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Engineering, hydrogeological and vadose zone hydrological aspects of Proterozoic dolomites (South Africa)

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Abstract: Large parts of the urban land between Pretoria (City of Tshwane Municipality, South Africa's capital city) and Johannesburg (South Africa's largest city) are situated on Proterozoic dolomites of the Malmani Subgroup (Chuniespoort Group, Transvaal Supergroup) formed in the Transvaal Basin. As South Africa's economic hub, development is progressively becoming denser, higher, and deeper underground, increasing the risks posed by surface subsidence and sinkholes. Tshwane also sources more than 40 million liters of drinking water per day (5-8% of requirements) from the dolomite aquifers. A second basin comprising the Ghaap Group is found to the more arid western portions of the country. Even though a fair understanding exists with respect to the karst aquifer hydraulics and the surface stability issues, a distinct knowledge gap exists in the karst vadose zone. Recent research efforts focused on vadose zone hydrology has resulted in a significantly improved understanding of the behaviour of variable saturated soil and fractured rock systems, both at discreet localities and on a regional scale. However, with more than 90% of the sinkholes in this region forming due to water ingress from leaking pipelines (especially given that the latter non-revenue water is estimated in the order of 30% of the reticulated supply), the flow mechanisms, and unsaturated or vadose zone behaviour of the karst system becomes increasingly important. The ingress scenario results in downward erosion of soil (chert rubble, residual dolomite, transported soil or other residual products of younger caprock) with percolating water. The high lithological variability in South African karst adds to the uncertainty, and is related to chert abundance, the presence of residual dolomite (wad), subsurface cavities (receptacles) and so forth contributing to the heterogeneity and anisotropy. The review paper presents state-of-the-science on the karst vadose zone, including recent advances, appropriate geological models, and knowledge gaps.

Highlights:

- Complexity in South African karst affects hydrogeology and surface stability.
- Majority of sinkholes occur due to water ingress.
- Groundwater is used from dolomite aquifers.
- Instability and contamination are both affected by the vadose zone properties.
- Improved geological models contribute to safe land and groundwater use.

Keywords: soluble rock; subsidence; karst; Chuniespoort Group; Ghaap Group; sinkhole

1. Introduction

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 ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). 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 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:

(a) Its significant age of almost 3 billion years
(b) Three periods of karstification post deposition prior to present karst development cycle
(c) 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
(d) 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. For that reason, this paper aims to (i) introduce the vadose zone as fundamentally important in understanding engineering geology and hydrogeology of karst, (ii) review conceptual models of the karst vadose zone, (iii) address the properties of the vadose zone in Proterozoic dolomites of South Africa, and (iv) comment on lessons learnt and knowledge gaps in the understanding of unsaturated flow in karst systems and the implications on stability and groundwater quality and recharge rates.

2. Literature

2.1. The Vadose Zone

The *vadose zone*, also referred to as the *unsaturated zone* or *zone of aeration*, 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, plant water availability, hydropedology (e.g. Bouma 2006), and perched wetland hydrology (e.g. Dippenaar 2014a, Melly et al. 2017), the field of vadose zone hydrology has expanded to the geological and engineering domains. The vadose zone stretches from the land surface through the soil zone and intermediate zone, and incorporates the complete capillary fringe (where the medium may be saturated, but is always at negative pore water pressures). This is separated from the phreatic zone in unconfined systems by the *water table* or *phreatic surface*, referring to the surface where pore water pressure equals atmospheric. The water table is represented by the *water level* in a well as capillary forces will result in deviations. The *phreatic zone* is characterised by positive pore water pressures and complete saturation of pores with water (Figure 1; Dippenaar et al. 2014).

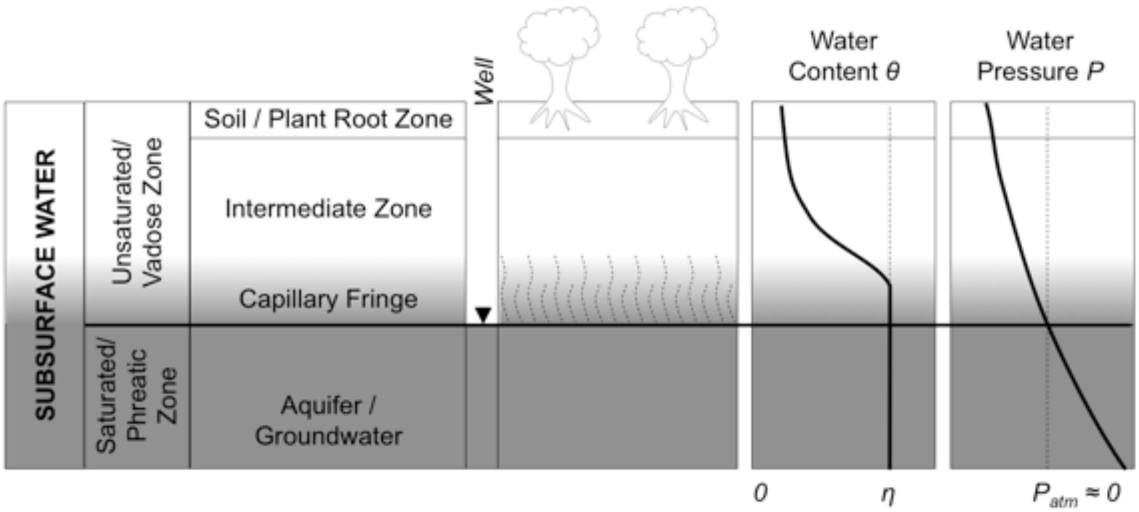

Figure 1. Distribution of water in the Earth's crust (from Dippenaar et al. 2014).

Recent advances in quantifying partially saturated subsurface flow are published extensively for intergranular systems (e.g. Dippenaar 2014b;2014c; Dippenaar and Van Rooy 2014;2015; Dippenaar et al. 2014) and subsequently also for fractured systems (e.g. Brouwers and Dippenaar under review; Dippenaar and Van Rooy 2016; Jones et al. 2017a; Jones et al. 2017b). Karstic vadose zone systems, however, are more complex due to high anisotropy and heterogeneity exacerbated by long periods of chemical dissolution. This is addressed further at the hand of major South African dolomites and their associated properties affecting surface stability and groundwater recharge and quality.

2.2. Karst

Karst refers broadly to a series of distinctive landforms and underground drainage systems resulting due to chemical decomposition, dissolution or solutional erosion of soluble rock such as carbonates and evaporites (e.g. Ford & Williams 2007; Keary 2001; Lapidus 1990). Karren, defined as “channels or furrows, caused by solution on massive bare limestone surfaces” and which “vary in depth from a few millimetres to more than a meter” and which separated by ridges, commonly characterise karst, in which the “topography is chiefly formed by the dissolving of rock” (Monroe 1970).

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.

Several conceptual models of karst systems are depicted in Figure 2 and in Figure 3; 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 (Figure 2), whereas the Proterozoic mature systems in temperate South Africa represent mainly pinnacle karst (Figure 3).

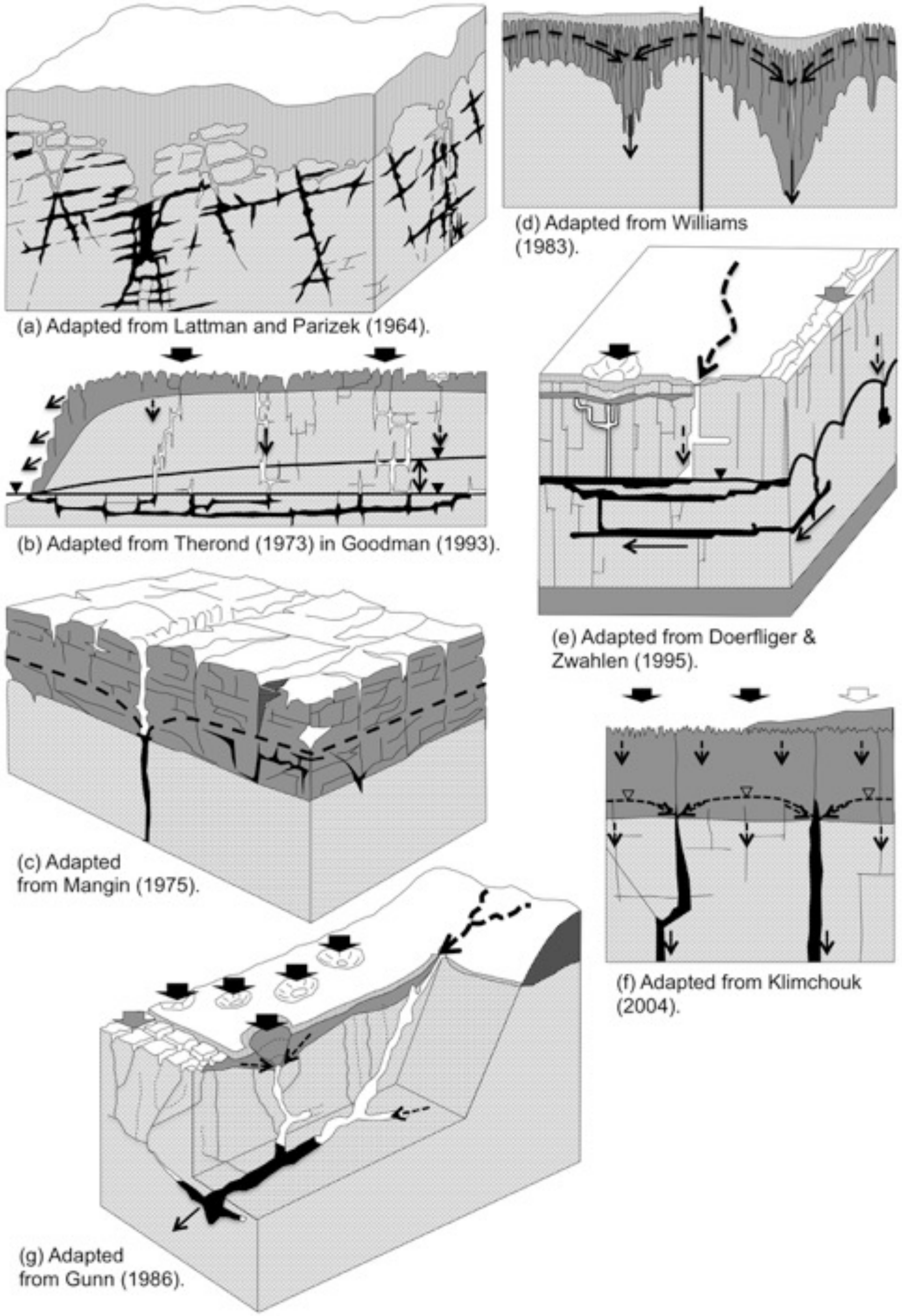

Figure 2. **Conceptual models of karst systems with specific reference to the occurrence of epikarst.**

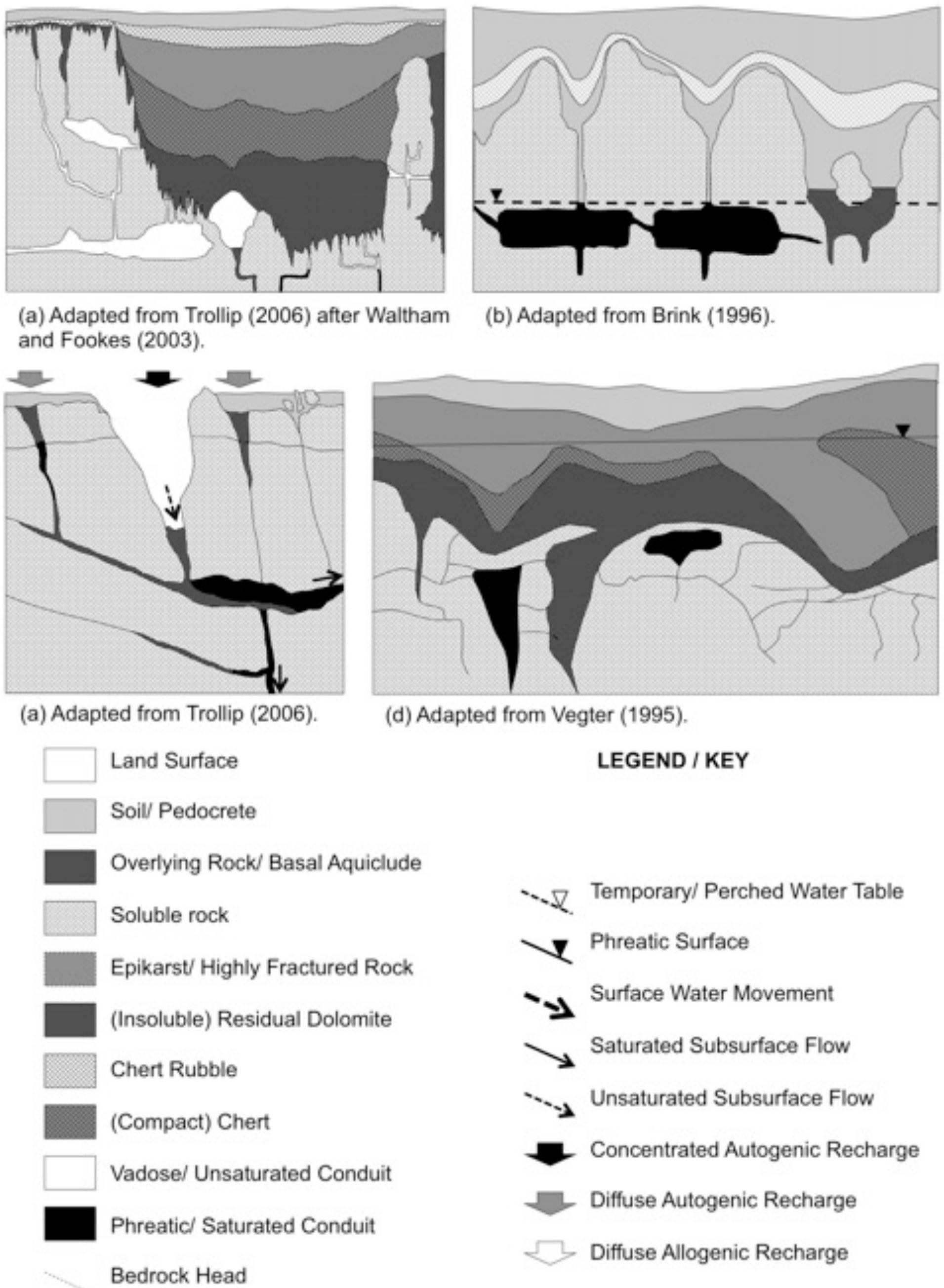

Figure 3. **Conceptual models of karst systems in South Africa where epikarst is notably absent and replaced by pinnacled karst.**

2.3. The Karst Vadose Zone

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 rock as a governing zone of water storage or movement (e.g. Gunn 1986; Williams 2008; White 1969). 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 and/ or fractured zone, resulting in a perched water system (Mangin 1973, 1975; Williams 1983; Klimchouk 2004) 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.

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.

In order to understand the role of the vadose zone in surface stability and subsurface hydrology in karst terrains, a suitable conceptual model is required. Although numerous such models exist for karst terrains, none truly seem to hold indefinitely when considering the older, more mature karst terrains found in, for instance, South Africa.

3. South African Karst

3.1. Lithostratigraphy and development

Late Archaen to early Proterozoic rocks of the Transvaal and Griqualand-West Supergroups are distributed between three basins on the Kaapvaal Craton, namely the Transvaal and Griqualand-West Basins (the latter subdivided into the Ghaap Plateau and Prieska Sub-basins) in South Africa, and the Kanye Basin in Botswana (Eriksson et al. 2009). 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 (Figure 4; Figure 5), and is detailed extensively by e.g. Altermann and Wotherspoon 1995, Eriksson et al. 2009.

For the Ghaap Group, majority of the dolomite and limestone is contained within the Schmidtsdrif and Campbell Rand Subgroups, and is overlain by the younger iron-formations of the Asbestos Hill Subgroup. For the Chuniespoort Group, the dolomite and limestone are in the Malmani Subgroup, and is overlain by the Penge Formation iron-formations. All these associated 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 and chert representing secondary replacement of the limestone (Brink 1979), where dolomite replacement is defined as dolomitization (Monroe 1970). The formations of the Malmani Subgroup is subdivided based on the presence or absence of stromatolites and chert, with the Eccles and Monte Christo Formations having interlayered chert, and the Lyttleton and Oaktree Formations being poorer in chert with more stromatolites (e.g. Eriksson et al. 2009).

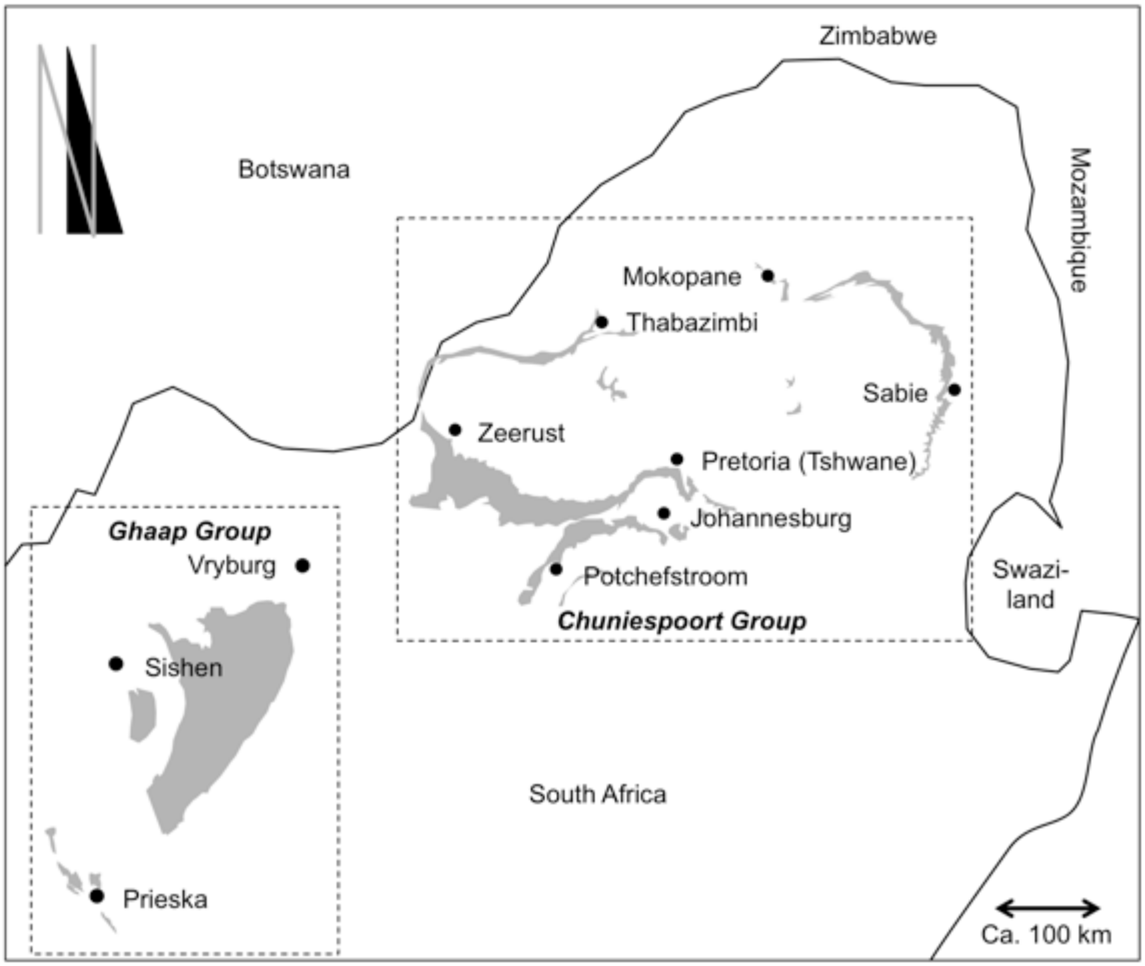

Figure 4. Distribution of the major dolomites of South Africa shown in grey shading (adapted from Eriksson et al. 2009).

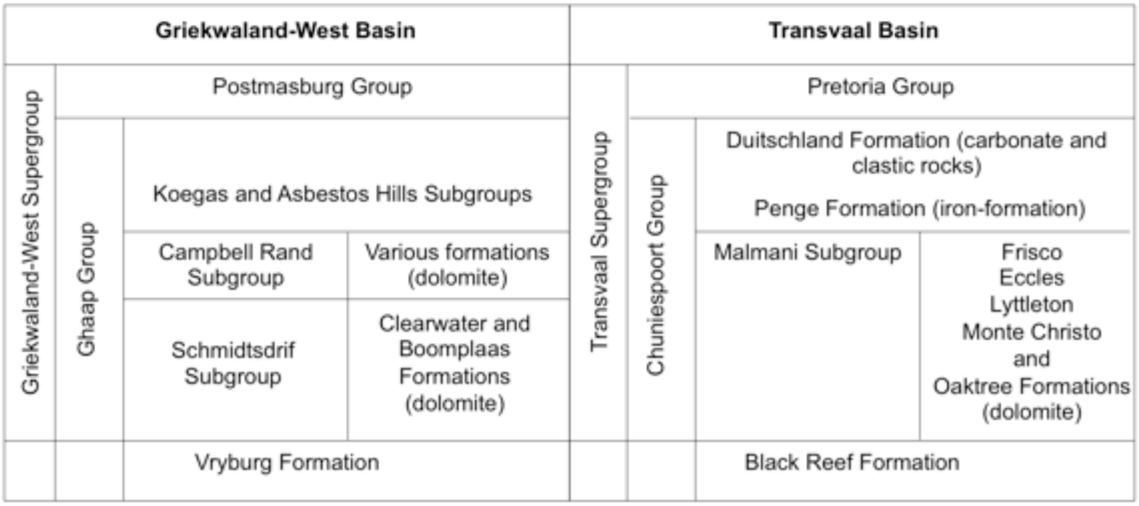

Figure 5. Stratigraphy and depositional sequences of the Ghaap and Chuniespoort Groups (adapted from Eriksson et al. 2009).

Karst is well developed in the Malmani Subgroup and Campbell Group, although surface morphology is not typical of karst due to the high concentration of insoluble impurities in the rock coupled with the semi-arid climate, the latter most notable in the west. Residuum comprises mostly of chert fragments in a matric of manganiferous and ferruginous oxides following dissolution of dolomite with highly variable thickness (Martini 2009).

Examples of South African karst are shown in Figure 6, and examples of sinkholes (a-e) and springs (f-h) in Figure 7.

(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 rapid 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).

Figure 6. Examples of South African karst.

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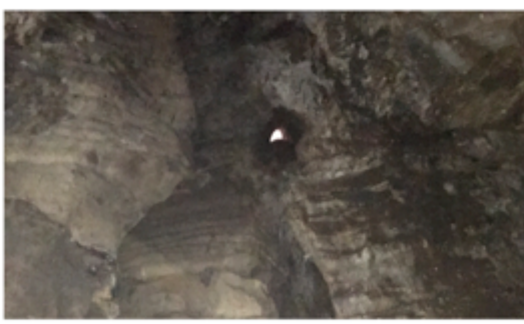
(a) Sinkhole in Bapsfontein (eKurhuleni, © JL van Rooy 2017).

(b) Damage to house due to sinkhole in City of Tshwane (© Matthys Dippenaar 2012).

(c) Dolomite sinkhole in a cemetery (City of Tshwane, © MA Dippenaar 2010).

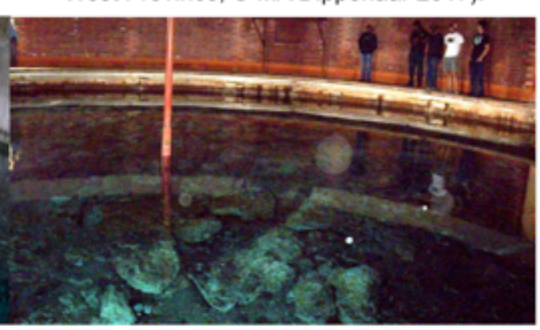
(d) Dolomite sinkhole in a cemetery (City of Tshwane, © MA Dippenaar 2010).



(e) Daylight hole in roof of Sterkfontein Cave (City of Tshwane, © MA Dippenaar 2017).

(f) Marico Eye (near Groot Marico, North-West Province, © MA Dippenaar 2017).

(g) Inside collection chamber of Lower Fountain spring partially supplying City of Tshwane (© MA Dippenaar 2017).



(h) Inside collection chamber of Grootfontein spring partially supplying City of Tshwane (© MA Dippenaar 2017).

Figure 7. Examples of South African karst springs and sinkholes.

3.2. Karst hydrogeology and karstification

The phreatic zone and process of carbonate dissolution in soluble rock environments is thoroughly addressed in international literature (e.g. Dragila et al. 2016; Knochenmus and Robinson 1996; Martin and White 2008; Waltham and Fookes 2003, 2005; White 1969). Bakalowicz (2005) notes in detail that flow in phreatic systems depends on the type of porosity and the type of recharge, and 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. Characterisation of karst hydrological systems and the modelling thereof are detailed in literature (e.g. Ford and Williams 2007; Kovács 2003; Taylor and Greene 2008).

In non-karstic terrain recharge is generally a function of the weathered vadose zone hydraulic properties and the secondary permeability of the fractured bedrock above the groundwater table. In karstic terrain, however, recharge is either direct as concentrated infiltration through swallow holes (or palaeo-sinkholes), or a result of delayed infiltration associated with vadose zone water storage due to the possible presence of an epikarst zone which allows for water movement from the regolith into the fractured soluble bedrock. This highlights the need to first identify whether the landscape is truly karstic rather than fractured. Further to this, Dubois et al. (2014) extensively detail the dissolution and hydrodynamical erosion processes involved in *karstification by total removal* and *ghost-rock karstification*. *Ghost-rock features* result from ghost-rock karstification, and include large weathered features, weathered corridors, ghost-endokarst and weathered galleries.

The vadose zone 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 the 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 assymetrical 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.

Karst hydrological research in South Africa has been focussed around topics of (i) hydrogeology, including concepts of aquifer vulnerability, recharge and water supply (e.g. Bredenkamp et al. 2007; Bredenkamp 2007; DWAF 2006a; DWAF 2006b; Holland 2007; Holland and Witthüser 2009; Leibundgut 1997; Leyland et al. 2006; Leyland and Witthüser 2010; Meyer 2014; Van Rooy and Witthüser 2008), or (ii) 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; Naidoo 2014).

3.3. Hazards and risks posed by dolomite/ karst landforms

The South African Bureau of Standards (SABS 2012a;b) 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); the term “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).

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.

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; Kleinhans and Van Rooy 2016; Momubaghan 2012; Oosthuizen 2013; Oosthuizen and Van Rooy 2015; Richardson 2013; Trollip 2006; Trollip et al. 2008).

4. The South African Karst Vadose Zone

Numerous authors have conceptualised the South African karst vadose zone (e.g. Colvin et al. 2003, Jennings et al. 1965; Leyland et al. 2006; 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. Material within the grykes and above the pinnacles comprises chert rubble, residual dolomite, residuum of younger caprock, younger infill of historic karst features, or transported soils. Sinkholes 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. Sinkholes with direct connection to the dolomite aquifer are generally referred to as swallow holes.

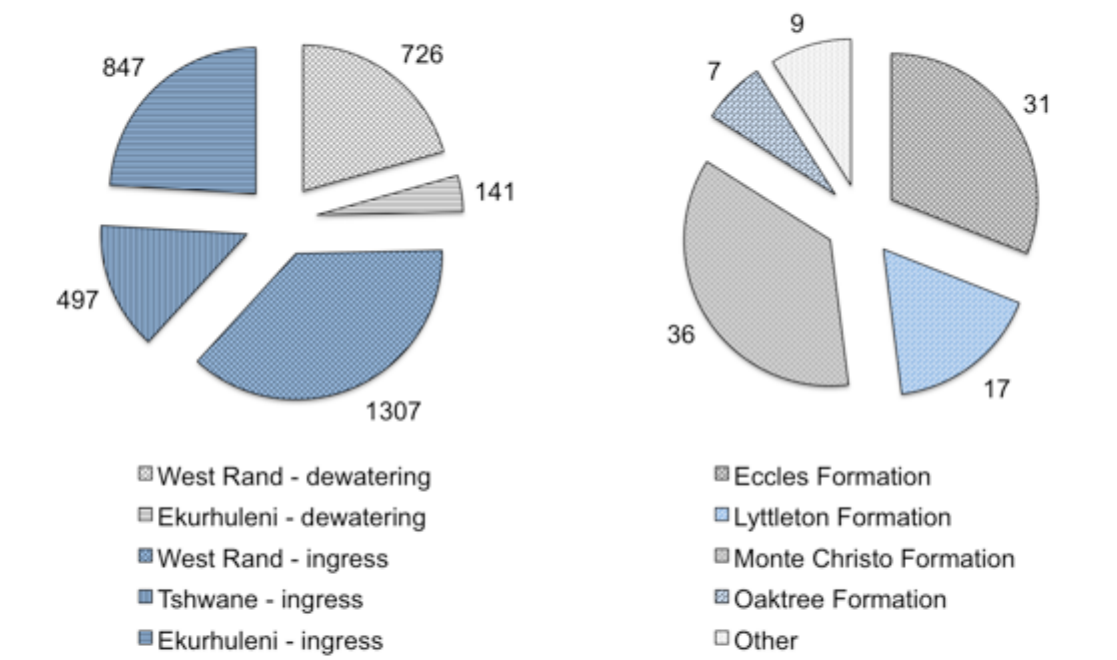
The karstic vadose zone plays two fundamental roles. Firstly, the vadose zone serves as protection to the phreatic zone in karst aquifers from contamination, subsequently protecting the very vulnerable groundwater that is used widely as municipal and domestic water supply. Through the aquifer vulnerability 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 of Vías et al. (2003) (relating concentration of flow *C* such as swallow holes, properties of the overlying layers *O*, and precipitation *P*), to specifically better account for the vulnerability of karst aquifers in semi-arid southern Africa. DWAF (2006a,b) quantified hydraulic parameters for selected dolomite regions in South Africa (Table 1).

Table 1. Hydraulic properties of the main dolomite regions in South Africa (MAP – mean annual precipitation) (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%)

Secondly, 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 2017 in press) (Figure 8). 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 (Constantinou and Oosthuizen 2014).



(a) Sinkhole event densities for dewatered and non-dewatered (ingress) areas in Gauteng (blue-shaded – ingress scenario).

(b) Sinkhole event occurrences by geological formations (grey-shaded – chert-rich; blue-shaded – chert-poor).

Figure 8. Sinkhole statistics for Gauteng (data from Constantinou and Oosthuizen 2014).

Development in karst terrains is governed by the South African National Standards series SANS 1936:2012 (SABS 2012a;b). All dolomite stability 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 (which may occur in the vadose or phreatic zone). The influences of residual dolomite (either red silty sands with variable amounts of chert fragments or the low density leached, chert free and Mn-rich material termed *wad* in South Africa) and possible presence of 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 rotary percussion drilling methods, generally leading to mixed and contaminated material retrieved, further increasing uncertainty in the conceptual model.

Residual soils in other lithologies are typically packed into a higher dry density, 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 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 2). 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 improved due to weathering associated with subsurface water.

Table 2. Properties of the ground profile overlying bedrock with negligible interstitial porosity (K – hydraulic conductivity; S – storage).

	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 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 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

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.

5. Conclusions

Despite the recent contributions, the collation of engineering geological and hydrogeological 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 the groundwater table (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*. Limited contributions to the properties of the weathered dolomite profile concentrated on residual dolomite (manganese-rich oxisols and/ or wad), either due to pedological interest or due to the perception that wad is a major contributor to subsurface erosion resulting in surface instability during water ingress events (Bester et al. 2017; Buttrick 1986; Day 1981; Dowding and Fey 2007; Hawker and Thompson 1988).

International and local knowledge and research on the engineering geology and hydrogeology of karst environments are largely about hydrological systems governed by networks of shallow dissolution caves serving as subterranean conduits for groundwater flow, vertical swallow holes connecting surface water directly with groundwater, roof collapse of existing cavities to create sinkholes and swallow holes, and delayed recharge from the highly fractured epikarst zone on fresh bedrock.

Proterozoic dolomite occurrences in South Africa has been exposed to three karstification periods prior to the present day processes operating since the break-up of Gondwanaland. The exposed karst landscape was subsequently filled in and covered by younger sediments after each exposure to the surface and at least five tectonic uplift events occurred during the past 80 Ma. The different erosion base levels, more recent variations in climate, and recent anthropogenic influences render the South African karst to be unique in the World.

In redefining the general description of residual dolomite, a link can possibly be established between bedrock mineralogy, overburden properties and flow. Increased detail in the description and related properties of the karstic profile is required to better understand vertical and spatial heterogeneity and implications on infrastructure development and groundwater utilisation.

Understanding the relationship between the highly variable bedrock topography formed through karren (pinnacles and grykes), the presence of residual dolomite of very low density and high water retention in these deeply weathered grykes, the possibility of epikarst (highly weathered and fractured dolomite rock) overlying fresh dolomite, and the risks posed by sinkhole and subsidence events is becoming crucial. With the vast majority of recent sinkholes in South Africa being ascribed to concentrated water ingress rather than the historic mine dewatering scenarios, these catastrophic events are clearly a vadose zone flow process rather than solely a groundwater management one. A thorough understanding of how water moves through the karstic vadose zone, incorporating the various materials, in the chemically decomposed dolomite of the Gauteng region and the semi-arid physically weathered Ghaap plateau, is therefore vital in risk mitigation to both sinkhole formation, groundwater recharge and contamination.

It should be well understood that simplified box models of complex terrain justifiably contain all potential landforms, risks and flow paths on a single diagram; it should be inferred to possibly be much less connected hydraulically, and it should be noted that tertiary karst porosity may be severely influenced by secondary fractured porosity, very low permeability fresh dolomite bedrock, and high anisotropy and heterogeneity in both the vertical and spatial dimensions.

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