karst vadose zone into the bedrock cave systems and the mobilisation material from the vadose zone into solution cavities are unique processes to the karst environment.

3.3. Conceptual Models of Karst highlighting the Vadose Zone

A number of conceptual models of karst systems is depicted in Box 10 and in Box 11; the latter also supplies the legend to all the conceptual models. All models have been adapted from the original sources. Of interest is the presence of epikarst in international literature, mostly related to younger more juvenile karst systems (Box 10), whereas the Proterozoic mature systems in temperate South Africa represent pinnacle karst (Box 11).

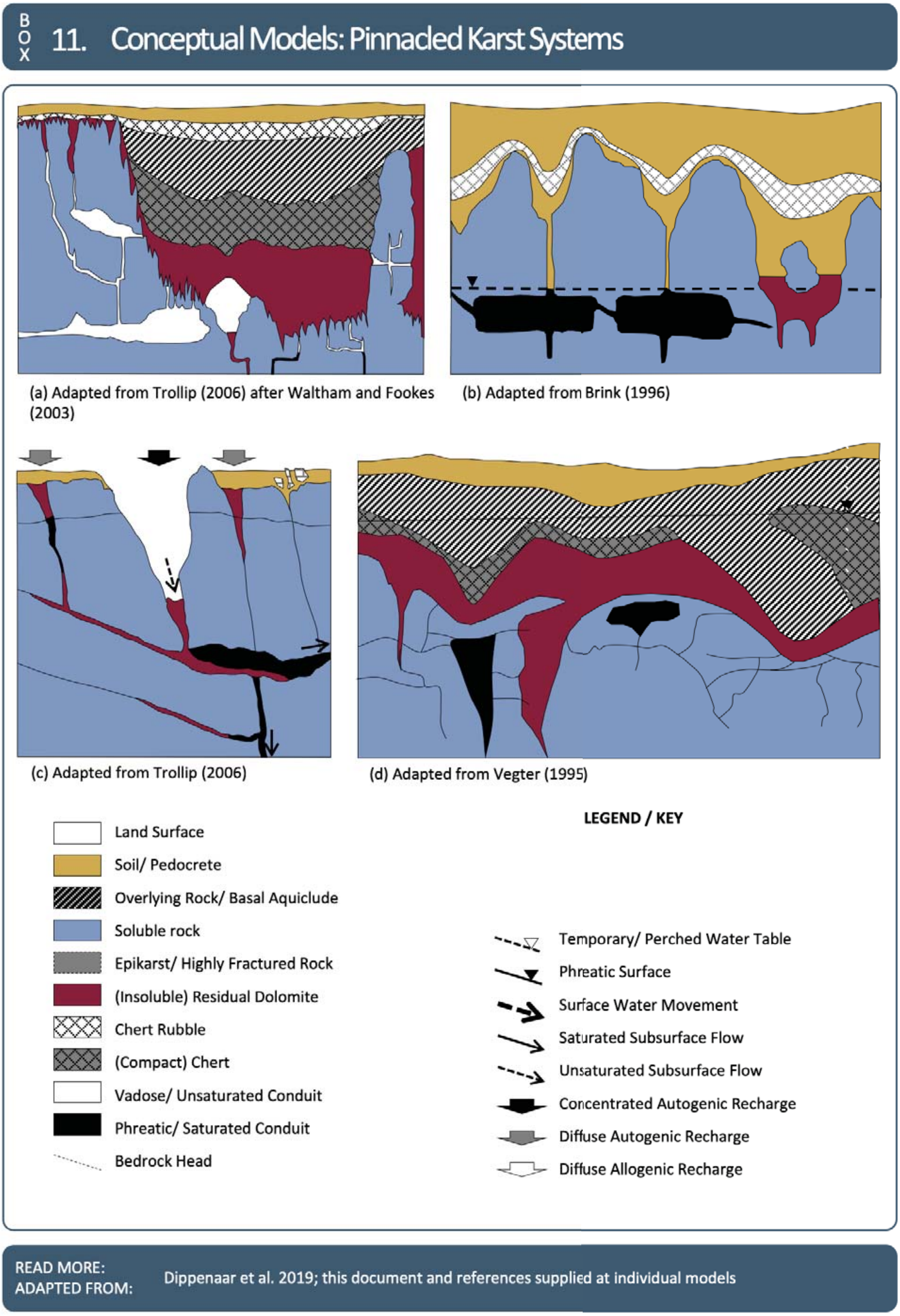
Box 10. Conceptual models: epikarstic systems (legend in Box 11).

BOX 10. Conceptual Models: Epikarstic Systems



READ MORE:
ADAPTED FROM: Dippenaar et al. 2019; this document and references supplied at individual models

Box 11. Conceptual models: pinnacle karst systems.



SECTION C: DOLOMITE WEATHERING AND SOILS

Duan SWART, Matthys A DIPPENAAR, J Louis VAN ROOY & Riaan A DE KOCK

4. DOLOMITE, WEATHERING, AND WEATHERING PRODUCTS

4.1. Dolomite Bedrock

Bedrock generally has low porosity and low to moderate uniaxial compressive strength (UCS). Results from VZSA09 and VZSA10 (a dolomite mine) indicate that the porosity of the dolomite rocks from the study area ranges between 0.09 and 0.52% with an average of 0.23%. The Schmidt Hammer Rebound values for the dolomites from the mine were 35.67-58.00 MPa with an average of 45.02 MPa. The index-to-strength equation from Sachpazis (1990), Kahraman (2001) and Shalabi (2007) supplied Uniaxial Compressive Strength values averaging 125.61 MPa and 97.47 MPa respectively.

Dolomites are not really appreciably affected by physical weathering. This is evident in multiple locations, especially in the Northern Cape within the Ghaap Group of the Transvaal Supergroup where soil layers are extremely shallow, and rocks are unaffected (e.g. Dippenaar et al. 2019).

Booth (2015) analysed the effect that both chemical and physical weathering has on karst landscapes and concluded that speleogenic wall retreat rates or karst development is greatly affected by acid solution, hydraulic shear forces and erosion by corrosion. In other words, the aforementioned mechanisms of weathering all have a significant influence on karst landscape development.

Dolomite bedrock is mostly made up of calcium and magnesium carbonates, with silica in the form of SiO_2 being present mostly in the form of chert. X-Ray fluorescence spectroscopy (XRD) results from South Africa (VZSA10; §10). Results are shown in Box 12. Note that values recorded as loss on ignition (LOI) are the carbonate anions volatilising under heating. The relationships between the cationic groups reported are acceptable.

4.2. Carbonate Dissolution

Carbonate dissolution is explained in Box 13. In such reactions, dissolution is primarily driven by acidic water. The Malmani subgroup, due to its age has undergone multiple tectonic events resulting in multiple discontinuities, which act as pathways for solutions to access parts of the rock mass not otherwise accessible due to the low porosity of these rocks (<0.2%) (Richardson 2013). The buffering of acidity through dissolution explains why after 2.5 Ga multiple dolomite ridges still exist, even in water-deficit climates. In subsurface conditions, precipitation infiltrates through soil and fractures where the higher levels of P_{CO2} and organic acids drive mineral weathering.

The various dolomite formations within the Malmani Subgroup contain different structures and compositions, all of which affect the final weathering product. Attributes such as discontinuities on both micro and macro scale affect degree and extent of weathering as these discontinuities act as preferential flow paths which dictate the formation of karst topography (Brink 1979). The composition and structure of the parent material affects both composition and structure of the residual product (Buttrick 1986). The weathering surfaces are also a product of a combination of rock composition and structure.

The dissolution rates determined in VZSA10 (§10) range from 0 to 6.4 g/min with an average of 2.33 g/min. The large variations in dissolution rates can be attributed to differences in Ca^{2+} concentrations or varying degrees of different impurities within each sample. Chert-rich dolomite formations, i.e. the Monte, Christo and Eccles, dissolve slower than the chert-poor formations, i.e. Oaktree, Lyttelton and Frisco. The variations in dissolution rates of samples from the same formation may be due to with the very old age of the Malmani Subgroup and the long-time available for post-depositional changes to original chemical composition of these rocks. The impurities greatly affect dissolution rates and may explain why dissolution rates in the chert-rich and chert-poor formations also vary.

Box 12. Composition of South African Dolomites.

B O X 12. Composition of South African Dolomites

Total (XRF)	LOI	Mn	ZrO_2	SrO	Cr_2O_3	BaO	V_2O_5	Na_2O	TiO_2	MgO	CaO	Mn_3O_4	P	K_2O	Al_2O_3	SiO_2	Fe	Sample ID
100.629	38.492	0.217	0.006	0.003	<0.01	0.005	<0.004	<0.01	<0.004	17.640	25.724	0.302	0.003	0.014	0.155	17.591	0.494	R511-1
100.328	24.701	0.138	0.008	0.003	<0.01	0.010	<0.004	<0.01	0.003	11.366	16.503	0.191	0.004	0.042	0.304	47.028	0.188	R511-3
99.900	44.984	2.557	0.005	0.003	<0.01	0.004	<0.004	<0.01	<0.004	18.906	30.125	3.550	0.004	<0.008	0.093	0.604	1.137	R511-4
100.079	46.046	0.514	0.005	0.003	<0.01	0.005	<0.004	0.039	<0.004	20.785	30.567	0.714	0.004	<0.008	0.156	0.752	0.701	R511-7
100.866	35.232	0.391	0.006	0.003	<0.01	0.005	<0.004	<0.01	0.032	15.946	23.446	0.542	0.004	<0.008	0.177	24.363	0.800	R511-8
100.559	25.530	0.352	0.009	0.003	<0.01	0.011	<0.004	<0.01	0.019	10.950	16.938	0.488	0.008	0.169	0.854	43.913	1.205	R512-1
100.980	2.274	0.047	0.010	0.004	0.010	0.013	<0.004	<0.01	<0.004	0.963	1.448	0.066	0.006	<0.008	0.141	96.028	0.141	R512-4
100.163	46.442	0.262	0.006	0.004	<0.01	0.004	<0.004	0.028	<0.004	21.355	30.899	0.363	0.002	0.018	0.126	0.556	0.259	R512-9
100.330	45.297	0.330	0.005	0.003	<0.01	0.005	<0.004	<0.01	<0.004	20.649	30.133	0.458	0.006	0.032	0.268	3.064	0.284	R533-1
100.027	46.466	0.311	0.005	0.003	<0.01	0.005	<0.004	0.040	<0.004	21.269	30.504	0.432	0.005	<0.008	0.085	0.949	0.187	R533-4
100.286	46.508	0.755	0.006	0.004	<0.01	0.001	<0.004	0.022	<0.004	21.092	30.680	1.048	0.004	<0.008	0.122	0.243	0.388	R533-6
100.075	0.460	0.141	0.011	0.004	<0.01	0.020	0.005	<0.01	<0.004	0.114	0.141	0.195	<0.003	0.028	0.231	98.597	0.188	R37-2
100.112	44.444	0.160	0.005	0.004	<0.01	0.006	<0.004	<0.01	0.009	20.194	29.780	0.223	0.006	0.306	0.549	3.993	0.405	R37-4
100.072	23.732	0.208	0.007	0.003	<0.01	0.008	<0.004	<0.01	<0.004	11.134	15.946	0.289	0.007	0.031	0.224	48.556	0.168	R37-5
100.952	1.383	0.019	0.006	0.001	<0.01	0.016	<0.004	<0.01	<0.004	0.015	0.037	0.027	0.028	<0.008	0.135	40.294	41.345	R37-6
99.486	25.595	0.383	0.013	0.004	<0.01	0.043	<0.004	<0.01	0.106	3.842	27.107	0.531	0.015	0.354	1.970	38.467	0.987	R579-1
100.208	39.587	2.249	0.009	0.005	<0.01	0.017	<0.004	<0.01	0.031	14.365	30.886	3.123	0.007	0.027	0.513	9.633	1.403	DINO 2
100.337	45.677	0.775	0.006	0.002	<0.01	0.005	<0.004	0.049	<0.004	20.356	30.476	1.076	0.005	0.017	0.278	1.484	0.627	DINO 3
100.084	45.538	1.007	0.005	0.003	<0.01	0.003	<0.004	0.022	<0.004	19.889	30.257	1.398	0.005	0.000	0.142	1.250	1.099	DINO 6
99.468	42.120	0.611	0.005	0.004	<0.01	0.001	<0.004	<0.01	<0.004	3.218	50.264	0.848	0.006	0.172	0.399	1.767	0.470	DINO 7
99.778	37.881	0.367	0.007	0.002	<0.01	0.004	<0.004	<0.01	<0.004	17.108	25.116	0.510	0.004	0.001	0.033	18.429	0.491	DINO 10
99.597	37.982	0.512	0.007	0.003	<0.01	0.004	<0.004	<0.01	<0.004	16.594	25.378	0.711	0.004	-0.001	0.001	17.049	1.321	DINO18
100.147	46.170	0.148	0.006	0.012	<0.01	0.010	<0.004	0.022	<0.004	21.744	30.867	0.206	0.020	0.059	0.112	0.432	0.328	G
99.339	44.398	0.008	0.010	0.039	<0.01	0.021	<0.004	0.022	0.048	20.546	29.711	0.011	0.042	0.305	0.886	2.810	0.308	A
99.565	40.798	0.399	0.006	0.005	<0.01	0.002	<0.004	<0.010	0.007	0.628	52.357	0.553	0.007	0.435	0.623	3.740	0.313	TB 7
99.808	36.017	0.120	0.007	0.004	<0.01	0.004	<0.004	0.012	0.006	19.778	28.611	0.166	0.010	0.066	0.389	14.224	0.353	TB 9

READ MORE:
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Box 13. Carbonate Dissolution.

BOX 13. Carbonate Dissolution

(a) Carbonate Dissolution

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

Chemical weathering entails the decomposition of a rock by changing its chemical composition which may cause partial or total change in chemical identity. Carbonates such as limestone or dolomite weather in water surplus environments through chemical decomposition by means of carbonate dissolution. Water becomes slightly acidic due to enrichment with atmospheric CO_2, further enhanced by the movement of water through the ground, causing a weak carbonic acid to form. At these acidic pH values, carbonate rocks can dissolve over time, removing ions in aqueous phase and leaving practically no solid residuum. The reaction results in hard water, enriched in Ca^{2+}, Mg^{2+} and HCO_3^- ions, buffering the acidity and increasing pH values. The extent of carbonate weathering is controlled by numerous variables such as temperature, pCO2 (which affects the pH of the solution), geochemistry, as well as sample size and grain size. In carbonate formations, solutions often achieve saturation within the vadose zone

(b) Open-system Carbonate Dissolution

In open systems, carbonate is replenished continuously from the atmosphere, and organic material in soil further promotes acidity. Such reactions that produce acids involve atmospheric oxygen and organic carbon. Bacterial respiration is a vital source of organic carbon in the form of respiration, which occurs within soils containing organic material where ample oxygen is present. The production of these types of acids is common in highly-reducing organic-rich environments such as lakes, marine environments, wetlands, ponds and septic tank systems. Subsequently the rate of carbonate dissolution is higher in these shallower soils (typically upper few 100's of centimetres) where the acidity is maintained, corresponding also to high PCO2 and water supply.

$$CH_2O + O_2 \rightarrow HCO_3^- + H^+$$
Carbonic acid from respiration

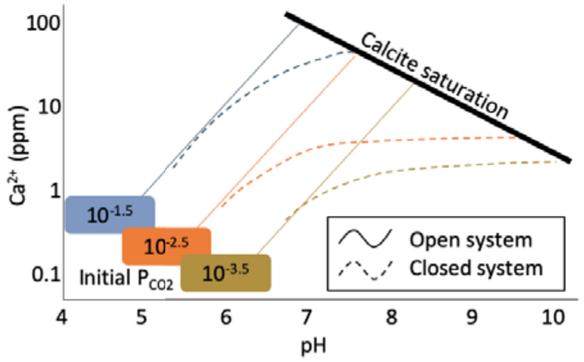
$$H_2S + 2O_2 \rightarrow SO_4^{2-} + 2H^+$$
Sulfuric acid from sulfide oxidation

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$$
Nitric acid from nitrification

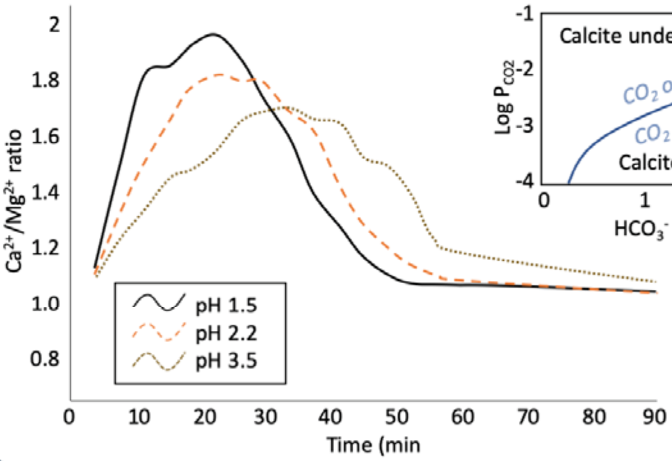
(c) Closed-system Carbonate Dissolution

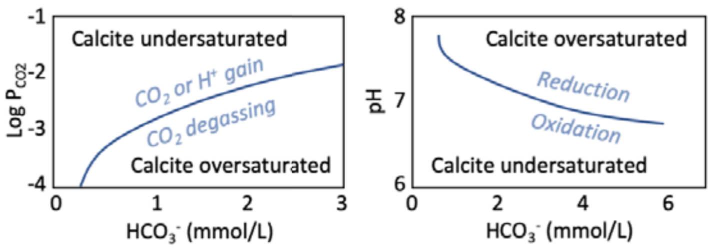
Under closed weathering systems, fluids have no access to soil or atmospheric CO_2. This means that CO_2 and other constituents are only replenished upon recharge. As the CO_2 is consumed, the P_{CO2} decreases and the pH and Ca^{2+} increase, thereby reducing dissolution rates.

Resulting from this, it is entirely possible for carbonate systems to exist where dolomite or limestone rock outcrops without any obvious chemical dissolution despite its propensity to chemical weathering.



(d) Calcite Solubility





Early stages of dolomite dissolution from fresh, unreacted surfaces is non-stoichiometric, implying that the $CaCO_3$ component is released faster than the $MgCO_3$ component. The large atomic radius of Ca^{2+} compared to that of Mg^{2+} is possibly the reason for this as this results in the Mg-O bond having higher covalency. At similar pH conditions, the calcite is therefore more soluble.

READ MORE: ADAPTED FROM: (a)-(c)Blatt et al. 1972; Booth 2015; Brink 1979; Richardson 2013; mysite.science.uottawa.ca; (d) Lund et al. 1973; Singurindy and Berkowitz 2003; Busenberg and Plummer 1982; Herman and White 1985)

Correlations between rock chemistry and dissolution rates may also be influenced by small changes between rock surface chemistry and whole sample chemistry, the small sample tested during XRF compared to rock specimen scale variations and the effects of geological changes e.g. silicification, dedolomitisation, partial dolomitization or metasomatism.

The original weathering surface features remained for the duration of the dissolution test and even until the entire rock was dissolved. It is not quite clear why the surface features are retained during dissolution but may be due to a combination of pre-existing cracks in the rock which act as preferred pathways for dissolution as well as thin laminations of $CaCO_3$. This is shown in Figure 4-1.

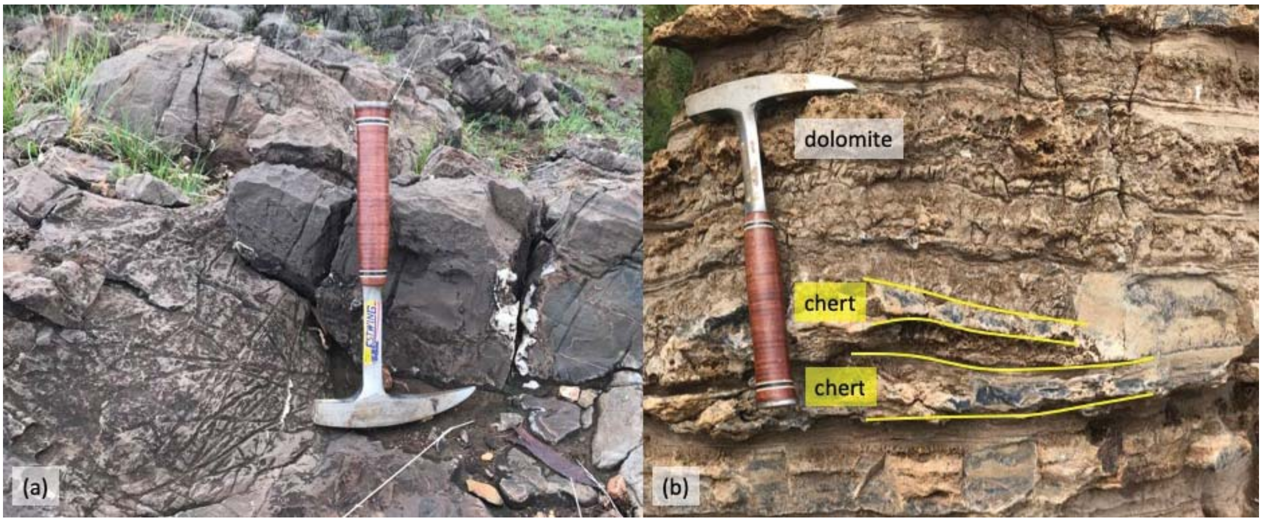


Figure 4-1. **Post-dissolution features of dolomite, showing (a) the elephant skin weathering pattern that is due to a combination between structural joints and dissolution along lineations, as well as (b) the influence of chert which is not prone to dissolution (VZSA10).**

4.3. Residual Dolomite and Wad

Residual dolomite and wad are described in Box 14. These soils are critical in terms of ground stability of a dolomite site (Buttrick 1986), and therefore the mechanical, hydrological, geochemical and structural properties or of extreme importance, hopefully to eventually be applied by a consultant when determining the inherent hazard class of dolomitic land.

The exact definition of *wad* is also not 100% certain, and is often open to interpretation. The terms *residual dolomite* and *wad* should not really be used interchangeable, as fundamental differences in properties can result in unanticipated behaviour. For that reason, the main focus of this section is to establish the properties of the more troublesome material, namely wad.

4.3.1. Composition and grading

The dissolution process completely removes calcium and magnesium oxide from the dolomite structure (Brink 1975; Wagener 1982). The general chemical composition of dolomite in relation to wad is shown in Table 4-1. Compositions of wad samples from VZSA11 (§11) are shown in Table 4-2 and expanded to show all components in Figure 4-2. bO is interesting for the Doornhoek sample where galena (lead sulphide) has historical been mined extensively.

Box 14. Residual Dolomite and Wad.

BOX 14. Residual Dolomite and Wad

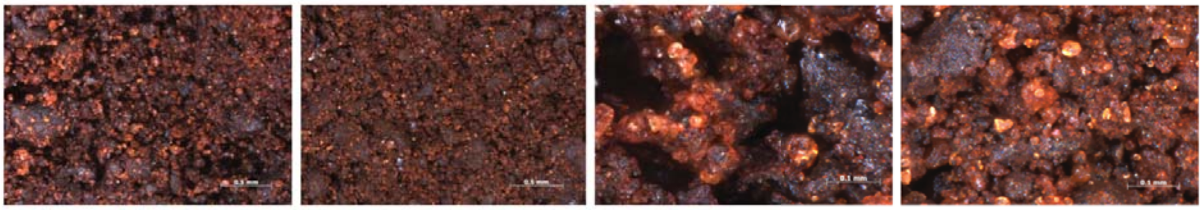
(a) Terminology

Residual dolomite, occasionally termed wad when possessing certain qualitative attributes, forms on the soil-rock interface and in grykes through the enrichment by removal of soluble material during leaching of dolomitic rock made up of $CaMg(CO_3)_2$. Due to the highly soluble nature of both calcite and magnesite in dolomite, there are typically completely removed, and some impurities such as Mn^{4+}, Fe^{3+} and chert (SiO_2) remain, making up the residual dolomite product sometimes known as wad.

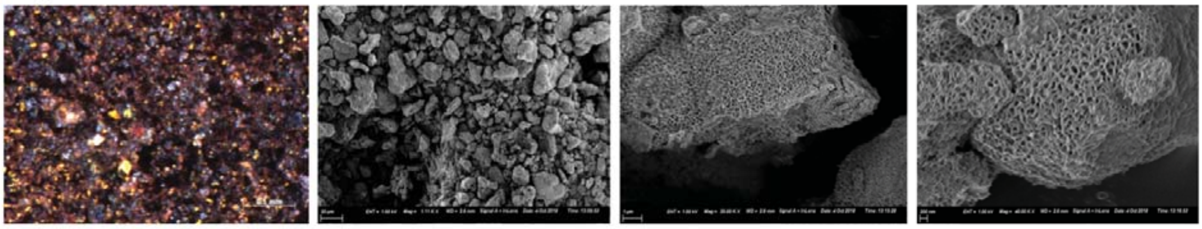
Where residuum has been transported and redeposited as a transported soil, it is not typically classified as wad. In-situ wad may vary from a soft powdery broken structure to an intact structure which is comparable to that of the dolomite rock from which it originates. The intact fabric is depicted as porous, with a sponge-like structure, which shows an increase in both porosity and permeability compare to dolomite rock.

- Wad is a dark, fine-grained, insoluble material formed from weathering of manganese-rich dolomite, and that it is assessed based on the fabric as being either structured or laminated, or non-structured or massive wad (Day 1981; Wagener 1982; Buttrick 1986).
- Non-structured wad has no inherent parent structure present that might have been reworked by mechanical processes or compression from overburden, subsequently destroying the structure and resulting in a powdery wad appearance (Day 1981; Wagner 1982); or with no distinguishing features (Buttrick 1986).
- Reworked wad has been mechanically reworked, destroying the relict structure of the residual massive or laminated (structured) wad material, and having undergone addition of external impurities.

(b) South African Wad



Stereomicroscope images of the Mooiplaas samples pre- and post-triaxial undrained testing. Left to to right: Undisturbed sample at x20 magnification; undisturbed sample at x94 magnification; post testing at x20 magnification; post testing at x94 magnification.



Stereomicroscope image of the Doornhoek samples. Left: x94 magnification.
SEM of Doornhoek silt-size aggregates at x1000 magnification; x20000 magnification; and x40000 magnification.

(c) Manganese Minerals

Mn-oxides commonly form coatings on other minerals and form reactive surfaces, such as on inert chert or quartz grains. Such Mn-oxides could readily take up water molecules, the amount of which is dependent on the structure of the Mn-oxide. Fine-grained birnessite can have a surface area of up to 300 m^2/g, allowing for the material to carry 15% to 25% of its weight in water. The chemical influences that Mn-oxides have on the surrounding environment and aqueous solutions far outweighs their concentrations. Dowding (2007) studied the Mn-rich soils in the Graskop, Mpumalanga, area and identified lithiophorite, birnessite and todorokite and goethite, hematite and maghemite as the common Mn and Fe minerals found in wad, respectively. Birnessite with the open coral structure can carry up to 25% of its weight as water.

READ MORE:
ADAPTED FROM: Bear Geoconsultants 2016; Beck and Sinclair 1986; Brink 1979; Buttrick 1986; Day 1981; De Beer 1985; Hajna 2002; Hawkins et al. 1986; Swart 2019; Wagener 1982 (a); Swart 2019 (b) Hawkins & Thompson 1988; Jenne 1968; McKenzie 1972; Post 1999 (c)

Table 4-1. **Chemical composition of dolomite rock compared to wad; weight % (Wagener 1982).**

Analysis	CaO	MgO	Al_2O_3	MnO	MnO_2	FeO	Fe_2O_3	SiO_2	CO_2	H_2O	Total
Dolomite	27.20	15.12	0.43	3.66		7.26		4.18	42.15		100
Wad 1			3.13		16.46		64.83	4.71		10.87	100
Wad 2			2.29		42.32		19.70	26.64		9.05	100

Table 4-2. **Chemical composition of wad; weight % (Swart 2019); * refer to figure below for all components.**

Analysis	CaO	MgO	Al_2O_3	MnO_2	FeO	Fe_2O_3	SiO_2	Total	* Other
Bokkraal (%)	0.13	0.35	3.57	10.76		16.50	62.00	93.31	LOI
Doornhoek (%)	0.08	0.73	2.67	11.46		25.50	45.90	86.34	PbO; LOI
Mooiplaas (%)	0.20	0.28	5.09	3.19		5.61	82.00	96.37	LOI
Highveld (%)	2.13	0.52	0.76	45.79		33.85	5.78	88.83	LOI

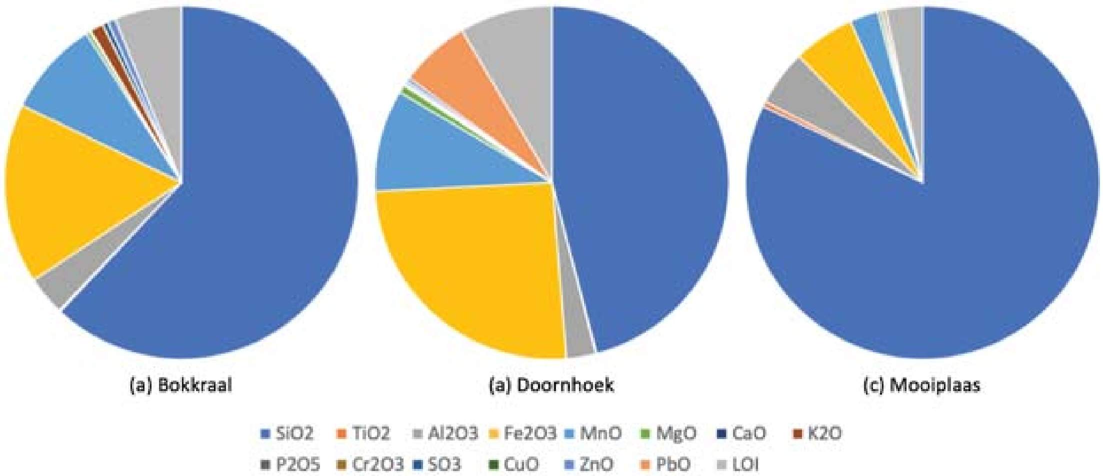


Figure 4-2. **Selected XRD results for wad; LOI – loss on ignition (VZSA11; Swart 2019).**

When wad is non-reworked, be it structured or non-structured, it typically grades as a clayey silt or silty clay with a low density and high void ratio (Bester et al. 2017; Buttrick 1986; De Beer 1985; Wagener 1982). Occasionally wad can contain a high amount of sand, especially when reworked, in which instance it grades as a sandy, clayey silt (Day 1981; Buttrick 1986). Grading curves of some South African wad soils are shown in Figure 4-3.

4.3.2. Mechanical and hydraulic properties

Porosity/ void ratio: Structured wad possesses more than double the average void ratio value than non-structured wad. The high porosities (and the void ratio values that usually exceed one and reaches 16.6) are due to the leaching process that requires the residual soil to occupy the same volume as the parent rock (Buttrick 1986).

In-situ moisture content: The natural moisture content usually exceeds the liquid limit of the material (Brink 1979; Buttrick 1986; De Beer 1985; Wagener 1982).

Permeability: Permeability of wad depends on the fabric, void ratio, particle size and degree of saturation, where fabric or primary features refer to the orientation and distribution of particles such as laminations. The highly voided material generally possesses a low permeability attributable to the circuitous nature and variable radial sizes of the interconnected voids. The intact structured wad typically has low to very low permeability and the non-structured wad a low permeability; values for both types are generally in the order of 10^{-7} m/s. Other factors affecting the permeability of wad would be the presence of any secondary structures such as fissures or bedding planes (Buttrick 1986). Values were confirmed in the order of 10^{-6} m/s (Swart 2019; VZSA11).

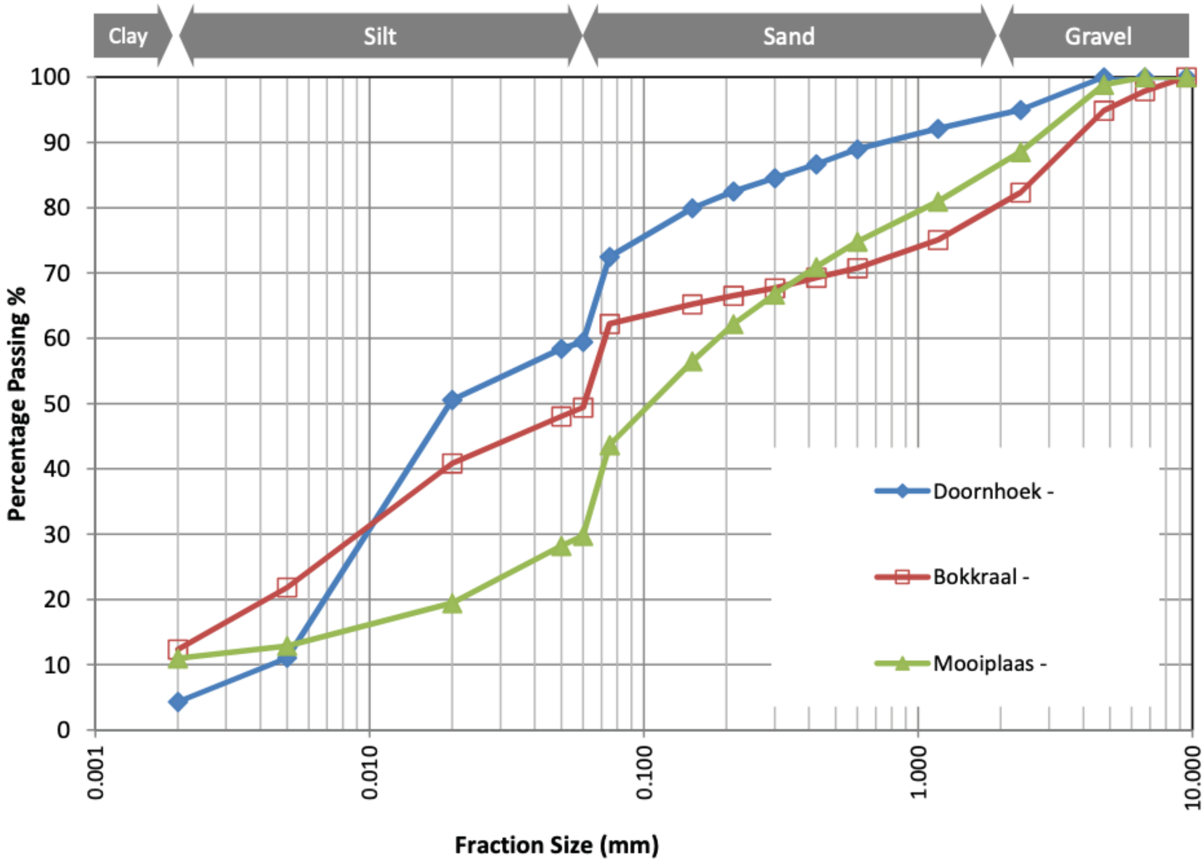


Figure 4-3. **Typical particle size distribution curves for South African wad (VZSA11; Swart 2019).**

Infiltration/ percolation: Linked to the permeability, infiltration (from surface) and percolation (from shallow subsurface) rates were determined by as documented in VZSA09. Compared to lower permeability, infiltration and percolation rates for a site in Pretoria averaged $5x10^{-5}$ m/s and $8x10^{-4}$ respectively. It is well understood that the accuracy of these values is limited by the possible subsaturation of site soils, the unsaturated state of the ground below the test conditions, and the likelihood of lateral dispersion remaining valid despite test assumptions (e.g. Dippenaar et al. 2014).

Translocation: As water flows through the preferred open pathways, reaching a high flow rate, erosion is expected to take place and remove wad material. The erosion may increase with the further opening of the fissure, or the material may lodge in a narrow opening and reduce flow, thereby terminating the erosion process. Secondary cementing of silica or calcite and clay or wad infill in the open fissures will decrease the permeability. Thus, the water percolating through the wad material cannot reach the required seepage for piping or erosion to occur, therefore making it hydrodynamically stable, notably in structured wad. The resultant chemical composition of residual dolomite is the consequence of enrichment of insoluble particles through removal of soluble material (Buttrick 1986).

Water adsorption: Manganese-rich minerals associated with wad, such as birnessite (an amorphous, silt-size Mn-oxide), can hold up to 25% of its weight as water (Dowding and Fey 2007; Post 1999). This, together with high liquid and plastic limits exhibited by certain wad materials, are related to the porous nature and the high specific surface area of the fine-grained material, thus allowing for large quantities of hygroscopic water (e.g. Buttrick 1986). Adsorption of water onto metal (Fe and Mn) oxide surfaces may be the governing factor in some wad materials rather than the fine grading (Bear Geoconsultants 2016).

Influence of structure: Wad's structure breaks down due to high pore pressures or shock loading that liquefies the material (Wagener 1982; Day 1981). The fabric of the wad can be completely destroyed through mechanical processes such as slumping or compression from the overburden. The reworking process changes the chemical composition and grading of the material by either increasing the fines content as infill in fissures or interconnected pores from water flowing through the soil profile, or by increasing the sand and gravel components through mechanical processes breaking down the chert layers. Therefore, the surrounding environment and the type and degree of reworking consequentially alters the hydrological properties. Destroying tmxz,xe relic structure and the secondary cementing would increase the permeability as well as allow the material to be more readily and easily eroded away. This is only true if a coarser grading or better-interconnected pores are attained from the reworking process (Buttrick 1986).

4.3.3. Lessons learnt and contributions

Wad is regarded as a complex material to test for its geotechnical properties. Firstly, retrieving a representative sample is difficult due to the variation of wad. Secondly, preparing an undisturbed sample for testing, be it cutting a block sample or extruding a Shelby tube, the wad tends to disintegrate and crumble along primary and secondary features. The galena present in the fissures of the Bokkraal sample caused difficulties during the preparation of the sample for the triaxial cell. The competent lead ores will create preferred flow paths for water and may result in flow rates high enough to cause erosion. When sampling in areas associated with lead ore, it should be noted that the wad may be highly fissured with galena, and possibly other ore, and special care must be taken to avoid the ore stringers and inclusions.

The Mooiplaas sample has been reworked to an abundant coarse material having the highest SiO_2 content and density, and lowest Fe- and Mn-oxide weight% values of the samples analysed. The Doornhoek sample is non-structured, therefore has not been reworked, having a low dry density and the highest Fe- and Mn-oxide content and lowest SiO2 weight% value. The reworking process clearly plays a major role in the geomechanical properties and geochemical content of wad.

Fundamental properties of wad are summarised in Box 15. The final results by Swart correspond to work published by Swart (2019) and the results of VZSA11 (§11). The Mooiplaas sample has the highest dry density than results of work previously done on reworked wad. Wad generally has a void ratio greater than one with the reworked wad usually having the lower void ratios than non-reworked wad. The properties of the reworked wad are highly dependent on the process and degree of reworking and the surrounding environment. Classifying wad into a single group based on the reworked fabric alone would be redundant because of the broad behavioural characteristics and properties possible. To reduce some of the ambiguity of the classification, evaluation of the wad fabric must include the type of reworking process, the degree of reworking and resulting geochemical content and grading.

The high liquid limits exhibited in certain wad materials are influenced by the fabric, the fine grain nature of the material and, as presented in this study, the presence of certain metal oxides. The magnitude to which each of these factors influences the behaviour of wad is not exactly defined and will vary considerably.

The fabric of wad is inherent to the structure of the parent rock, which is determined by the stress history of the rock. The fabric influences the behavioural characteristics and properties of the wad. The high void ratios are a usual consequence of the preserved structure. Wad is considered reworked when mechanical processes destroy the structured or non-structured inherent fabric or external impurities are added. The type of reworking process and degree of reworking affects the geomechanical and hydrological properties, and geochemical content of the material. The addition of coarse or fine grade material may have a bigger influence on the permeability of non-structure wad than mechanical processes alone. Wad is a complex material to sample, because of the variable nature of the material, and to test, due to the difficulties confronted during the preparation phase and possible presence of ore in certain localities. The Atterberg limits are usually high but also variable and the factors that govern these limits, especially the liquid limits, are the fabric, grading and presence of metal oxides, such as birnessite.

Box 15. Properties of Wad.

BOX 15. Properties of Wad

Author / Report	Fabric	Grading (%) Clay	Silt	Sand	Gravel	Dry density (kg/m^3)	Dispersiveness	PI (%)	LL (%)	e	SG	Permeabilty (m/s)
Brink (1979)	-	<29	-	-	-	285 - 722	-	5 -28	47 - 96	2,7-9,6	1,63-3,47	-
Day (1981)	Structured or Intact and; non-structured or Reworked	30	50	22	-	225 - 1327	-	14 - 27	61 - 125	-	-	-
		Clayey silt to silty clay										
Jones and Wagener (1981)	-	29	49	21	1	225 - 1327	-	10 - 29	61 - 125	1,1-11,2	2,9	-
		Clayey silt										
Jones and Wagener (1982)	-	Clayey silt to sandy silt				253 - 1481	-	15 - 23	40 - 135	-	-	-
Wagener (1982)	Intact (structured)	Clayey silt				225 - 1481	Not dispersive	-	-	0,9-11,2	-	High
	Powdery (non-structured)											
De Beer (1985)	-	11 - 59	-	-	-	273 - 1558	-	5 - 27	49 - 126	0,3-8,9	-	-
		Clayey silt										
Hawkins et al. (1986)	Laminated	-				500 - 600	-	18	71	-	-	-
Buttrick (1986)	Laminated or Structured	48	-	-	-	220 - 1221	Not to slighty dispersive	3 - 26	28 - 113	1,3-16,6	2,2-3,1	Very low to intermediate
		Clayey silt to sandy silty clay										
	Massive or Non-Structured	Sandy clayey silt				406 - 1516		11 - 27	27 - 136	0,97-6,2	1,94-3,0	Very low to low
Bear Geoconsultants (2016) Bester et al. (2017)	"pure" wad (Non-structured or Structured)	-				576 - 1075	Not dispersive	10 - 40	57 - 93	2-12	-	$1{,}5x10^{-6}$ - $1{,}2x10^{-8}$
Swart	Structured	9	89	2	0	309	Not dispersive	8	229	8,32	2,28-2,86	-
	Non-Structured	4 -28	53 - 68	4 -23	5 -21	593		20 - 33	67 - 145	3,87	1,79-2,89	$2x10^{-5}$ - $4x10^{-6}$
	Reworked	11 - 12	33 - 50	20 - 45	11 - 18	898 - 1751		12 - 17	29 - 94	0,55-2,07	2,72-2,93	$2x10^{-5}$ - $2{,}8x10^{-6}$
		Dependent on type and degree of reworking and environment										

Notes: PI - Plasticity Index; LL - Liquid limit; e - Void ratio; SG - Specific gravity.

READ MORE:
ADAPTED FROM: Swart 2019

The term *wad* which was original used to describe an earthy, black, manganese ore, is misused in most cases within, but not limited to, South Africa. The misuse of the term ‘wad’, as currently described by consultants, is due to the qualitative attributes given in the definition, being a dark gun blue, fine-grained material that stains fingers black. The material is known to be enriched in manganese although Buttrick (1986) found the iron content is generally double the manganese content in a typical non-reworked to slightly reworked wad. This definition may result in material being misinterpreted or incorrectly described. The following definitions are proposed:

- **Wad**: Dark, gun blue to purple, stains fingers purple to black, clayey silt with minor sand or gravel, enriched in metal oxides with Fe (w%) $\leq$ Mn (w%) and Fe_2O_3 (w%) $\leq$ MnO_2 (w%) and $SiO_2 < 50$ w%, insoluble material formed from leaching of manganese-rich dolomite and is divided into two groups assessed on the fabric, being structured or non-structured wad, partly powdery to partly indurated, with a spongy to brittle behaviour, a low density and a high void ratio, and a nearly unnoticeable weight in hand specimen when sample is free of ore metals.
- **Residual dolomite**: Dark reddish brown, stains fingers dark brown, intact or massive, sandy silt to silty sand with minor gravel or clay that is enriched in SiO_2 (>50 w%), in the form of chert and/or quartz particles, with Fe (w%) $\geq$ Mn (w%) and Fe_2O_3 (w%) $\geq$ MnO_2 (w%); insoluble material formed from weathering of chert-rich dolomite, or formed from the mechanical reworking of wad through the addition of impurities and break down of the original fabric to a degree where the open and relict structure and brittle to spongy behaviour is lost, and the density increases to a noticeable weight in hand specimen.

SECTION D: INTEGRATED KARST ASSESSMENT

Matthys A DIPPENAAR, J Louis VAN ROOY

5. ENGINEERING HYDROGEOLOGY OF KARST

The term engineering hydrogeology relates geotechnical and subsurface hydrological considerations, emphasising specifically how water affects engineering properties of earth materials (Dippenaar and Van Rooy 2019).

5.1. Land versus Water

Professional opinion on the use and management of dolomite or karst land and water is described in VZSA12 (§12), and the main outcomes of these facilitated sessions are shown in Table 5-1. Of interest is that the utilisation of karst water as a resource was red-flagged as being least optimally used. Given the extent to which dolomite land is developed in Gauteng, groundwater resources are mostly considered non-exploitable out of fear of dewatering scenario sinkholes and subsidences. Interesting to note in this regard is that:

(a) Lack of water level monitoring is seen as a reason for not using the water resource more, yet it is seen as a geotechnical weakness in the post-development management of dolomite land.
(b) Groundwater resource development is considered overly conservative to minimise the risk of dewater scenario sinkholes and subsidences, yet the relevance of the dewatering scenario is consistently queried by the geotechnical fraternities as ground movements are almost exclusively ingress scenario.
(c) Site investigation is pivotal, especially non-invasive techniques such as geophysics and invasive techniques such as drilling, but the relevance of the specific methods being employed are to be re-evaluated.

Table 5-1. Perspectives on karst land and karst water.

	Karst land	**Karst water**
Utilization of Resource	• Relevance of dewatering scenario • Density & types of development • Shared responsibility of dense developments • Dewatering scenario limits development in areas that are IHC1 • Site investigation techniques possibly not adequate, especially types of geophysics used	• Monitoring of abstraction and water levels, as well as the interpretation of monitored data • Deemed to be overly conservative re stability; not optimally using • Site investigation techniques possibly not adequate, especially types of geophysics used
Management and Mitigation of Risk	• Water level monitoring needed • New developments better managed than old developments • Completion of construction should be reported and policed	• Water quality has issues (hardness; urban pollution; sewerage and sewage) • Protection zoning is required

In further complicating our assessment and use of karst terrain, whether for construction or for water, is the relevance of our conceptual models. Mostly, conceptual models generate the assumption that all karst land comprise vast cavities waiting to collapse under load or dewatering, when the question still remains as to whether majority of the dolomite terrain is truly karstic, and whether dewatering is truly such as substantial trigger risk. A hydrological model superimposed on a ground model, even if only at conceptual level, will already substantially improve this knowledge.

Questions remaining include, for instance:

- Do we have epikarst with high storage and transmissivity, or do we have low residuum with high storage and low transmissivity?
- Exactly how direct is recharge, and what happens in the intermediate vadose zone with this percolating water?

- Do our simplified box models present every absolute worst-case outcome on a highly zoomed-in scale?
- Do we protect construction works by the no-use approach to groundwater, or could restricted use possibly promote better monitoring and knowledge about the influence of the water in karst terrains?

5.2. Integrated Surface Stability and Groundwater Vulnerability

Intrinsic vulnerability relates to the protection of the aquifer to contamination, and subsequently intrinsic instability is taken to refer to the same physical controls on instability. With specific vulnerability referring to the aquifer becoming more vulnerable by the contaminant itself and its ability to persist and mobilise, the specific instability is taken to refer to the increase in vulnerability by allowing for scenarios of concentrated ingress or groundwater lowering (Figure 5-1).

	INTRINSIC VULNERABILITY	INTRINSIC INSTABILITY	SPECIFIC INSTABILITY
ATMOSPHERE/ LAND SURFACE	Likelihood of infiltration: • Precipitation (intensity/ duration) • Topography/ slope • Land use/ land cover		Risk exacerbated by specific scenario: • Concentrated ingress
VADOSE ZONE	Likelihood of recharge: • Distance (depth to water) • Flow rate (K_{unsat}) • Confining layers	Hazard of sinkhole or subsidence formation: • Blanketing layer • Mobilisation potential and agents • Presence of cavities • Depth to groundwater • Receptacle development	
PHREATIC ZONE	Impact on aquifer: • Recharge rate • Aquifer media		Risk exacerbated by specific scenario: • Lowering of regional groundwater table (abstraction)
	SPECIFIC VULNERABILITY Risk exacerbated by specific contaminant, e.g.: Contaminant properties/ toxicity; Manner of contaminant disposition; Persistence, bioaccumulation		

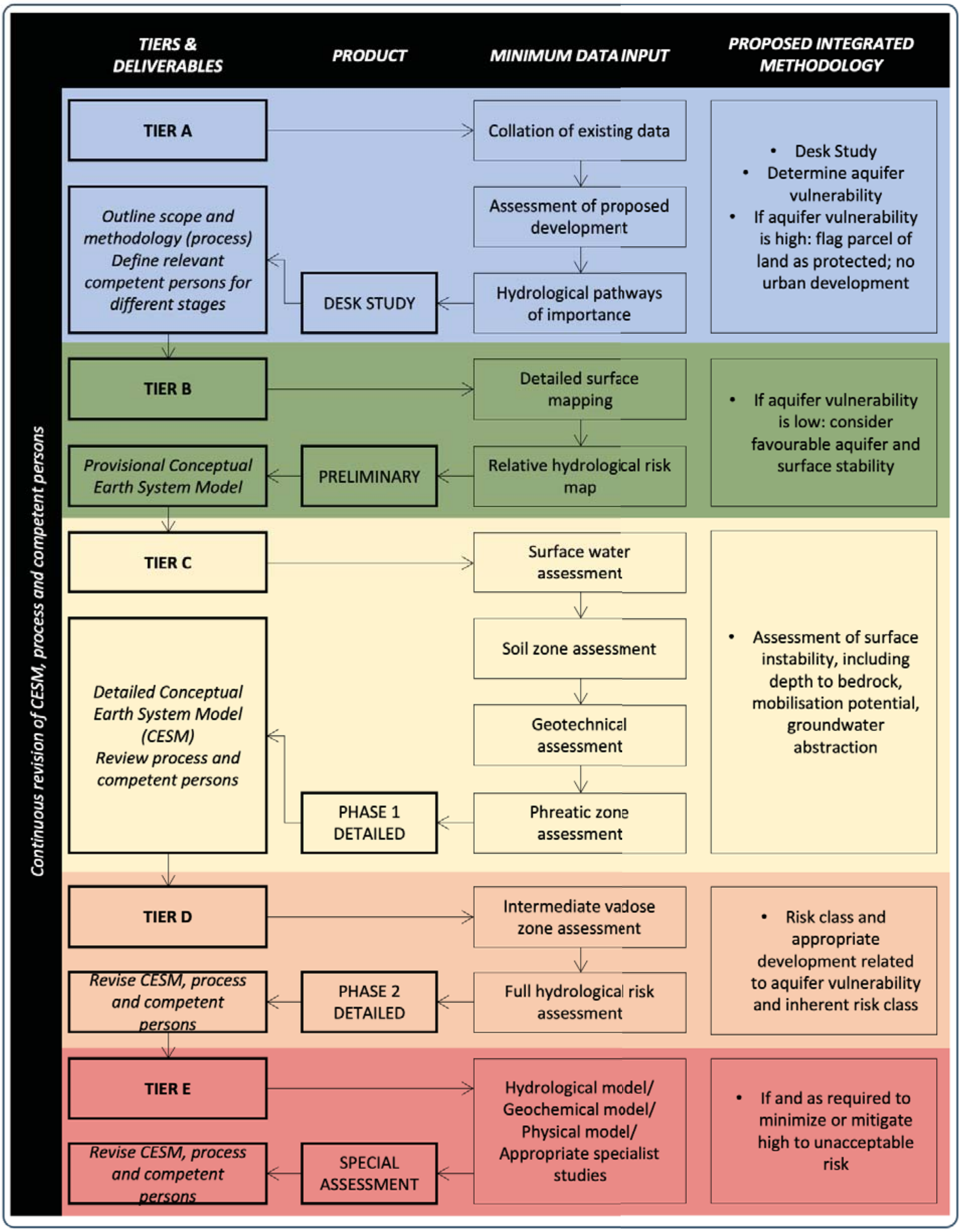
Figure 5-1. Applying concepts of intrinsic and specific vulnerability to instability, where intrinsic instability relates to the vadose zone, and specific instability to the scenario of ingress or groundwater lowering.

A Vadose Zone Assessment Protocol as presented by Dippenaar et al. (2014) and adapted in Box 16 relates the controls on aquifer vulnerability and surface instability to the data requirements and stages of assessment for the vadose zone.

Significant overlap exists between different professional work being done. However, each professional subdiscipline, in the context of hydrogeology and engineering geology, considers the other as a risk with the potential of the change in groundwater level to affect stability being an almost immediate red flag on the development of either. Better synthesis between the professional sciences will advance the conceptual models of the karst ground and hydrological systems substantially to the extent that a single model can be compiled. Understanding the properties and behaviour of the karst vadose zone is inevitably most important as all ingress of water and associated downward erosion of material depends on these.

Box 16. VZAP adapted to Dolomite Assessment.

BOX 16. VZAP adapted to Dolomite Assessment



READ MORE:
ADAPTED FROM: Dippenaar et al. 2014

SECTION E: DISCUSSION AND MAIN FINDINGS

Matthys A DIPPENAAR

6. SUMMARY

The project deliverables are met through contributions to the understanding of the karstic vadose one, emphasising the mechanical, geochemical and hydraulic properties of residual dolomite and wad, and dolomite bedrock.

Case studies entailed controlled laboratory and field investigations to address questions identified that are of relevance to karst systems with the notable emphasis on the vadose zone and variably saturated systems.

Main findings and contributions are detailed in Box 1 and include:

- According to Richardson (2013), the Eccles and Monte Christo Formations are the two with the most sinkholes, although they are also chert-rich and supposed to have slow dissolution rates. There are however many external factors that influence sinkhole development such as overburden mechanics and concentrated water ingress due to anthropogenic activities. The age and time of exposure to natural weathering processes may also have resulted I cavity development in all formations irrespective of their chemistry.
- Present-day dissolution rates do not directly dictate the likelihood of sinkholes forming. Present day karst is a product of past dissolution occurring over long periods of time. The likelihood exists that ground movement has already occurred in many instances where no chert is present, and that chert-rich formations have survived failure longer due to the resistance of the chert. This may to some extent explain why sinkhole occurrence at the present moment in time is more prevalent in chert-rich horizons.
- Hydraulic parameters were calculated and confirmed to be roughly in the order of 10^{-5} m/s for infiltration, 10^{-4} m/s for deeper percolation in soils, and 10^{-7} m/s for saturated hydraulic conductivities of residual dolomite soils.
- Hydraulic behaviour of the karst vadose zone may very likely be governed almost exclusively by the high storage of fractured dolomite (epikarst) and residual dolomite (wad). These have differing hydraulic conductivities and will also be influenced by the presence of karren features such as grykes. Dolomite systems in South Africa can, therefore, not at all be considered uniform in the vadose zone; even more so than for most other soil-rock systems.

7. RECOMMENDATIONS AND WAY FORWARD

It is well understood that this project could not nearly address all the knowledge gaps. However, the project team set out to inform – and believe to have done so – regarding the properties dictating the hydraulic behaviour of the possible strata making up the hydrostratigraphical model of Southern African dolomite karst systems. This in itself is highly beneficial to engineering geologists, civil engineers, hydrogeologists, and like-minded professionals, in that more trustworthy and validated parameters are available to input into models and designs, provided that due caution is taken regarding the obvious limitations of these studies.

It is recommended to progress yet further with this work into full-scale field studies and to assess the influence of improved parameters for different strata (or hydrostratigraphic units) in models.

SECTION F: SUPPORTING CASE STUDIES

Matthys A. DIPPENAAR

Individual case studies to be referenced as a chapter in a book.

8. INTRODUCTION TO SUPPORTING CASE STUDIES

The following section depicts case study descriptions, sampling, analysis, interpretation and results. The final conclusions have been collated and incorporated into the first sections of this document. Main findings are incorporated into the body text of this document, continuously referring to the case study in the appendix.

For the sake of integrated readability with other case studies in other vadose zone projects, notably as initiated by Dippenaar et al. (2014), study sites are labelled as Vadose Zone Study Areas or VZSAs with numbers following on those used in Dippenaar et al. (2014). For the sake of easy cross-referencing, experimental studies are labelled similarly. The work contained herein also form part of a greater research focus on vadose zone hydrology and engineering hydrogeology, and subsequently future studies will conform to the numbering.

9. VZSA09: HYDROLOGICAL AND GEOCHEMICAL ASSESSMENT OF A DOLOMITE MINE

Christel VAN STADEN, Sarah HEUER, Roger E DIAMOND & Matthys A DIPPENAAR

9.1. Motivation for Study

The Mooiplaas Dolomite Mine is situated with the northern portion of the pit underlain by Eccles Formation chert-rich dolomite and the southern portion by Lyttleton Formation chert-poor dolomite. A northwest-southeast striking syenite dyke furthermore divides the pit into a western section in the Aalwynkop Dolomite Compartment and the eastern section in the Laudium Dolomite Compartment.

Different lithological compositions, stromatolite occurrences, the presence or absence of wad (weathered altered dolomite residuum) and chert, and vastly different groundwater levels create for an interesting study site with respect to geological and hydrogeological heterogeneity.

The data and interpretation of bulk of this study is contained in Van Staden (2019; master's dissertation), with contributions of notably the site description and hydraulic testing contained in Heuer (2017; honours project).

9.2. Study Description

The site locality and regional geology are indicated on Figure 9-1 and Figure 9-2, and the average rainfall data in Figure 9-3. The Quarry is situated on the dolomites of the Malmani Subgroup of the Lower Transvaal Supergroup rocks. There are 3 formations which have an impact on the mining operations, the Lower chert-rich Monte-Christo Formation, the middle chert-poor Lyttleton Formation and the Upper chert-rich Eccles Formation. The Lyttleton Formation, with a lower silica content (0,1-4,5%) is most important for this quarry as it is mined for the metallurgical dolomite, and the Eccles Formation with a higher silica content (>4,5%), is mined for the building industry for aggregate (Umhlaba Environmental Consulting 2010).

The Zwartkop Dolerite Dyke compartmentalises the quarry into 2 compartments, the Aalwynkop and Erasmia compartments. The Zwartkop Dyke intruded as a result of the Pilanesberg Dyke Swarm and belongs to the Pilanesberg Province on the basis of age of intrusion and petrology (Verwoerd 2006). There is a clear dyke and fault which runs through the quarry.

9.3. Project Methodology

Geochemistry and isotopes are employed to infer movement of water through the subsurface. This, as well as rock mechanical and structural geological field description of the dolomite mine and the geomechanical properties of the wad and bedrock at the site, will allow for a detailed geological, geomechanical and hydrogeological conceptual site model to improve understanding.

All samples and field tests conducted are described below. Locations for field tests and water sampling positions are indicated on Figure 9-4.

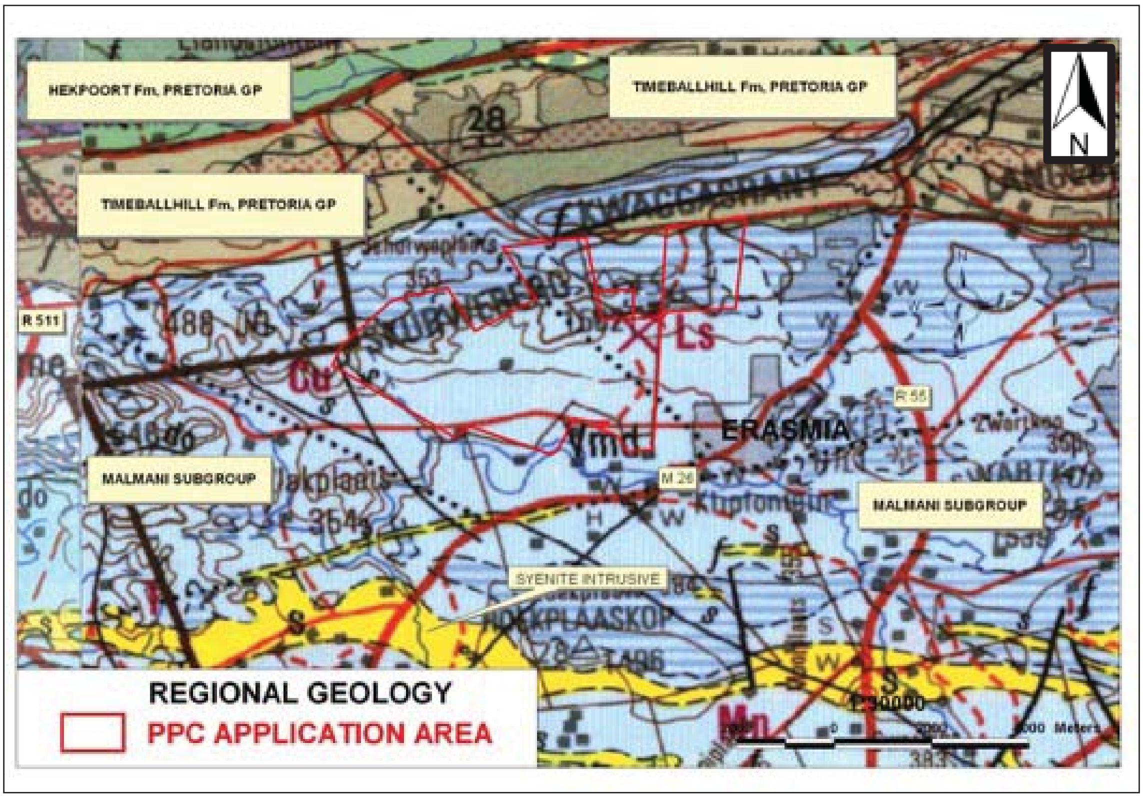


Figure 9-1. Locality and geology (1:250 000-scale geological map 2528 Pretoria).

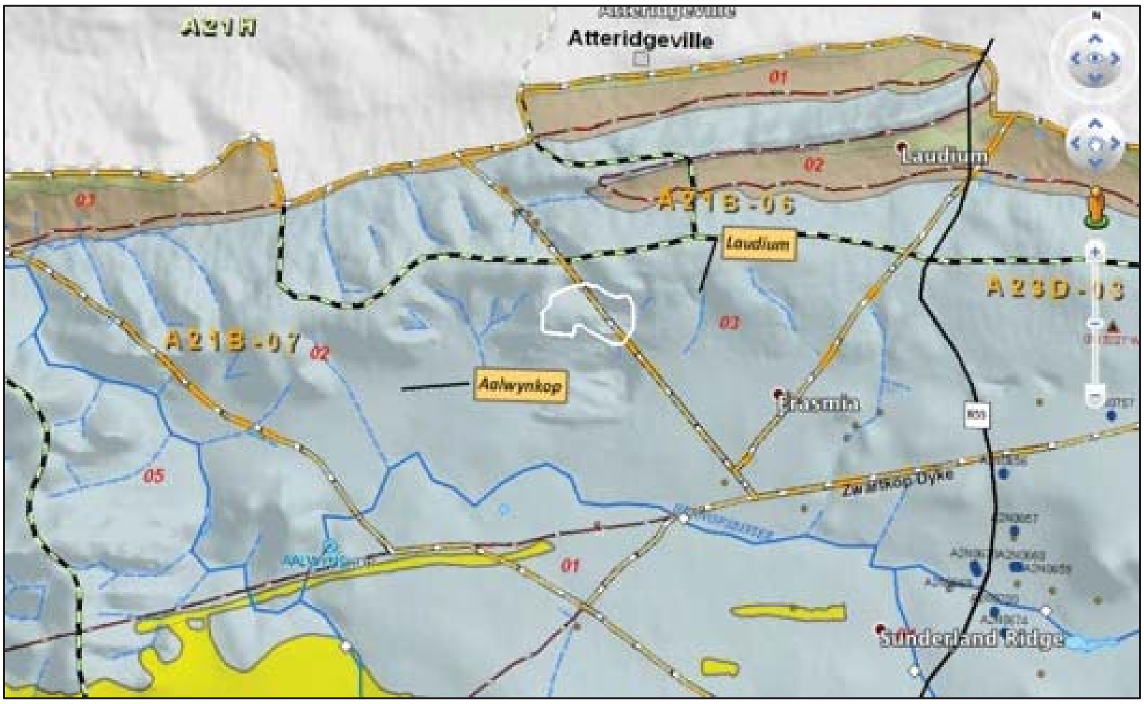


Figure 9-2. Dolomite compartments in relation to the study area (Holland et al. 2009).

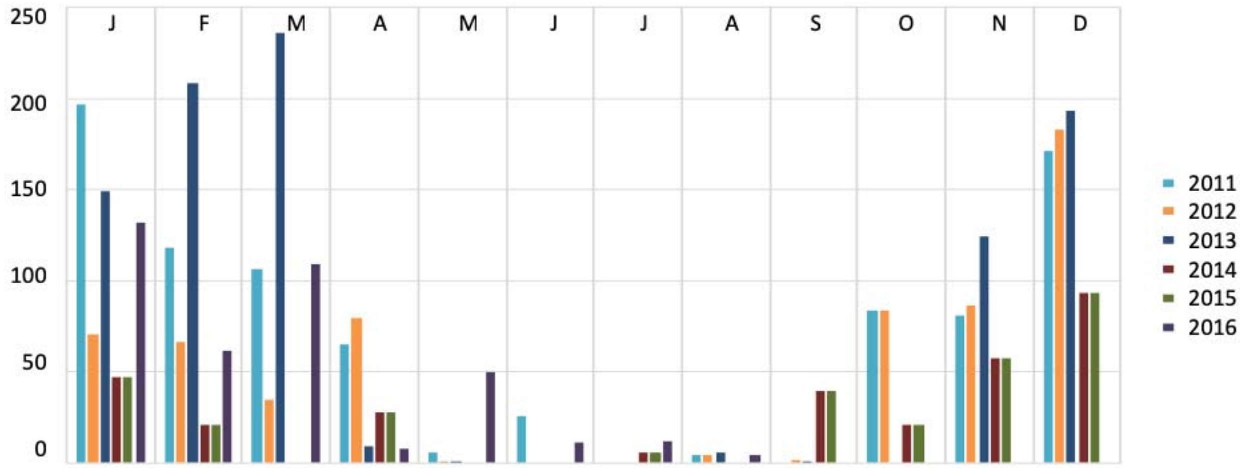


Figure 9-3. **Monthly rainfall for the period 2011-2016 (Irene Weather Station).**

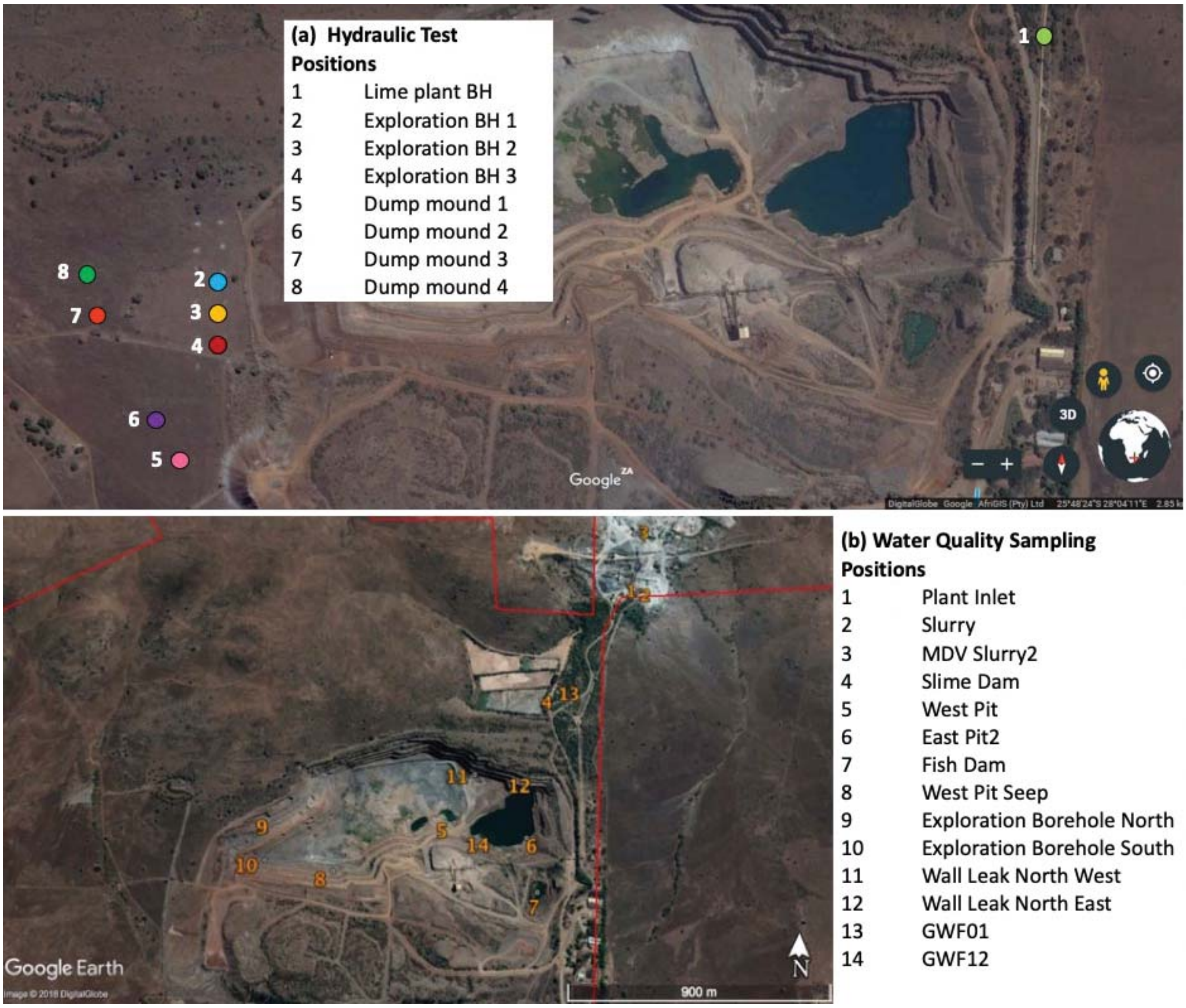


Figure 9-4. **Field test and water sampling positions (VZSA09).**

9.3.1. Water levels

Groundwater levels of the boreholes two boreholes (GWF01 and GWF12) in the study area were taken during the sampling period of April 2017 to September 2017. The third borehole in the study area, GWF13 was an artesian borehole during the sampling period therefor no water level data could be acquired for. Older water level data for all three boreholes in the study area was also acquired form Aquatico. These boreholes are monitored for water license purposes. The water levels for two exploration boreholes to the west of the study area were also taken by dip meter. As the mining progressed towards the west these boreholes were destroyed therefore only a few water levels where taken for the two exploration boreholes

9.3.2. Hydraulic tests

A number of field hydraulic tests have been conducted to infer hydraulic behaviour of the vadose zone. Percolation and infiltration tests were conducted according to applicable SANS or ASTM guidelines as detailed by Dippenaar et al. (2014). Test positions and tests conducted are shown in Figure 9-5 and Table 9-1.

Table 9-1. Hydraulic (percolation and infiltration) tests conducted (VZSA09).

Position	Locality	Number: percolation	Number: percolation	Total number
1	Lime plant BH	0	1	1
2	Exploration BH 1	1	1	2
3	Exploration BH 2	2	2	4
4	Exploration BH 3	1	1	2
5	Dump mound 1	1	1	2
6	Dump mound 2	1	0	1
7	Dump mound 3	1	1	2
8	Dump mound 4	1	1	2
TOTAL				**16**

9.3.3. Water sampling

In improving understanding of complex unsaturated flow systems through the karstic vadose zone, chemical and isotopic signatures of precipitation, soil moisture, groundwater and water from the pit lakes and dams are interpreted.

Water samples of several components in the study area were sampled monthly form April 2017 to September 2017. Rain water was also sampled in Monument Park Pretoria 15 km east of the study area from December 2016 until March 2019 (Figure 9-4; Figure 9-5). Samples retrieved are discussed below and are summarised in Table 9-2.

Rainwater

The rainwater of the region was measured and sampled on a similar basis as Chandra Mouli et al. (2005). A rain gauge was used for measuring and two 20 L buckets were used for ensuring enough sample could be collected for analysis as seen in Figure 9-6(a). The advantage of a simple rain gauge is that it is well calibrated by national weather services and no other equipment is required. However, the disadvantage of a rain gauge and the two 20 L buckets is that it requires daily operation and there is a risk of evaporation if the sample isn’t taken short after the rainfall. Therefore, the lids of the buckets were used to make a cone with a slit in to cover the bucket and the sampling of the rain water was done as soon as possible after the rain event. There was also a risk of water and air interaction in the sampling bottle during storage but this was minimised by keeping the sample in a fridge until analysis and by filling the bottles completely when possible.

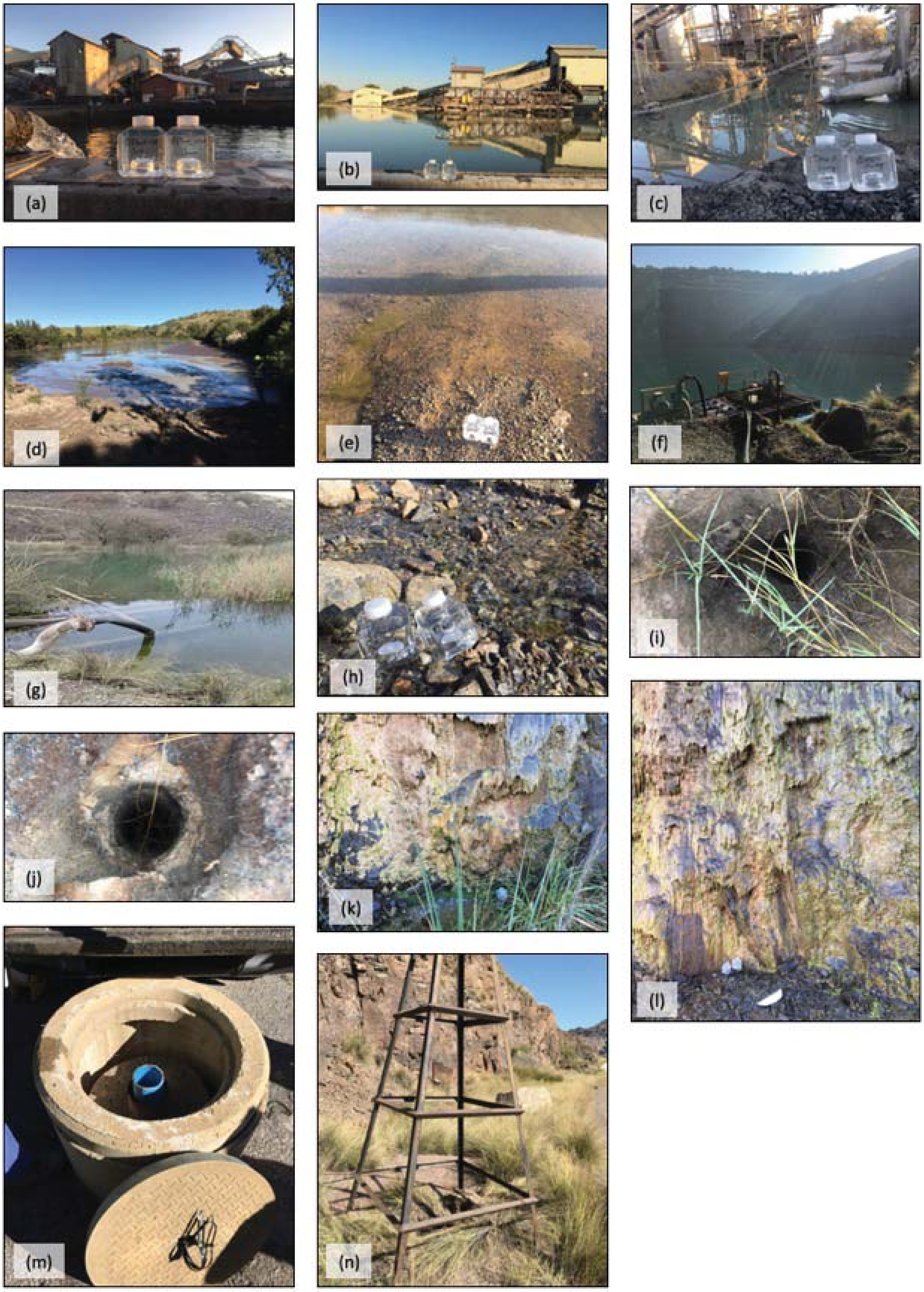


Figure 9-5. Sampling locations (VZSA09): Mooiplaas; (a) Plant inlet; (b) Slurry; (c) MDV Slurry; (d) Slime dam; (e)West pit; (f) East pit; (g) Fish dam; (h) West pit seep; (i) Exploration borehole north; (j) Exploration borehole south; (k) Wall leak north west; (l) Wall leak north east; (m) GWF01; (n) GWF12.

The sampling location of the rainwater was in Monument Park Pretoria 15 km east of the study area, which allowed easy and nearby access to the rain meter. This enabled more accurate and reliable sampling at a low cost. The rainfall data from the Irene weather station was used since the location of the rain meter didn't full fill the requirement of the IAEA/GNIP (International Atomic Energy Agency/Global Network for Isotopes in Precipitation) precipitation sampling guide. The rain was sampled after each rainfall event as of December 2016 till present and composite monthly samples was analysed for major chemical component and stable isotopes.

Table 9-2. Samples retrieved at VZSA09.

Position	Number of samples	Group
Plant inlet	7	Surface water
Slurry	7	Surface water
MDV Slurry	6	Surface water
Slime dam	6	Surface water
West pitlake	7	Surface water
East pitlake	6	Surface water
Fish dam	7	Surface water
West pit seep	3	Surface water
Exploration borehole North	2	Groundwater
Exploration borehole South	3	Groundwater
Wall leak north west	5	Groundwater
Wall leak north east	3	Groundwater
GWF01	6	Groundwater
GWF12	6	Groundwater
Rain water	6	Rain water
Total	80	-

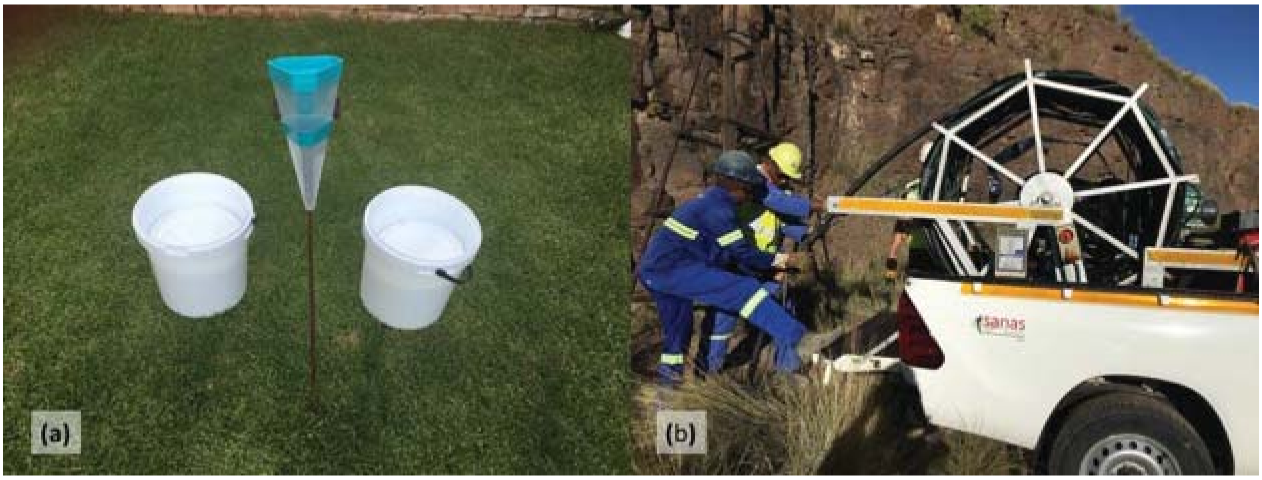


Figure 9-6. Sampling: (a) rain gauge and 20 litre water buckets for rainwater sampling; (b) purging of GWF12 (VZSA09).

Groundwater

The groundwater of PPC Mooiplaas is sampled monthly by Aquatico by use of a baler with no purging. However, during the first sampling session in April 2017 the two boreholes (GWF01 and GWF12) were purged before sampling as described by Weaver et al. (2007). Both of the borehole are extremely deep which, meant that a 100 m pump had to be used to purge the boreholes as seen in Figure 9-6(b). The depth of the boreholes made purging extremely expensive therefore it required re-examination into weather it truly was necessary is to purge. This was done by comparing the March 2017 chemistry analysis with that of the purged April 2017 chemistry analysis and the stable isotope data of the purged April 2017 results with the unpurged May 2017 data. It was found that the chemistry results of March 2017 and April 2017 and the isotopic results of April 2017 and May 2017 were very similar, therefor to save costs the rest of the sampling period no purging was done.

Surface water

There were four main surface water sources that were sampled: the processing plant, slimes dam, fish dam and the two pit lakes of the quarry. Grab samples were taken by hand in plastic bottles as described by Weaver et al. (2007).

Three other sources of samples were taken. The first is the west pit seep, this is water that seeps in to the west pit that appears and disappears in the south west corner of the west pit. The second is two exploration boreholes to the west of the pit that were filled with water viz. exploration borehole north and exploration borehole south. The last source are wall leaks that was sampled on the norther wall of the quarry. The one wall leak north west was sampled on the western side of the dyke that transacts the quarry and the other wall leak north east was sampled to on the eastern side of the dyke.

Duplicates and blank samples were present in each batch of chemical analysis to check the quality of the data. For the stable isotopes only duplicate samples were possible.

All the samples were analysed for the following:

- Alkalinity
- Chloride (Cl)
- Sulphate (SO4)
- Orthophosphate (PO4) as P
- Ammonium (NH4) as N
- Nitrate (NO3) as N
- Bromide (Br)
- Electrical conductivity (EC) @ 25°C, pH @ 25°C
- TDS
- Total Hardness
- Calcium (Ca)
- Potassium (K)
- Magnesium (Mg)
- Sodium (Na).

The chemical analysis was done by Aquatico that uses an automated spectrophotometer to analyse for alkalinity, Cl, SO4, PO4, NH4 and NO3. The metals like Ca, K, Mg and Na were analysed with an ICP-OES (Inductively Coupled Plasma-Optical Emission Spectroscopy).

Stable isotopes

All the samples were also analysed for deuterium and oxygen isotopes. The stable isotopes were analysed at the University of Pretoria with an instrument called the Los Gatos that uses a method called WS-CRDS (Wavelength-Scanned Cavity Ring Down Spectroscopy).

Data acquired

Older historic data was also acquired from Aquatico since they have been involved with PPC Mooiplaas groundwater monitoring since 2013. The sampling points they sample monthly is the ground water (GWF01, GWF12 and GWF02). GWF02 wasn’t considered part of this study since it is more than a km south of the study area. Other locations they sample on a quarterly basis include the two pit lakes the fish dam and several drinking water points on the site.

9.4. Results

9.4.1. Water levels

Water levels measured are shown in Figure 9-7 and summarised in Table 9-3. Levels for GWF01 is significantly more variable than for the shallower GWF02.

Table 9-3. Average groundwater level data.

	Average (m)	Minimum (m)	Maximum (m)
GWF12	3,78	3,15	10,51
GWF01	69,81	68,59	70,78

Figure 9-7. Groundwater levels for GWF01 and GWF12.

9.4.2. Hydraulic tests

Hydraulic test results are shown graphically in Figure 9-8. Results were interpreted for average rates for the entire dataset without skin effects (i.e. removal of initial data points from time=zero where plot slopes are notably different from later time data). Interpretations incorporated (i) all this data, (ii) average slopes between first and last data points representing the average slope, and (iii) average for the last time interval; i.e. last two data points (Table 9-5; Table 9-4).

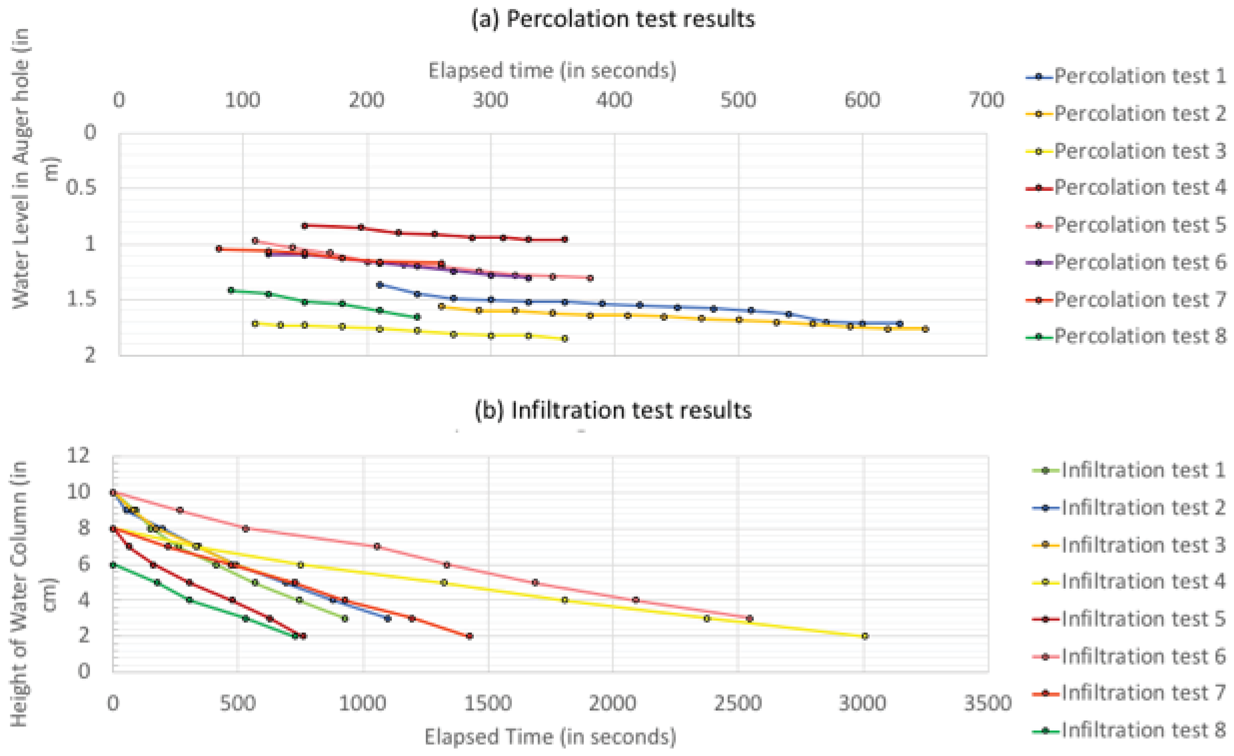


Figure 9-8. **Results from (a) percolation and (b) infiltration tests conducted at VZSA09.**

Table 9-4. **Infiltration test results in m/s (VZSA09).**

Position	(i) All data	(ii) General slope	(iii) Last increment	Average
1	8.72 x 10^{-5}	7.57 x 10^{-5}	5.46 x 10^{-5}	7.25 x 10^{-5}
2	7.85 x 10^{-5}	6.38 x 10^{-5}	4.63 x 10^{-5}	6.29 x 10^{-5}
3	8.11 x 10^{-5}	6.92 x 10^{-5}	4.22 x 10^{-5}	6.41 x 10^{-5}
4	8.81 x 10^{-5}	7.89 x 10^{-5}	7.35 x 10^{-5}	8.02 x 10^{-5}
5	2.93 x 10^{-5}	2.75 x 10^{-5}	2.17 x 10^{-5}	2.62 x 10^{-5}
6	-	-	-	-
7	4.26 x 10^{-5}	4.21 x 10^{-5}	4.35 x 10^{-5}	4.27 x 10^{-5}
8	5.68 x 10^{-5}	5.50 x 10^{-5}	5.03 x 10^{-5}	5.40 x 10^{-5}
AVERAGE	**6.64 x 10^{-5}**	**5.89 x 10^{-5}**	**4.75 x 10^{-5}**	**5.75 x 10^{-5}**

Table 9-5. **Percolation test results in m/s (VZSA09).**

Position	(i) All data	(ii) General slope	(iii) Last increment	Average
1	-	-	-	-
2	8.095 x 10^{-4}	8.33 x 10^{-4}	3.33 x 10^{-4}	6.59 x 10^{-4}
3	4.815 x 10^{-4}	5.6 x 10^{-4}	1.00 x 10^{-3}	6.81 x 10^{-4}
4	6.349 x 10^{-4}	6.19 x 10^{-4}	6.67 x 10^{-4}	6.40 x 10^{-4}
5	1.22 x 10^{-3}	1.22 x 10^{-4}	3.33 x 10^{-4}	5.59 x 10^{-4}
6	9.52 x 10^{-4}	1.00 x 10^{-3}	6.67 x 10^{-4}	8.73 x 10^{-4}
7	8.07 x 10^{-4}	7.22 x 10^{-4}	2.00 x 10^{-4}	5.76 x 10^{-4}
8	1.60 x 10^{-3}	1.6 x 10^{-3}	2.00 x 10^{-3}	1.73 x 10^{-3}
AVERAGE	**1.97 x 10^{-3}**	**2.07 x 10^{-3}**	**7.43 x 10^{-4}**	**8.17 x 10^{-4}**

9.4.3. Water sampling

The laboratory data were assessed as follows:

- With each batch of chemical and isotopic samples a duplicate sample were also included. The results for the duplicate samples were generally consistent and resulted in a relative percent difference (RPD) of less than 10%.
- Each batch of chemical analysis also included a blank sample of deionised water, and the results tended to extremely low compared the all other results.
- The cation-anion charge balance of the water analyses is variable depending on the concentration assumed for those parameters below the laboratory detection limit. In general, the cation-anion charge balance was acceptable.
- Based on the above, the laboratory data are considered acceptable for the purposes of this assessment.

The isotope data obtained from all samples are shown in Figure 9-8. The isotopic data from the Pretoria GNIP (Global network of Isotopes) station was used to obtain a more localised meteoric water line viz. PMWL (Pretoria meteoric water line). The deuterium excess was assigned as 11.8% and is assumed to indicate the initial composition of the evaporated water.

- The $\delta^{18}O$ range from -9.9‰ to 3‰
- The δD range from -72.6‰ to 10.2‰

The isotopes show an evaporation trend especially for the slimes dam which corresponds with the circumstances of the slime dam. Some rainfall events could also be used for tracing purposes as the rainfall sample for May 2017 have very distinct isotopic signatures of -72‰ of δD and -9‰ $\delta^{18}O$.

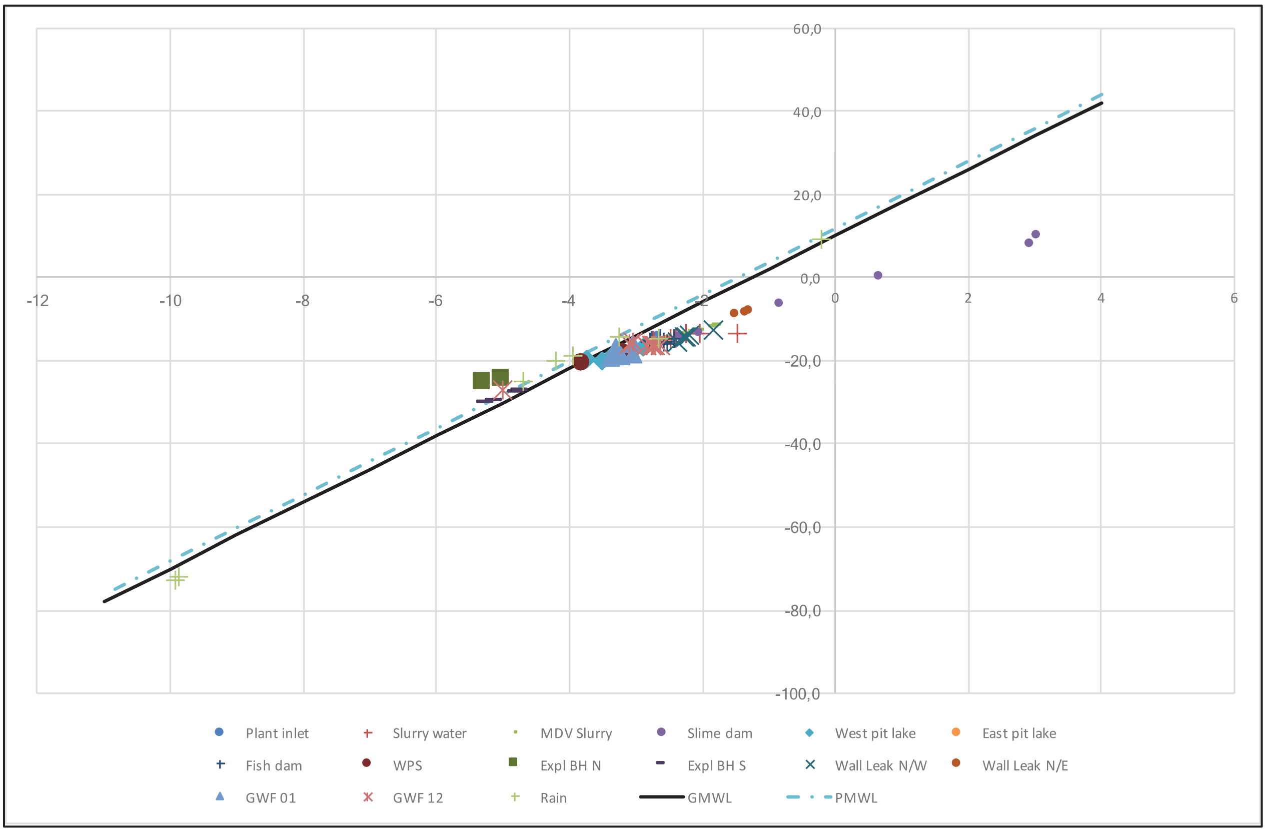


Figure 9-9. **$\delta^{18}O$ vs. δD of samples relative to global meteoric water line (GMWL) (Craig 1961) and long-term Pretoria meteoric water line (PMWL) (Meyer 2014) at VZSA09.**

10. VZSA10: DOLOMITE BEDROCK

Riaan DE KOCK, Freddy MTHOMBENI, Duan SWART, J Louis VAN ROOY & Matthys A DIPPENAAR

10.1. Motivation for Study

This research aims to better understand the geomechanical and hydrological behaviour of dolomite bedrock, notably with different compositions of different formations occurring in different hydrometeorological regions of South Africa.

The data and interpretation of bulk of this study is contained in De Kock (2018; honours project), with contributions contained in Swart (2019; master's dissertation).

10.2. Methodology

The study methodology was twofold, namely (i) Mooiplaas Mine and (ii) Stratigraphical Transects.

10.2.1. Mooiplaas Mine

Firstly, grab samples were collected from the Mooiplaas Dolomite Mine. These were analysed. The porosity of the dolomite rock samples was calculated from the pore volume (V_V) (determined from the Saturation method) and the bulk volume (V) (determined from the Buoyancy method).

The Schmidt Hammer Rebound test produced the Schmidt hammer rebound (SHR) values were determined using a Schmidt Hammer in the field. The uniaxial compressive strength of the rocks was determined from the published index-to-strength equations (Sachpazis 1990; Kahraman 2001; Shalabi 2007).

The slake durability test was conducted on the collected rock samples using tap water and spring water (pH = 5.1). For tap water used as slaking fluid, the Initial weights of the samples were taken as shown in the Table 8. Thus the various percentage of retention of the samples was obtained. It was observed that the rock sample percentage retention after the 1st cycle ranged between the values of 99.40% to 99.96% with an average of 99.67%. While after the second cycle of the slake durability test it was found that the rock sample retention percentages ranged from 99.02% to 99.89% with an average of 99.44%.

10.2.2. Stratigraphical Transects

Rock samples of the Malmani Subgroup were collected from stretches of road along the R511 (Hartbeespoort to Diepsloot), R512 (Pelindaba to Lanseria) in Gauteng, the R533 (Graskop to Pilgrim's Rest) in Mpumalanga, N4 at Dinokana (North West), south of Thabazimbi, and along the R37 and R579 at Chuniespoort in Limpopo. Dolomite bedrock from Aha Hills and Gcwihaba Caves in the Ngamiland District of Botswana were also analysed. Sampling locations are summarised in Table 10-1 to Table 10-6.

Table 10-1. Sampling positions: R511 (VZSA10).

Sample	Location	Comment
R511-1	25°52'6.90"S, 28° 0'45.42"E	Few samples. Granite-Dolomite Contact. Excavated/deposited shale/slate present. Elephant weathering. Soil a combination of granite and dolomite residuum. Crest. No soil rock interface samples
R511-2	25°51'13.80"S, 28° 0'3.00"E	More samples. Elephant dominant, some karts, minimal stromat. Soil is light brown sand silt. Moving away from granite. Some chert layering visible. Interesting textures. Nice sample with clear dolomite dissolution. Flat area. Only rock-soil interface samples.
R511-3	25°50'56.29"S, 27°59'42.62"E	Large boulders excavated. Elephant, smooth and karst present. Same as R511-2. Midslope. Rock soil interface sample.
R511-4	25°51'42.07"S, 28° 0'28.02"E	Enormous excavated boulders that have a purplish tinge to them. Granite dolomite mixed residuum. One interesting sample which is either a precipitate or dissolution horizon on dolomite, looks like pumice.
R511-5	25°50'34.33"S, 27°59'7.51"E	Few samples. Difficult to sample. More chert rich. Mid slope
R511-6	25°50'18.87"S, 27°58'35.06"E	Outcrop on side of road. Thick dolomite layer, thin chert layer. Dolomite on top of "syenite" dyke. Elephant skin. Highly weathered. Dolomite becoming pink. Rock soil interface samples
R511-7	25°49'21.44"S, 27°58'29.05"E	No surface sample. Large transported boulders. Very pink. Elephant weathering. Much less granitic soil. No soil-rock interface sample.
R511-8	25°48'58.77"S, 27°59'3.98"E	Huge dolomite ridges. Dips at 10-15 degrees. Many samples also from rock soil interface. Some elephant, mostly karst. Found a scorpion. Google earth street view image is old. A lot of road cuts have been made. Typical bread and butter structure (alternating dolomite and chart layers, both having the same thickness)
R511-9	25°48'20.59"S, 27°59'28.29"E	Same as R511-8
R511-10	25°48'1.52"S, 27°59'34.47"E	Dolomite-Shale contact

Table 10-2. Sampling positions: R512 (VZSA10).

Sample	Location	Comment
R512-1	25°48'52.86"S, 27°53'40.62"E	Elephant skin weathering. Lots of rock soil intersect samples Highly dissolved dolomite Sampled from roadcut Folded
R512-2	25°49'16.26"S, 27°53'32.10"E	Elephant skin weathering Bread and butter dolomite and chert Stromatolite banding Folded
R512-3	25°49'29.11"S, 27°53'29.19"E	Same as 2
R512-4	25°49'44.80"S, 27°53'24.21"E	Same as 3
R512-5	25°50'4.03"S, 27°53'9.47"E	Same as 4. Dolomite layer becoming thicker, chert becoming thinner
R512-6	25°50'22.70"S, 27°53'2.86"E	Much less dolomite exposed. Soil becoming more granite residuum rich. Crest
R512-7	25°50'33.83"S, 27°53'0.61"E	Chert thinning out
R512-8	25°50'37.43"S, 27°52'59.68"E	Good roadcut. Sample from rock soil interface. Thick dolomite thin chert
R512-9	25°50'51.09"S, 27°52'59.87"E	Same as 8
R512-10	25°51'10.34"S, 27°53'2.31"E	Change geology from dolomite to “granite”
R512-11	25°53'42.00"S, 27°53'15.36"E	First proper evidence of geology change

Table 10-3. Sampling positions: Dinokana (VZSA10).

Sample	Location	Comment
DIN01	25°27'55.08"S, 25°48'3.42"E	Dolomite and Chert
DIN02	25°28'4.91"S, 25°47'36.96"E	Dolomite and Chert with Manganocrete
DIN03	25°28'22.37"S, 25°47'32.17"E	No Chert or very thick Chert and Dolomite bands
DIN04	25°28'23.16"S, 25°47'32.28"E	With Chert. At foot of crest
DIN05	25°28'25.50"S, 25°47'31.85"E	Abundant chert bands. Crest
DIN06	25°28'7.75"S, 25°47'28.50"E	Calcrete and Manganocrete present. Lesser chert. Look at different weathering surfaces
DIN07	25°26'28.75"S, 25°46'51.10"E	Lesser chert. Flat area. Smooth weathering surface
DIN08	25°26'24.83"S, 25°46'34.00"E	Lesser Chert. Flat area. Angular weathering surface. Manganocrete
DIN09	25°26'6.04"S, 25°46'39.54"E	Stromatolites in chert. Thin Chert bands. Angular weathering surface. Flat area. Abundant QTZ veins
DIN10	25°26'4.27"S, 25°46'39.68"E	"Contact"l Dip Direction= 60 deg; Dip = 10 deg Flat area. Minor chert
DIN11	25°25'44.94"S, 25°46'46.81"E	Sharp weathering. Thick chert bands. Foot of crest
DIN12	25°25'48.54"S, 25°46'23.02"E	Elephant skin A Angular B Large Outcrop
DIN13	25°25'45.19"S, 25°45'56.41"E	Chert band. One has course-grains but smooth surface The other is angular
DIN14	25°24'46.15"S, 25°45'1.73"E	Elephant A. Mid crest. Chert bands. Lesser chert
DIN15	25°26'25.51"S, 25°46'48.54"E	Flat. Thick chert bands. Manganocrete present
DIN16	25°27'29.16"S, 25°47'58.09"E	
DIN17	25°27'35.87"S, 25°49'25.86"E	
DIN18	25°31'7.54"S, 25°53'58.63"E	Asbestos? flat Chert rich
DIN19	25°31'46.34"S, 25°53'44.95"E	Asbestos?
DIN20	25°31'16.79"S, 25°52'21.97"E	No asbestos
DIN21	25°31'17.83"S, 25°52'32.99"E	Angular. No asbestos

Table 10-4. Sampling positions: Sabie (VZSA10).

Sample	Location	Comment
First stop	25°22'31.99"S, 30°41'49.80"E	Variably weathered chert rich, stromat rich, well bedded, folded, colluvium. From Sudwala caves
Second stop	25°22'7.75"S, 30°41'57.43"E	More intact but same as 1. WAD present From Sudwala caves
Third stop	25°10'8.79"S, 30°46'0.78"E	Jointed, dark grey very hard
R533-1	24°55'42.80"S, 30°47'1.39"E	Foot of slope. Not the contact between dolomite and QTZ. Karstic weathering
R533-2	24°55'30.22"S, 30°46'12.80"E	Rounded/sub-angular colluvium, dark
R533-3	24°55'16.01"S, 30°46'10.09"E	Colluvium. Large rounded boulders

R533-4	24°55'2.30"S, 30°45'55.60"E	Roadcut exposed slightly weathered dol with alternating chert rich layers. Stromats present
R533-5	24°53'57.79"S, 30°45'8.32"E	Roadcut exposed slightly weathered dol with alternating chert rich layers. Stromats present
R533-6	24°53'8.60"S, 30°44'39.50"E	Large Boulders of layered chert and dolomite. Large stromat domes. WAD present

Table 10-5. Sampling positions: south of Thabazimbi (VZSA10).

Sample	Location	Comment
TB 01	25°13'18.90"S, 27°35'35.40"E	
TB 02	25°13'17.60"S, 27°35'38.20"E	
TB 03	25°13'17.20"S, 27°35'39.30"E	Contact, darker
TB 04	25°13'18.20"S, 27°35'40.30"E	
TB 05	25°13'16.20"S, 27°35'36.40"E	
TB 06	25°13'12.30"S, 27°35'26.90"E	
TB 07	25°13'17.20"S, 27°35'32.50"E	Smooth, almost plate-like, looks like slab
TB 08	25°13'19.50"S, 27°35'31.20"E	
TB 09	25°13'21.80"S, 27°35'30.30"E	

Table 10-6. Sampling positions: Chuniespoort (VZSA10).

Sample	Location	Comment
R37-1	24°13'27.24"S, 29°29'51.30"E	Mixed zone of various types of Dolomite
R37-2	24°13'39.60"S, 29°29'48.96"E	Well jointed and bedded Clear chert layers with equal dolomite thickness
R37-3	24°14'4.80"S, 29°31'7.68"E	Foot of slope. Multiple types of Dolomite, chert-rich and poor
R37-4	24°14'11.52"S, 29°31'21.72"E	Bread and butter becomes more prominent
R37-5	24°14'44.10"S, 29°32'9.42"E	Only bread and butter chert-rich Dolomite
R37-6	24°15'9.72"S, 29°32'25.50"E	Thin bedding. Manganese present
R579-1	24°17'5.22"S, 29°27'54.42"E	Elephant skin weathering. Bread and butter chert-rich dolomite

Sampling was from outcrops and based on visual distinction. It is assumed that these visual changes may be linked to changes in formations and/ or behaviour. The samples were collected from near surface fresh rock, with some surface indications of weathering effects.

The geochemistry of the 26 samples was obtained from X-Ray Fluorescence (XRF) and all samples were also exposed to non-standardised dissolution tests. The dissolution test was conducted on identical pieces of the 26 samples sent for XRF analysis. This was done in order to reduce chemical differences between the XRF samples and dissolution samples.

Further evaluation of possible chemical differences was conducted by determining the density difference between XRF samples and dissolution samples. Densities were determined by weighing each sample and determining the volume of each sample using Archimedes' water displacement method.

The dissolution test procedure was carried out with a 10% HCl solution, stored indoors for 24 hours to achieve a temperature of 26°C prior to the commencement of the experiment. Each sample was fully submerged and removed after 10 minutes, rinsed with water to prevent any further dissolution reactions, placed in an oven to dry and then weighed. The changes in weight related to the 10-minute dissolution were compared to the original sample weights and comparative rates of dissolution between samples determined.

The primary objective of the dissolution test is to determine the properties that govern dissolution rates, and ultimately whether there are any correlations between the different formations within the Malmani Subgroup and dissolution rates.

10.3. Results

10.3.1. Mooiplaas Mine

Results are indicated in Table 10-7.

Table 10-7. Porosity and UCS values (VZSA09;VZSA10).

Sample No.	Porosity (%)	IS (50) (Mpa)	UCS (MPa)			Av_SHR (MPa)	UCS (MPa)		
			(Singh et al. 2012)	(Akram & Bakar 2007)	(Kahraman 2001)		(Sachpazis 1990)	(Kahraman 2001)	(Shalabi et al. 2007)
L2	0.45					55.33	169.86	15.12	130.48
L3	0.15	6.36	144.37	158.25	63	46	129.82	13.27	100.61
L4	0.15	6.4	145.28	159.16	63.33	46.33	131.25	13.33	101.68
L5		9.18	208.39	222.53	86.71	46.67	132.68	13.4	102.74
L6	0.16	6.63	150.5	164.41	65.27	48.67	141.26	13.78	109.14
L7	0.19	7.09	160.94	174.89	69.14	58	181.3	15.7	139.01
L8	0.15	6.62	150.27	164.18	65.18	50	146.98	14.04	113.41
L9	0.09	4.53	102.83	116.54	47.61	52	155.56	14.43	119.81
L10		6.44	146.19	160.08	63.67	47.33	135.54	13.52	104.88
NR1	0.26	6.86	155.72	169.65	67.2	43.67	119.81	12.84	93.14
NR2	0.2	9.27	210.43	224.58	87.47	44	121.24	12.91	94.21
NR3	0.17	5.29	120.08	133.86	54	40.67	106.94	12.32	83.54
1	0.39	6.22	141.19	155.06	61.82	38.67	98.36	11.98	77.14
2	0.27	6.62	150.27	164.18	65.18	35.67	85.49	11.48	67.54
3	0.29	2.87	65.15	78.71	33.65	37.67	94.07	11.81	73.94
4		3.58	81.27	94.89	39.62	42.67	115.52	12.67	89.94
NL1	0.15	5.27	119.63	133.41	53.83	37.67	94.07	11.81	73.94
NL2	0.51	4.82	109.41	123.15	50.05	42.67	115.52	12.67	89.94
NL3	0.12	6.82	154.81	168.74	66.87	41.67	111.23	12.49	86.74
Min	0.09	2.87	65.15	78.71	33.65	35.67	85.49	11.48	67.54
Max	0.51	9.27	210.43	224.58	87.47	58	181.3	15.7	139.01
Mean	0.23	6.16	139.82	153.68	61.31	45.02	125.61	13.13	97.47

10.3.2. Stratigraphical Transects

The XRF results show a large variation in percentages of SiO_2 (0.604-98.597%), CaO (0.037-52.357 %) and MgO (0.015-21.744 %), possibly due to some chert being present in the samples, and that not all the samples were from dolomite having the typical Ca/Mg ratio. Two samples have particularly high SiO_2 contents of 96% (R512-4) and 98.5% (R37-2) respectively, with the remainder of the samples having much lower values. The LOI (Loss on Ignition) ranges from 23.732 to 46.508% with an average of 39.549%, and likely represents the carbonate fractions of the samples.

The largest contributor to impurities is SiO2, with sample R37-6 being an outlier sampled from the Banded Iron Formation of the Penge Formation. Samples R511-4 and DINO 2 have high Mn_3O_4 content at 3.55% and 3.123% respectively.

It is difficult to determine from which formations the samples originated as no baseline data are available for the various formations of the Malmani Subgroup. The distribution of the formations in North-West was aligned with the 1:210 000 North-West Dolomite Management Unit's map from the Department of Water and Sanitation (Holland, n.d.), and in Gauteng along the R511 and R512 it was taken from the map (Figure 14) by Obbes (1994).

Dissolution rate results are assumed to be determined by the chemical compositions of the various samples due to constant temperature, pH, sample volumes, time elapsed and P_{CO2} (Figure 10-1).

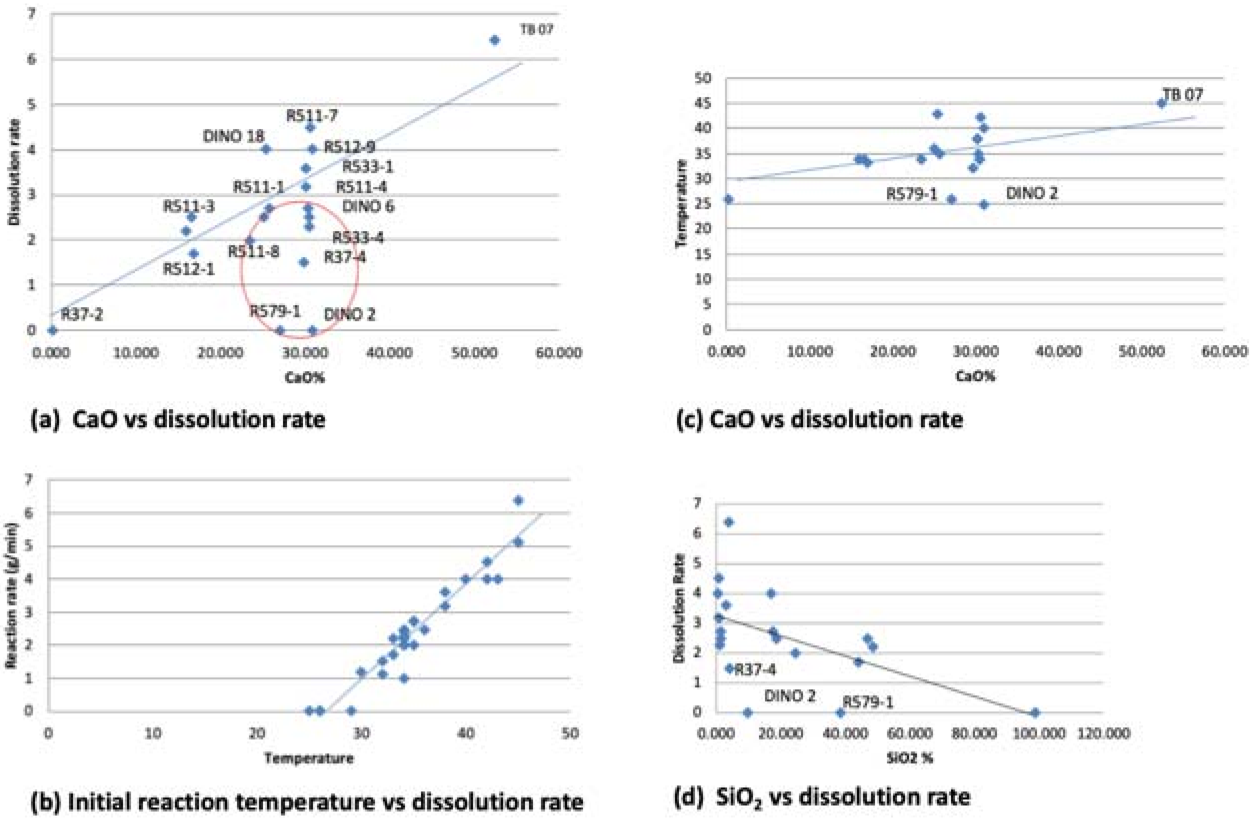


Figure 10-1. **Results from dissolution tests (all dissolution and reaction rates in g/min; all CaO and SiO_2 in weight percent); VZSA10.**

The tests were initiated at 26°C, but as soon as the reactions started the temperature of the solution increased significantly as the reaction between dolomite and acid is exothermic (Singurindy et al. 2003). There is also a correlation between initial temperatures and degree of effervescence. The higher the degree of effervescence, the hotter the initial temperature of the dissolution test. Samples with higher effervescence activity show a smaller variation between initial and final temperatures from the start to the termination of the test (samples R511-7, R512-9, DINO 18, and all TB samples). A correlation also exists between the CaO content and dissolution rate, effervescence intensity and reaction temperature. These correlations may be explained by the higher concentrations of Ca^{2+} compared to that of Mg^{2+} (Button 1975).

Ca^{2+} enters the solution more readily than Mg^{2+} possibly due to the difference in ionic radius (Ca^{2+}=1.00 µm, Mg2+=0.72 µm) as explained with Fajan's Rules (Singurindy et al. 2003). This explains why samples with a higher CaO percentage dissolve quicker (e.g. TB 07). Based on this it can also be seen that it is the Ca^{2+} cations which would dictate saturation with a much smaller effect from Mg^{2+} cations. Mg^{2+} also adds to the dissolution rate, but the higher the Mg^{2+} concentration, the lower Ca^{2+} availability per surface area, which results in slower dissolution rates.

Button (1975) concluded that acid-testing of rock samples is a reliable method of identifying low-Mg, high-Ca carbonates. Dolomitization, the process whereby limestone undergoes cation exchange reactions when in contact with Mg-rich water in a shallow marine environment, changed large parts of the original limestone of the Malmani Subgroup to dolomitic limestone. These limestones that did not fully dolomitize and parts of the rock are still rich in Ca^{2+} (Button 1972).

A different reason as to why certain samples contain more Ca2+ than others is due to a process known as dedolomitization whereby dolomite undergo reactions with Ca2+ -rich fluids to form limestone, essentially the opposite of dolomitization

Dedolomitisation occurred in varies locations in the Malmani Subgroup, e.g. Mpumalanga and North-West provinces (Richardson 2013) where it was caused by the intrusion of the Bushveld Igneous complex (Richardson 2013) and the Pilansberg Alkali Ring Complex (Button 1976). There are also multiple constituents that may decrease the dissolution rate.

According to Letterman (1995), insoluble impurities reduce the reaction rate of a carbonate rock as the impurities reduce the area available to dissolution and it can be assumed that chert-rich samples will dissolve slower than the chert-poor samples. This may explain why sample DINO 2 did not dissolve at all and most chert-rich samples showed slower dissolution rates compared with the average rate.

There are a number of exceptions to the rule amongst the 26 samples tested and the general trend of increased reaction rates with a CaO% increase (Figure 15) is not always true. Samples DINO 2 and R579-1 were both covered in a precipitation which was not detected in the XRF analysis and R37-4, R511-8 and R533-4 (circled in red on Figure 150 had thick layers of chert on the top and bottom thereby reducing the faces available for dissolution to 4 instead of 6. The reaction rate for DINO 18 is abnormally high due to a thick layer of CaCO3 which ran through the sample and once again was not specifically analysed during the XRF.

The generally expected trend of increased chert content versus decreased dissolution rate is evident in Figure 10-1(d), but again with a number of exceptions. Anomalies again included samples DINO 2, R579-1 and R37-4 due to reasons explained previously.

11. VZSA11: RESIDUAL DOLOMITE AND WAD

Duan SWART, J Louis VAN ROOY & Matthys A DIPPENAAR

11.1. Motivation for Study

This study aims to improve understanding regarding the geomechanical and hydrological behaviour of wad in relation to the geochemical composition and the microstructure, and to determine the limits of geotechnical testing on this material. The structure and properties of wad are highly dependent on the parent material's stress history and the history of the soil itself.

The data and interpretation of bulk of this study is contained in Swart (2019; master's dissertation).

11.2. Methodology

Five undisturbed, Shelby or block samples, and eight disturbed samples, at each locality, were taken from accessible areas at various excavations, sinkholes, road cuts, and abandoned and active mines. The vast sampling area allows for comparing structured, non-structured and reworked wad as well as material from slightly different climates. A summary of the samples is provided in Table 1. A number of tests were conducted to expand the understanding of residual dolomite, including dispersion, grading, Atterberg limits, chemical analyses, triaxial shear and permeability, and field and lab permeability tests, along with photographs of the soil taken at various magnitudes.

Table 11-1. Samples retrieved for VZSA11.

Name	Fabric	Sample type	General locality	Province
Highveld	Structured	Block	Excavation south of Pretoria	Gauteng
Sudwala caves	Structured	Disturbed	Excavation at Sudwala caves	Mpumalanga
R533	Non-structured	Disturbed	Road cut near Pilgrims Rest	Mpumalanga
Doornhoek	Non-structured	Shelby	Old mine south of Zeerust	North West
Mooiplaas	Reworked	Shelby	Active mine near Laudium	Gauteng
Bokkraal	Reworked	Shelby	Old mine south of Zeerust	North West
Carletonville	Reworked	Block	Sinkhole at Khutsong	Gauteng
South Downs	Reworked	Disturbed	Sinkhole at South Downs College	Gauteng

11.2.1. Triaxial tests

60 mm diameter thin wall Shelby tubes were pushed into various soil faces and excavations by hand to retrieve the undisturbed Bokkraal, Mooiplaas and Doornhoek wad samples. The Shelby tube samples were carefully extruded and cut into 50 mm diameter and roughly 100 mm to 150 mm high cylindrical samples at the University of Pretoria Civil Engineering Laboratory. The ASTM D4767 report is the standard used for the triaxial tests. The samples were encased in a thin rubber sheath with porous disks on either end and placed into the triaxial cell and secured by two rigid plates. The cell was then filled with water, and the fluid exerted a hydrostatic static compressive stress around the sample. Mooiplaas-A, Mooiplaas-B and Mooiplaas-C samples underwent consolidated-undrained (CU) triaxial tests at 50 kPa, 100 kPa and 200 kPa confining pressure respectively, and each was sheared at a rate of 0.01 mm/min after being consolidated at 100 kPa isotropic confinement. Side drains were placed on the Mooiplaas-A sample whereas the rest of the samples had no side drains. CU tests were done to better understand the stress path and

behaviour of the material by recording the pore water pressure readings during the application of the deviator stress. Three triaxial consolidation and permeability tests were conducted on the Mooiplaas-D, Bokkraal and Doornhoek samples at 100 kPa confining pressure.

11.2.2. Crumb test

The crumb test procedure is described in Maharaj (2013) and was used due to its simplicity and reliability for unique soils. Undisturbed 'crumbs', 40 mm in diameter, were taken from each sampling locality and each one was dropped gently into a jar of distilled water as not to disturb the water. Readings were taken at 10 minutes, 1 hour and 2 hours to confirm if the material was either dispersive or non-dispersive.

11.2.3. XRF and XRD

The geochemical composition of the samples were analysed at the University of Pretoria. Samples from each locality were milled and prepared in the lab. The XRF (X-Ray Fluorescence spectroscopy) samples were analysed using the ARL Perform'X Sequential XRF instrument and Quantas software. The XRD (X-Ray Diffraction) samples were prepared according to the standardized Panalytical back loading system, which provides nearly random distribution of the particles. The samples were analysed using a PANalytical X'Pert Pro powder diffractometer in θ–θ configuration with an X'Celerator detector and variable divergence- and fixed receiving slits with Fe filtered Co-Kα radiation (λ=1.789Å). The phases were identified using X'Pert Highscore plus software. The relative phase amounts (weight%) were estimated using the Rietveld method.

11.2.4. Foundation indicators

Three disturbed samples from Mooiplaas, Bokkraal and Doornhoek, were sent to BM du Plessis Civil Engineering labs for grading and Atterberg limits analyses following SANS 3001 series as the standard proceed. Cone penetrometer test method, following the procedure stated in the BS: Part2: 1990, was used to determine the liquid limit of the wad.

11.2.5. Stereomicroscope

A stereomicroscope is an optical microscope (model: Ziess Stereo Discovery V20) designed for low magnification for observation of a sample's microstructure, typically using reflected light from the surface. Undisturbed wad samples and samples post shearing and consolidation were analysed at x20, x45, x70, x94 magnification and photographs of the most representative sections of the samples were also taken at these magnifications.

11.2.6. Scanning Electron Microscope (SEM)

The morphology of undisturbed samples was observed using a Ziess Gemini SEM under different magnifications best suited for the material. Investigating the microscopic structure of the soil grain may build an understanding as to where certain minerals are present and to better establish the governing factors of the high and variable liquid limits.

11.2.7. *Permeability tests*

Falling head tests were conducted on several samples in order to establish the hydraulic conductivity (K), or permeability, of the soil. Disturbed fine-grained samples were packed in a Perspex column, sandwiched between two coarse-grained, 30 mm length, quartz filters. The coarse quartz filters are used to ensure material is not entrained when water is introduced and will not inhibit flow. After placing the sample between the filters, the column is gently tapped to achieve denser packing. The samples averaged in length between 130 mm and 150 mm, with a diameter of 60 mm. The initial stage entails introducing an influx of water large enough to create a significant head, which is allowed to flow through the sample with the intent of creating uniform conditions, partial consolidation and partial saturation throughout the length of the sample. Once all the initial gravitational water has drained, the test is started by adding water, increasing the head to that of the initial water influx, and allowing the water to drain through the material. The drop in head is measured every 15 minutes until all the gravitational water has flowed through. The drop in head is placed against time to ensure steady has been reached and to determine the hydraulic conductivity of the remolded material.

11.2.8. *Specific gravity*

The specific gravity of each sample was obtained by relating the weight of oven dry soil to the weight of water as stipulated by the ASTM D5550-14 using Micromeritics AccuPyc II 1340 Pycnometer. This method uses Helium gas to create a vacuum to measure the particle density.

11.3. Results

11.3.1. *Triaxial tests*

Triaxial consolidation and triaxial permeability tests were done on the Doornhoek wad and Bokkraal road-cut wad samples. The Mooiplaas samples were successfully extruded placed into the cell and underwent CU triaxial shearing and permeability tests. The samples' stress-strain relationships follow the idealised elastic-strain softening plastic model, which indicates a reduction in strength after failure as strain increases (Knappett and Craig 2012) as shown in Figure 11-1(a). Figure 11-1(b) shows that the Mooiplaas samples behaved as normally consolidated fine-grained soil and Figure 11-1(c) gives the effective stress path of the material that contracted during shearing. The triaxial test results are summarised in Table 11-2.

Table 11-2. Triaxial test results (VZSA11).

Samples	Dry density (kg/m³)	E-moduli (MPa)	Shear strength	Permeability (m/s)
Mooiplaas	1034-1751	3-28	c' = 6,5kPa ϕ' = 14,2°	9.00×10^{-7}
Bokkraal	1237	-	-	2.80×10^{-6}
Doornhoek	539	-	-	2.70×10^{-6}

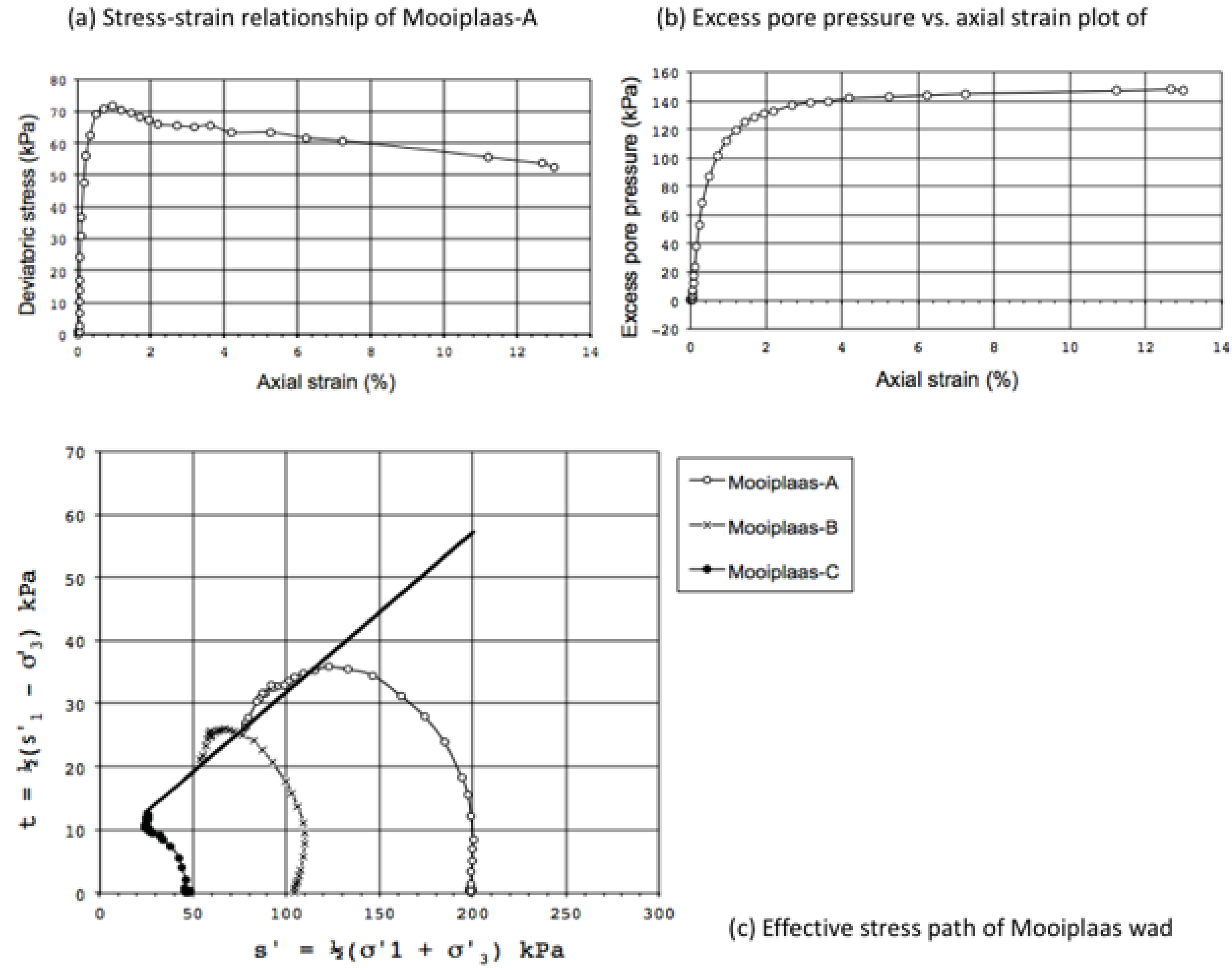


Figure 11-1. **Mooiplaas: (a) stress-strain graph showing sample underwent strain softening post failure; (b) pore pressure-strain relation showing the material contracted and behaved as normally consolidated clay; (c) effective stress path of the material in an s'- t space revealing the material contracted during shearing.**

The Bokkraal Shelby samples obtained from the abandoned underground mine shaft were successfully extruded; however, when the sample was being prepared for the triaxial cell, problems were encountered when attempting to cut the sample. The Bokkraal sample from within the underground mine was highly fissured with galena being present in the fissures. Therefore, the soil is not a representative sample, as the lead sulphide mineral would have taken up the load during the triaxial shear testing. Thus, the sample was not used for triaxial testing. The samples taken from the road cut at Bokkraal was sampled at a very shallow depth (±50 cm) to surface. It was observed when extruding the three Shelby samples that the soil was desiccated and highly reworked. Consequently, a sample with insufficient height for shearing was successfully extruded out of the Shelby tubes.

The soil excavation face at Doornhoek was slightly moist and stiff to very stiff in some places due to the fabric of the wad and presence of lead ore. Thus, a Shelby tube could not be pushed in by hand any further than a few centimetres. The soil sample extruded out of the Shelby tube was of insufficient height for triaxial shear testing.

The Mooiplaas, Bokkraal and Doornhoek samples underwent isotropic consolidation at 100 kPa confining pressure and experienced full primary consolidation under 2 minutes, verifying that the sufficient permeability makes the side drains placed on Mooiplaas-A sample unnecessary for the material.

The Mooiplaas samples' dry density values are higher than any other values previously found on wad. The wad was retrieved from a narrow gryk, about 1.5 metres wide, and is highly reworked. This is evidential in the microstructure photos, the grading and chemical composition of the wad as it contains a high amount of chert grains that contribute to the higher density. The material sustained relatively high loads with little deformation as can be seen in Figure 11-1(a), agreeing with Buttrick's (1986) findings. The material severely contracted during shearing due to the high initial void ratio. However, imagery in Box 14(b) suggests voids are still present post shearing.

11.3.2. Dispersivity and crumb tests

Majority of samples completely disintegrated when placed into the distilled water, suggesting all strength and cohesion lost when saturated. The Doornhoek sample only partly crumbled with a few pieces staying intact at the beginning of the test. However, most of the sample disintegrated after an hour of being placed in the water.

The crumb test performed on the wad material from the eight localities rendered the samples to be non-dispersive.

11.3.3. Composition and grading

The results of the XRF and XRD analysis of the wad samples are shown in Table 11-3.

Table 11-3. Chemical and mineralogical composition (VZSA11).

XRF (wt %)	Bokkraal	Doornhoek	Mooiplaas
SiO2	62.00	45.90	82.00
TiO2	0.14	0.09	0.46
Al2O3	3.57	2.67	5.09
Fe2O3	16.50	25.50	5.61
MnO	8.78	9.35	2.60
MgO	0.35	0.73	0.28
CaO	0.13	0.08	0.20
Na2O	<0.01	<0.01	<0.01
K2O	1.18	0.11	0.25
P2O5	<0.01	0.04	<0.01
Cr2O3	0.02	<0.01	0.02
NiO	<0.01	<0.01	0.02
V2O5	<0.01	<0.01	0.02
ZrO2	<0.01	<0.01	0.05
SO3	0.50	0.22	<0.01
CuO	<0.01	0.02	<0.01
ZnO	0.72	0.34	<0.01
PbO	<0.01	6.43	<0.01
LOI	6.12	8.47	3.34
Total	99.99	99.94	99.93
XRD (wt %)	**Bokkraal**	**Doornhoek**	**Mooiplaas**
Goethite	11.79	12.82	1.9
Kaolinite	2.48	4.4	6.99
Muscovite	5.2	2.46	-
Quartz	80.54	80.32	86.22
Talc	-	-	4.9

Grading, Atterberg limits and classification according to the Unified Soil Classification System are shown in Table 11-4 and Figure 4-3.

Table 11-4. Foundation indicator test results (VZSA11): grading; PI – plasticity index; LL – liquid limit; USCS – Unified soil class.

Sample	Clay %	Silt %	Sand %	Gravel %	PI (%)	LL (%)	USCS
Mooiplaas	12	50	20	18	12	29	SC
Bokkraal	11	33	45	11	16	49	SL
Doornhoek	4	68	23	5	33	121	MH

The grading of the reworked wad samples is dependent on the parent rock composition but more importantly on the mechanical processes experienced by the wad material, if any. The Mooiplaas and Bokkraal samples have been reworked, consequently losing the inherent parent structure as well as an increase the amount of sand size chert grains, therefore affecting the grading and the chemical composition of the material. The XRF results show the Bokkraal and Mooiplaas samples have very high SiO2 content. These reworking processes have affected the Atterberg limits of the material, in this case lowering the liquid limit, which is expected of soil that contains more inert, coarse material.

The Doornhoek has not been reworked, consequently, preserving the non-structured fabric inherent to the parent rock and maintaining the fine grading with no added impurities. It contains only 4% clay; the lowest of all samples tested but has the highest liquid limit (121%). The Doornhoek sample has the highest content of Fe and Mn oxides at 34.85%, of which nearly 10% of the material is made up of Mn-oxide.

The high liquid limits may result from adsorption of water onto metal (Fe and Mn) oxide surfaces rather than the adsorption of the clay structure (Bear Geoconsultants 2016).

Mn-oxides are typically poorly crystalline (i.e. amorphous) and generally no attempt is made to distinguish the exact Mn mineral. When a large quantity of Fe-ions is present in the soil, an extensive amount of substitution with the Mn-oxides will occur, resulting in the crystal structure to morph and the infrared (IR) spectra, or XRD 'peaks' used to identify the minerals, to broaden and shift. Further difficulty is experienced as many of the common Mn-oxides found in wad share similar IR spectra to other common minerals found in soil.

Referring to the XRD results, none of the samples contain any Mn-oxide minerals discussed in Box 14. Birnessite, the most common mineral in wad, has the same IR peak as kaolinite, a common clay mineral. This is the same for Mn-oxides manganite and todorokite with respect to goethite and mica or gibbsite. Therefore, the minerals identified in Table 4 may not be the only constituents of the soil and a more detailed approach to identifying the minerals is needed.

11.3.4. Stereomicroscopy and SEM

Images were taken of majority of the samples using the stereomicroscope and SEM. Box 14(b) supplies images taken of the undisturbed Mooiplaas samples pre- and post-triaxial shearing and of an undisturbed Doornhoek sample at various magnifications.

The Mooiplaas samples, when looking at the microstructure, are mainly made up of fine to medium sand size chert grains and very fine to sand size clumps of wad with Fe-oxides on the surface of the chert grains and wad. The undisturbed sample is highly reworked, thus has no structure and is highly voided, some voids are 0.1 millimetres across. The post shear testing sample has a reduced void ratio; however, many voids are still present after consolidation and shearing. The voids are still present due to the load applied being insufficient to overcome the clay bridges and inter-granular shear strength.

Examining the Doornhoek sample through the stereomicroscope and SEM reveals explanations for the extremely high liquid limit of a material with only 4% clay, exhibiting relatively large voids between the indefinable individual grains that make up the soil. At x1000 magnification, the individual grains are defined with open voids visible between the various grains. At magnification of x20 000 and x40 000, the single grain appears to be highly voided and exhibits a coral or sponge type structure. The appearance of black birnessite at x9000 and x25000 published by Cheney et al. (2008) is very similar to these, as well as those discussed by Day (1981), Wagener (1982) and Buttrick (1986) in massive or non-structured wad and it was famously described by Wagener to have the appearance of "Rice Crispies". This structure is typical of physico-chemically formed birnessite (Jiang et al. 2010; Bruins 2016). The presence of this highly voided metal oxide, birnessite that can carry up to 25% of its weight as water, will have a major influence on the high liquid limit (125%) of this clay-poor material.

11.3.5. Permeability columns

Six of the eight samples successfully underwent permeability tests using Perspex columns. The hydraulic conductivities (K) are summarized in Table 11-5. The table includes the triaxial permeability test results and falling head infiltration and percolation field test results conducted at the Mooiplaas sample locality (VZSA09 §9.4.2) by Heuer (2017) for easy comparison.

Table 11-5. Hydraulic conductivities (m/s) determined in undisturbed conditions in the field; on undisturbed samples in triaxial cells; and on remoulded samples in permeability columns.

Sample	Fabric	Undisturbed; field (Heuer 2017)	Undisturbed; triaxial (Swart 2019)	Remoulded; columns (Swart 2019)
Highveld	Structured	-	-	-
Sudwala caves	Structured	-	-	3.0e-5
R533	Non-structured	-	-	2.3e-5
Doornhoek	Non-structured	-	2.7e-6	4.0e-6
Mooiplaas	Reworked	2.81e-4 to 9.52e-4	9.0e-7	2.0e-5
Bokkraal	Reworked	-	2.8e-6	-
Carletonville	Reworked	-	-	2.0e-5
South downs	Reworked	-	-	2.0e-5

Heuer's (2017) falling head infiltration and percolation tests at Mooiplaas mine in Laudium is in close proximity to the Mooiplaas sample locality. The undisturbed Mooiplaas sample underwent a triaxial permeability test post 100kPa consolidation. The triaxial results yielded much lower permeability value than the field tests that may be due to lateral dispersion and the soil not being fully saturated at the time of measurement readings. Other possible reasons may be sample disturbance when retrieving, transporting and cutting of the sample, the isotropic consolidation caused a much denser packing of grains or the sample tested had greater clay content. When the samples were cut for triaxial, many samples disintegrated due to the friable nature of the soil. The samples that maintained structure, and that was ultimately used, may have been from pockets of the reworked material with greater clay content.

Majority of the other samples tested had hydraulic conductivity values in the order of 10^{-5} m/s, typical of a silty soil. The Doornhoek sample had undisturbed triaxial and remoulded column K values in the same order of magnitude (10^{-6}). The fabric didn't influence the K value for this particular sample and suggests the grading, and added impurities when reworked, influences the change in permeability for non-structured wad.

11.3.6. Mechanical properties

Table 11-6 summarises results from the specific gravity tests and includes values of dry density and void ratio, determined from weighing saturated and dried undisturbed samples at a constant volume.

Table 11-6. Dry densities, void ratios and specific gravities of analysed wad samples.

Sample	Fabric	Dry density (kg/m³)	Void ratio	Specific gravity (kg/m³)
Highveld	Structured	309	8.32	2886
Sudwala caves	Structured	-	-	2860
R533	Non-structured	-	-	1796
Doornhoek	Non-structured	593	3.87	2896
Mooiplaas	Reworked	1034-1751	0.55	2727
Bokkraal	Reworked	1237	1.34	2897
Carletonville	Reworked	898	2.07	2760
South downs	Reworked	-	-	2934

12. VZSA12: FACILITATED KARST DIALOGUES

Matthys A DIPPENAAR, J Louis VAN ROOY

12.1. Motivation for Study

Two facilitated dialogues formed part of the project. The first entailed a closed session with invited professionals working in the civil and government spheres with respect to water and land suitability in dolomite terrain. The second dialogue formed part of a two-day symposium jointly organised by the following parties:

- University of Pretoria
- Ground Water Division of the Geological Society of South Africa
- South African Institute for Engineering and Environmental Geologists
- Geotechnical Division of the South African Institution of Civil Engineers.

12.2. Main Outcomes

Results from the dialogue as described in §5.1. Specific comments were as follows:

- Epikarst (accumulated gravel in gryke bottoms) may have high apparent yield. Scale is important as it may be absent or > 30 m deep.
- Knowledge on epikarst in SA is limited or non-existent due to destructive nature of SI methods used in dolomite terrain.
- Experience in Northern Cape (Kuruman) is deep Kalahari sediment infilled grykes are the only readily available source of groundwater and pumping may lead to surface instability (unconsolidated sediments may consolidate)
- Transition zone from soil (wad/residual dolomite) to rock may be fractured dolomite bedrock or leached bedrock zone. Discolouration on joints occur down to great depths in the bedrock.
- Groundwater data are not collected during stability site investigations. Recording water levels 12 hours after drilling is not good enough and all holes are backfilled and sealed after investigation. Standpipe type piezometers may provide additional long term info.
- Accessibility of data is another problem with stacks of data in brown envelopes which can be regarded non-existent because it is not electronically available.
- The SKA is a good example of how science can be advanced. All possible data should be collected even if it is not used on a project. Someone may use it in future. It seems like stability investigations are part of a vicious circle with fieldwork, data collection and then crunching old numbers again.
- Data curatorship is important.
- Geophysical methods should be looked at again.
- It may be worthwhile to establish experimental sites. Suggestions to use CoT parks in dolomite land. These sites can then be used for research, training and teaching as well as public awareness. This ties in with the lack of awareness on groundwater/surface water amongst the public and their behaviour towards e.g. water

use/restrictions. Possible funding to establish such sites from National Lottery, Bottled water producers (Clover), CoT, DST.

- The mechanics of sinkhole formation needs to be investigated again. Experience has shown that it is not necessarily a vertical system of joints and cavities below sinkholes, but could be more typical horizontal karst fractured systems serving as conduits along which material is eroded and removed.
- Anthropogenic influence can to some extent be divided into the pre-SANS1936 era and the post SANS1936 approach. Recent standard of services, precautionary measures and dolomite risk management are contributing to safer developments, but also restrictions due to being conservative.
- Dolomite risk management must include water management/monitoring. The inability to monitor groundwater and standard requirement to quantify the hazard due to dewatering – even if dewatering is highly unlikely – limit/prevent development on low hazard dolomite land.
- Just adding data requirements/collection for possible future use costs money and someone has to pay.
- Data collected during a single project only give a snapshot and not a comprehensive data set. Again long-term data collection costs money. Funding is a problem.
- Water sensitive design is not recommended or suitable in dolomite/karst land.
- “Specific” and “apparent” terminology needs to be clarified ito yield and hydraulic conductivity.
- There are a number of historic thumb suck approaches/values/ways e.g. it is safe to lower the groundwater by 5 m after which surface instability will start. Many of these values were never tested/validated.
- SANS1936 does provide guidelines to optimally utilise land; hazard vs responsibility.
- Water constitutes a single resource (surface & groundwater) with the vadose zone in many instances the unknown/ignored link between the surface and groundwater.
- An integrated approach is needed to describe/quantify how water reaches the karst aquifer
- Everybody agreed that how we develop and how we protect both karst land and karst water is the fundamental issues that need to be researched/developed.

SECTION G: BIBLIOGRAPHY

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