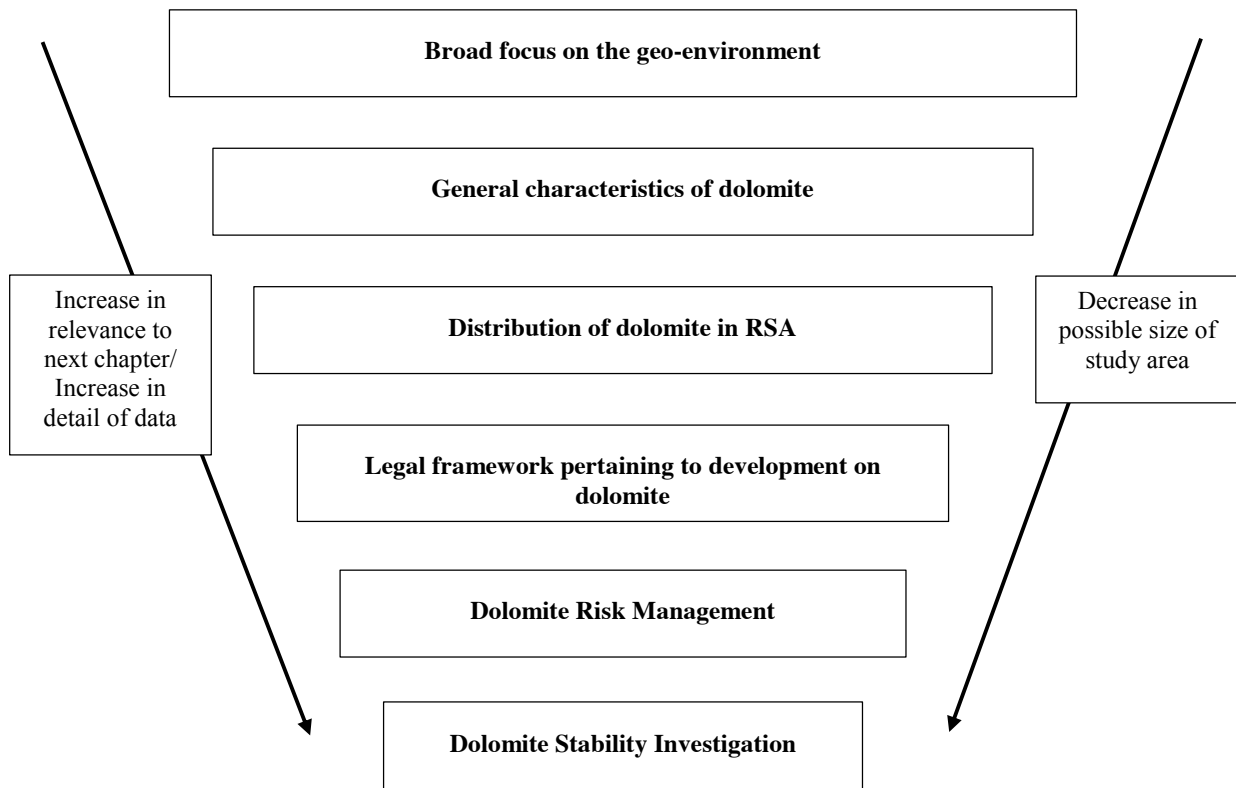


2 Geo-environmental setting of dolomite

In the following section the development of a basic structure for a dolomite stability investigation will be done by refining the broad concepts related to the subject. The discussion will begin with a broad overview on the geo-environment and the general characteristics of dolomite. These concepts will be further refined with the specific implications of dolomite in South Africa, based on a structural and lithological distribution thereof. The management of development on dolomite will be described based on the setting of the legal framework regarding development on dolomite. The criteria for investigation of all development on dolomite rests upon the evaluation and assessment of the metastable condition of the dolomite underlying the development, which will be the final phase of this section.



2.1 The geo-environmental concept

The geo-environmental concept is a broad and relatively undefined concept used in conjunction with environmental management. This concept is based to a large extent on the concept of sustainable development (Pretorius, 2009). This concept refers to integration of geological and environmental affairs with the society and development thereof as a whole (Hrasna, 2002). These may be applicable to various environmental and geological areas of interest, such as riverbeds, wetlands, mountainous areas, dolomitic terrains, soil conditions,

etc. According to Pretorius (2009), in a movement towards sustainable management of natural resources, integration is needed between natural resource information and socio-economic aspects related to this information. This concept is represented in the new guideline for Geohydrological Assessments (DWAF, 2008) where the natural environments (surface/ground water, geology and ecosystems) are integrated with the social environment (water use, land use, social setting and interaction).

Hrasna (2002) furthermore defines the geo-environment as the part of the lithosphere that directly influences the conditions and development of the society as a whole. The basic components are rocks, soil, relief, groundwater and geodynamic phenomena. If specific focus is given to the “rock” component of the geo-environment, the depth thereof depends on the scope of human interface with the crust. The quality of the environment and the land uses associated with certain geo-environmental areas directly affects the society and development thereof, based on the geo-environmental conditions pertaining to the certain area (Hrasna, 2002). The implication of the interaction between the society and the geo-environment as well as the consequences of each will be discussed in the following sections.

2.2 Characteristics of dolomite

In this section the various characteristics of dolomite is discussed so as to set the background to dolomite induced risk. The author of this document has conducted a detail study on the characteristics of dolomite in 2011 (Pretorius, 2011), and this section will therefore just briefly discuss each of the aspects. The extent of the risk related to development on dolomite can only be discussed if the background setting of dolomite is firstly discussed. This will be done based on a) origin and composition of dolomite, b) weathering and dissolution properties of dolomite and c) the formation process related to sinkholes and subsidences.

2.2.1 Dolomite

Dolomite has been discussed in literature long before the modern-day geotechnical classification and management frameworks have been developed. The first mention of dolomite in South Africa was in November 1871, when T.F. Burgers, the second President of the Transvaal Republic, found the Eye of Wonderfontein. He described it as a rock with a “poreuzenbodem” and “overall holten” (Wagener, 1984). Penning and Crutwell (1885) were the first to name the “Olifantsklip” and described it as “a peculiar blue, fine grained calcareo-siliceous rock”, which they named chalcedolite (Wagener, 1984).

Dolomite is a carbonate rich sedimentary rock composed mainly of the mineral dolomite, which is a calcium magnesium carbonate ($\text{CaMg}(\text{CO}_3)_2$) (Buttrick, 1986). The calcium and magnesium ratio (Ca:Mg) may vary between 1:1 and 1:5, in which case the calcium has substituted the magnesium (Bradley *et al.*, 1953). In some cases iron and manganese may also be present, which together with the magnesium, makes the dolomite structure diadochic. In

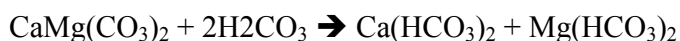
this case, the composition of dolomite will be $\text{Ca (Mg, Mn, Fe)(CO}_3)_2$ (Buttrick, 1986).

Extensive studies by Young (1934) indicated that dolomite has been formed by dolomitisation and recrystallization of limestone. Limestone originates from the remains of shallow, warm, clean-water, marine dwelling organisms. The shells of these organisms accumulate into piles and precipitated to form ormmicrite and calcite cement, which later became limestone (Beukes, 1987).

The dolomite within South Africa is seen as one of the earliest carbonate platform successions on earth (Beukes, 1987; Alterman and Wotherspoon, 1995), and has been dated at 2550 ± 3 Ma (Walraven and Martini, 1995).

2.2.2 *Weathering and dissolution*

Due to the composition of dolomite, it is soluble in an acid. The following is an example of such a reaction:



CO_2 is taken up by rainwater and water moving through the soil, and in this process forms a weak carbonic acid. Due to the low porosity of dolomite (less than 0.3 % (Brink, 1979)), water cannot percolate directly into the rock, and therefore moves along the many cracks, joints and fissures in the rock (Buttrick, 1986). The resultant bicarbonate-rich water is transported in the cracks, fissures, joints and caves and emerges at springs (Trollip, 2006). Through this process, the underlying un-weathered dolomitic bedrock is overlain by more jointed and weathered dolomite, grading upward into the remaining insoluble matrix structure which usually consist of mainly manganese oxides, chert and iron oxides. Due to this constant dissolution process, the higher, more weathered material get compacted with time, resulting in a stronger, less permeable and less porous material (Trollip, 2006). This entire sequence may be overlain by younger material. When water percolates down through this horizontally layered succession of material, the less densely compacted material may weather away, leaving possible voids in-between more competent material.

According to Buttrick (1986), wad is a black or blue-grey, fine-grained, highly compressible and erodable, clayey silt or silty clay, which is rich in silica, manganese oxides and variations of lesser components such as FeO , Al_2O_3 , MgO , CaO , NaO , P_2O and Cr_2O_3 and is derived as a weathering product of a magnesium carbonate. Ferroan soils are basically the same as wad, but differ slightly in terms of colour and are rich in silica and iron oxides, rather than manganese oxides. Buttrick (1986) indicated that it is advisable to use the term “wad” to refer to both iron manganiferous soils and manganiferous iron soils.

In some cases, according to Wagener (1984), after the dolomite has been weathered away, chert may be encountered in the form of angular gravels or boulders ranging from 10 mm to 6

m in length and 1 m in diameter. When the chert is exposed to the surface for a prolonged time, it may weather down to a friable white material with a fine texture.

2.2.3 Sinkholes

The term “sinkhole” is derived from the formation process associated therewith, when ground subsides (sinks) into a hole under the ground (Waltham *et al.*, 2005). These features usually occur suddenly and are in many incidences catastrophic (Buttrick & Van Schalkwyk, 2005). Sinkholes may lead to loss of live, and/or damage to property. In South Africa, the cost to repair a sinkhole (excluding structural damage) is usually around R200 000 (CGS, 2010).

Sinkholes form by one, or a combination, of the following processes: 1) bedrock dissolution, 2) rock collapse, 3) soil down washing and 4) soil collapse. Classification of sinkholes may become confusing due to all the various combinations of the above mentioned processes, but the following six main sinkhole classifications exists (Waltham *et al.*, 2005):

- Solution sinkhole – very large feature, occurring over a long period (>10 000 years) through natural lowering of the floor by means of dissolution of the soluble rock.
- Collapse sinkhole – rapid failure of the roof of a cavity, falling inward into the cavity.
- Caprock sinkhole – rapid failure of insoluble material overlying the soluble rock, falling into the cavities developed in the soluble rock.
- Dropout sinkhole – rapid failure of the overlying cohesive soil into the fissures of the soluble rock underlying the insoluble material.
- Suffusion sinkhole – down washing of non-cohesive material into the fissures in the soluble rock below over an extended period of time.
- Buried sinkhole – a soil filled surface dissolution.

In South African dolomite, the predominant and most significant types of sinkholes are collapse and caprock sinkholes. The common features between these types of sinkholes are that they develop due to the fracturing, breakdown and collapse of unsupported bedrock that remains above the dissolution cavities in karst (Waltham *et al.*, 2005). Reference may be made to Pretorius (2011), in which the formation process of sinkholes is discussed in more detail.

From personal experience of drilling in areas underlain by dolomite and chert, the chert bands are the predominant factor in dolomite stability assessments. The weathered zones are mostly encountered directly above or below the chert bands, suggesting the development of preferential fluid flow paths creating highly weathered zones within the dolomite. This in turn may cause development of extensive cavities and disseminated voids above and below the chert layer, which may upon infiltration of water, accept overburden to the extent of the volume of the developed cavity. The solid chert layers often carry the overburden to such an

extent that the size of the cavity is of such a size that the roof collapses. This may in many cases be enough to form sinkholes or subsidences.

The focus of this document is assessment-related and therefore a detail explanation of the formation process is not necessary.

The triggering mechanisms related to sinkhole formation may however be regarded as important in risk assessment, and this must be pointed out and identified during the initial surveys. This forms part of the quantification process of possible risks related to sinkhole development. Jennings *et al.* (1966) was the first to propose a list of possible triggering mechanisms:

- 1) Excessive water entering the arch material, possibly causing a loss of strength in the material. This is by far the most common trigger in South Africa.
- 2) Earth tremors causing vertical and lateral accelerations resulting in externally applied forces on the materials of the arches.
- 3) Differential ground movements resulting from subsidences associated with mining, which may upset the geometry of the arch.
- 4) Sustained subsurface loading of a vibratory nature.

A.B.A Brink stated in a discussion on the Far West Rand (in Wagener, 1984) that the accelerated development of surface subsidences and sinkholes is directly related to the artificial lowering of the water table. This is related to the settlement of the material as well as the ingress of water through fissures into the deeper water table.

SANS 1936 defines a sinkhole as a “feature that occurs suddenly and manifests itself as a hole in the ground”. This definition summarizes all of the above-mentioned types under a single definition. For all practical purposes, the SANS 1936 definition of a sinkhole will be used in this document. Due to the complexity of the formation process and the lack of sufficient information to classify sinkholes based on surface surveys, no distinction will be made between the various types of sinkholes as classified above.

2.2.4 *Subsidences*

Subsidences are enclosed depressions that are less defined than sinkholes, and occur slower (Trollip, 2006). They manifest as a pan-like depression in the ground, and are usually bordered by concentric cracks in the ground. These features form as a result of compression of low-density dolomite residuum at depth. In South Africa, and for the purpose of this study, the term subsidence refers to the geomorphological feature as discussed above, and not to the mechanism of formation.

The SANS 1936 (Part I) defines two main types of subsidences, de-watering-type subsidences

and surface-saturation-type subsidences. The third type of subsidence is rather an incompletely developed sinkhole, which merely has the form of the previously mentioned formations.

A *de-watering-type subsidence* generally occurs gradually and manifests itself as a large depression in the ground. The mechanism of formation is based on the lowering of the water level from within the compressible dolomite residuum and other weathered material (Trollip, 2006; SANS 1936, Part I; CGS, 2010). Due to the extraction of water from the pore spaces within the highly compressible soils, the consolidation of the material increases. Wagner (1984) states that a possible 30 m lowering of the water table may be equivalent to placing an additional 300 kPa load halfway between the level of the old and new water tables. The compression of the material then manifests itself as a surface depression. The size of this depression is dependent on the rate of water extraction (Jennings, 1966), the amount of compressible material and the depth of the material, i.e. the thickness of the overburden.

The *surface-saturation-type subsidences* are generally smaller in diameter (5 m) than the de-watering type subsidences, but are also dependent on the type of subsurface material, depth of the material, thickness of the overburden and also the availability of preferential water infiltration pathways (Trollip, 2006; SANS 1936, Part I; CGS, 2010). These subsidences are not dependent on lowering of the groundwater table, but occur due to the infiltration of surface water mobilising the highly weathered subsurface material. Due to the mobilisation and erosion of the underlying material, the overburden consolidates and manifests itself as a subsidence.

2.2.5 Risk related to dolomite

Due to the disastrous impacts associated with development on dolomite, dolomite may, according to the definition of a disaster in the Disaster Management Act (57 of 2002), lead or potentially lead to a disastrous situation. According to the Disaster Management Act (57 of 2002, section 1), a disaster may be defined as a progressive or sudden, widespread or localized, natural or human-caused occurrence which-

(a) causes or threatens to cause-

(i) death, injury or disease;

(ii) damage to property, infrastructure or the environment; or

(iii) disruption of the life of a community; and

(b) is of a magnitude that exceeds the ability of those affected by the disaster to cope with its effects using only their own resources

The related and interdependent concepts of hazard and risk are used when assessing the disaster associated with dolomite. These concepts intrinsically form part of the

implementation of **risk management** on dolomite. It is therefore essential to fully define and differentiate between these concepts. The interrelation between these concepts and its implication on development on dolomite and risk management is discussed in the following section.

SANS 1936, Part I, defines hazard as: “a source of potential harm” and risk as: “the effect of uncertainty of objectives “

The Oxford and Collins dictionaries respectively define *hazard* as 'a thing that can cause damage' and 'a thing likely to cause injury' and *risk* as 'the possibility of meeting danger' and 'the possibility of incurring misfortune or loss', that is, the 'possibility' of the 'thing' happening (Buttrick *et al.*, 2001).

In the context of assessing the stability characteristics of sites underlain by dolomite, *hazard* refers to: the feature (as described in sections 2.2.3 and 2.2.4 above) that manifests and is determined by the characteristics of the dolomite profile. The scale of the hazard is expressed as small, medium, large and very large size sinkhole. This may be quantified by means of geotechnical and geophysical surveys, geotechnical drilling, water level evaluations and geotechnical test pit analyses (Buttrick *et al.*, 2001).

The *inherent risk* of a site refers to: the probability of a certain size sinkhole or subsidence occurring within the postulated scenario of land use and dewatering or non-dewatering. This is therefore evaluated during the assessment of the entire site. The worst-case scenario must be postulated, ensuring the appropriate measures are adhered to.

According to Buttrick, *et al.* (2001), the development risk associated with development on dolomite refers to the likelihood and extent of loss of life, loss or damage to property, or financial loss and is rated in two categories, namely acceptable or unacceptable. This is based on the above-mentioned concepts of hazard and risk, together with the socio-economic factors which need to be considered in time.

2.3 Distribution of dolomite in South Africa

In this section the structural distribution of the dolomite within South Africa is briefly discussed followed by a discussion of the spatial distribution of dolomite within South Africa. This is of significance when compared to the urban settlements across South Africa.

Approximately 3% of South Africa is underlain by soluble rock (Wagner, 1984). Of this, 98% of the soluble rocks are the dolomites in the Chuniespoort Group of the Transvaal Sequence and the Cambell Group of the Griquatown West Sequence (van Schalkwyk, 1981).

2.3.1 Transvaal Supergroup

The Transvaal Supergroup is from the late Archaean to early Proterozoic time, and is divided

into three structural basins: the Transvaal and Griqualand West Basin in South Africa and the Kanye Basin in Botswana (see Figure 2 below). The Griqualand West Basin is furthermore subdivided into the Ghaap Plateau and Prieska sub-basins (Eriksson *et al.*, 2001). The Transvaal Supergroup is composed of various clastic, volcanic and chemical formations and has been subjected to various deformation phases, including the intrusion by the approximately 2060 Ma Bushveld Complex (Walraven and Martini, 1995). The Transvaal Supergroup encompasses one of the world's earliest carbonate platform successions (Beukes, 1987; Altermann and Wotherspoon, 1995). This includes well-preserved stromatolites and a full record of early cyanobacterial and bacterial evolution (Klein *et al.*, 1987; Altermann and Schopf, 1995).

The economic importance of the Transvaal Supergroup includes the extensive banded iron-formation (BIF) and the world's largest manganese deposits. Mississippi Valley-type base metals and structurally controlled gold deposits are also found within the Supergroup (Martini *et al.*, 1995; Altermann, 1997; Tyler and Tyler, 1996). From a dolomite stability perspective, the most important formations within the Transvaal Supergroup are the Chuniespoort and the Campbell groups (see Figure 2 below).

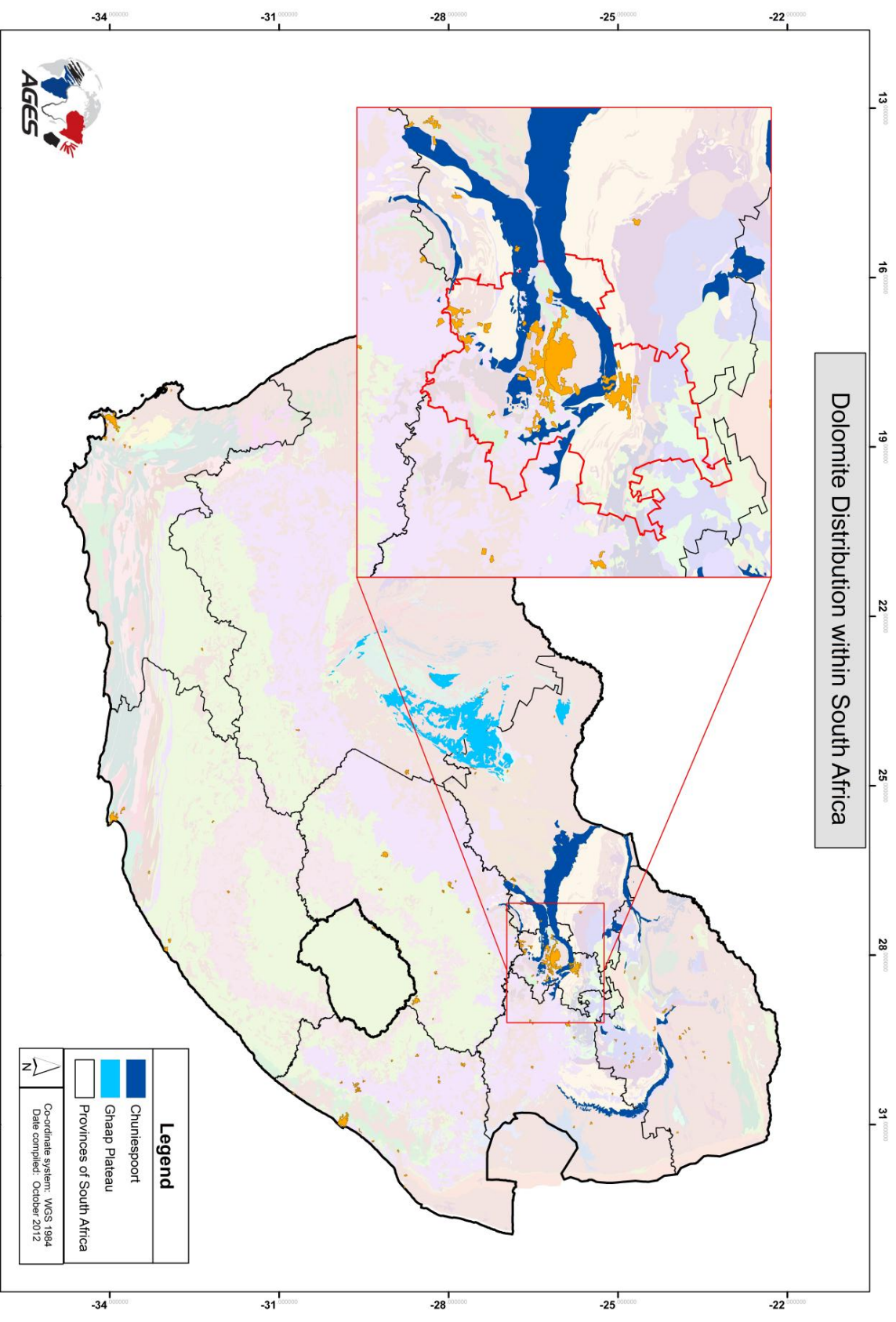


Figure 2: Spatial distribution of the Transvaal Supergroup (Source: ENPAT, 2000)

2.3.2 *Chuniespoort Group*

The Chuniespoort Group is subdivided into seven formations, the lower five consisting almost predominantly of dolomite and chert. The lower five formations, called the Malmani Subgroup, is underlain by the Black Reef Quartzite Formation, which forms a thin border below the dolomite. The thickness of this quartzite normally does not exceed 50m, except in the north- eastern Transvaal where it is up to 500m thick (Wagener, 1984; Brink, 1979). The Chuniespoort Group is overlain by the Timeball Hill and Rooihogte Formations of the Pretoria Group. The top two layers in the Chuniespoort are the Penge and Deutschland Formations, which have an unconform contact. The Penge Formation has been in part metamorphosised by the Bushveld Complex, and therefore exhibits various mineralogical variations (Miyano *et al.*, 1987). This variation in the Penge Formation makes the formation hard to identify during general drilling investigations.

2.3.3 *Malmani Subgroup*

The Malmani Subgroup is subdivided into five formations, based on the chert content and the presence or absence, as well as the variety of stromatolite structures (SACS, 1980). Extensive research has been conducted on the Malmani Subgroup succession and the successions above and below it. This research may include:

- Obbes, A.M. 2000. The structure, stratigraphy and sedimentology of the Black Reef – Malmani – Rooihogte succession of the Transvaal Supergroup Southwest of Pretoria
- Button, A. 1972. The stratigraphic history of the Malmani Dolomite in the eastern and north-eastern Transvaal.

The purpose of this study is not an in-depth research on the structural and lithological features of the various formations, but rather a stratigraphic breakdown and stability related interpretation of each of the formations, based on the chert content and structure and the presence of highly weathered material, such as wad. This stability related interpretations are also based on personal communication with Mr PW van Deventer (2011).

In the study done by Obbes (2000), the Rooihogte-Malmani-Black Reef succession was mapped out with high precision and detail. He furthermore identified some members within the formations. Table 1 is a representation of the structure subdivision of the Malmani Subgroup. This is followed by a discussion of each of the lithologies occurring within the Malmani Subgroup.

Table 1: Lithological subdivision of the Chuniespoort and Malmani dolomites

Supergroup	Group	Subgroup	Formation	Member	Lithology	Reference names *	
Transvaal	Pretoria		Rooihooigte	Pologround	Sandstone and interbedded siltstone		
					Shales and interbedded siltstones		
			Bevets	Chert conglomerate in ferruginous matrix	Bevets Conglomerates		
				Shales and siltstones			
			Frisco		Chert-free dark-brown dolomite	Mixed zone	
			Eccles	Leeuwenkloof	Giant Chert Breccia	Upper chert and dolomite zone	
					Chert-rich light-grey dolomite		
			Lytelton		Chert-free dark-brown dolomite	Principal chert poor zone	
		Chuniespoort	Malmani	Monte	Crocodile River	Chert-rich grey-brown dolomite	Lower chert and dolomite zone
	Rietspruit				Chert-rich and colour-banded dolomite		
	Mooiplaats				Chert-rich light-grey dolomite		
	Rietfontein				Chert-free light-grey dolomite		
	Oaktree				Chert-free dark-brown dolomite		
			Black Reef		Interbedded quartzite and shale	Transition Zone	

Source: After Obbes (2000). * The reference names referred to above forms part of the study done by Button, A (1972). These were correlated on the basis of their chert content.

Oaktree Formation:

This formation consists of dark-grey, chert free dolomite, and is characterised by large stromatolitic domes, shale marker beds and forms the transitional zone from the lower Black Reef siliciclastic sedimentation to platform carbonates. It is between 10 and 200 m thick, with carbonaceous shales, stromatolitic dolomites and locally developed quartzites (Erikson *et al.*, 2001). This zone is classified as the “transition zone” by Button (1972). Due to the paucity of the chert appearing in this layer, the carbonaceous mudstone and shale, as well as the conglomerates, this zone is not of great geotechnical risk from a dolomite stability perspective due to the fact that sufficient build-up of fluids is highly unlikely. But extensive formation of wad may take place in weathered areas due to the high manganese content of the dark dolomite.

The transition between this formation and the overlying Monte Christo Formation is gradational and is taken at the change from dark-brown to light-grey dolomite and a corresponding increase in the chert content (Obbes, 2000).

Monte Christo Formation:

This Formation is between 300 – 500 m thick and starts from the bottom with stromatolitic and oolitic platform dolomites grading into an erosion breccia at the top (Erikson *et al.*, 2001). This chert-rich formation is subdivided into four members by Eriksson and Truswell (1974), based on the chert-in-shale breccias, chertified stromatolite marker beds and the presence or absence of stromatolites (Eriksson and Truswell, 1974). This formation is classified as the “lower chert and dolomite zone” by Button (1972). He furthermore classifies this zone into chert-poor and rich zones. This formation is predominantly characterised by the abundance of chert and the light colour of the associated dolomite. These chert layers vary in thickness from thin laminae up to a thickness of 2 m (Button, 1972). This chert layer plays a very important role in the sinkhole forming process, due to the possible accumulated build-up of fluids, creating preferential pathways and weathering zones above and below the chert layers. This in turn may cause development of extensive cavities and disseminated voids, which may upon infiltration of water, accept overburden to the extent of the volume of the developed cavity. The solid chert layers often carry the overburden to such an extent that the size of the cavity is such that the roof collapses. This may in many cases be enough to form sinkholes or subsidences. Jennings (1966) has done extensive research on the bearing capacity, void ratio and size of cavity and size of sinkhole formation.

This formation may be identified based on the light colour of the dolomite and development of sedimentary structures such as oolites, ripple marks, interference ripple marks, climbing ripples, and rarely beds of edgewise conglomerates (Button, 1972).

Lyttelton Formation:

The Lyttelton Formation consists of 100 – 200 m of shales, quartzites and stromatolitic dolomites (Erikson *et al.*, 2001). The dolomites of this formation are dark-grey in colour, but weather to a dark chocolate-brown colour. This formation is furthermore characterised by a subdued topography. This formation is classified as the “chert-poor zone” by Button (1972). The chert developed in the formation is present in thin, discontinuous lens-like layers. This layer is furthermore characterised by various clastic layers and disseminated, plate-like chert and dolomite erosion breccias (Button, 1972). The dark weathering of the layer is attributed to the high manganese content. This in turn will lead to the formation of wad and ferroan soils. The disseminated voids and occurrences of wad in this formation may lead to the development of dewatering type subsidences, but will rarely lead to the development of sinkholes. The transition zone from the Lyttelton Formation is gradational over a few meters, and is identified by a change in the colour of the dolomite to a lighter colour, as well as the chert content in the dolomite.

Eccles Formation:

The Lyttelton Formation is overlain by the cherty Eccles Formation, which may be up to 600 m thick (Erikson *et al.*, 2001). This formation is characterised by the light-grey interbedded dolomite and chert bands. It is classified as the “upper chert and dolomite zone” by Button (1972). This formation resembles the Monte Christo Formation to a certain extent with regard to the occurrence of chert, which may take place in bands from a fraction of a millimeter to 2 meters thick. The formation is furthermore characterised by a renowned “bread and butter dolomite” formation of the chert. This consists of chert bands, about 3 cm in width, spaced about 15 cm apart. The interlayered areas are presumed to be areas where dolomite has not yet fully developed, or in some cases, where wad is evident, the dolomite has been weathered away. From personal experience of drilling in this formation, the chert bands are the predominant factor in dolomite stability assessments. The weathered zones are mostly encountered directly above or below the chert bands, suggesting the development of preferential fluid flow paths creating highly weathered zones within the dolomite. These areas may become possible receptacles for overburden up to the extent of the volume of the possible cavity. This formation may be regarded as a formation with higher risk related to dolomite instability. The Eccles Formation is separated from the overlying Frisco Formation with a prominent erosion breccia, which is in many cases referred to as the “Giant Cherts” (Bischoff, 2012).

Frisco Formation:

This formation is the top formation of the Malmani Subgroup, and is composed predominantly of stromatolitic dolomites. This layer may be up to 400m thick, and becomes more shale rich to the top of the formation (Erikson *et al.*, 2001). The dolomites of this formation are dark-

grey in colour and weather to a dark-brown colour. This zone is classified as the “mixed zone”. The chert present in this zone is usually banded lighter and darker grey on a centimeter to centimeter scale. This formation has less predominantly formed chert bands, but may result in the formation of wad in highly weathered areas.

2.3.4 *Ghaap*

The Griqualand West basin is subdivided into the Ghaap Plateau and Prieska sub-basins (Eriksson *et al.*, 2001). The Ghaap Group is furthermore subdivided into the Schmidtsdrif, Campbell Rand, Asbestos Hills and Koegas Subgroups (in stratigraphic order). The Asbestos Hill and Schmidtsdrif Subgroups are uniform across the entire basin, the Koegas Subgroup is preserved only in the southern part of the basin, but the Campbell Rand Subgroup is comprised of different sedimentary facies in the Prieska and Ghaap Plateau sub-basin. The Table 2 is a basic account of the stratigraphy of the Ghaap Group, with the Vryburg Formation at the base of the representation:

Table 2: Lithological subdivision of the Ghaap and Cambellrand dolomites

Supergroup	Group	Prieska Sub-Basin		Ghaap Plateau Sub-Basin			
		Subgroup	Formation	Subgroup	Formation		
Transvaal	Ghaap	Asbestos Hill	Danielskuil	Asbestos Hill	Danielskuil		
			Kuruman		Kuruman		
			Kliphuis		Kliphuis		
		Campbellrand	Klein Naute			Campbellrand	Tsireng
							Gamoiaan
							Koggelbeen
							Papkuil
							Klipfontein-heuwel
							Fairfield
							Reivilo
							Montevillo
							Nauga
		Schmidtsdrif				Schmidtsdrif	Clearwater
							Boomplaas
							Vryburg

Source: After Eriksson *et al.*, 2001.

Schmidtsdrif Subgroup

The Schmidtsdrif Subgroup consists of the Boomplaas and Clearwater Formations. The former consists of stromatolitic and oolitic carbonate platforms, grading into the later shales, tuffites and BIF-like cherts. The Schmidtsdrif Subgroup grades into the Cambellrand Subgroup.

Formations of the Ghaap Plateau Sub-basin

The Montevillo Formation is composed of giant stromatolitic domes, succeeded by microbial laminates, shales and siltstone. This formation correlates in age to the Oaktree Formation of the Malmani Subgroup (Altermann and Nelson, 1998). The Reivillo, Fairfield, Klipfontein, Papkuil and Klippan Formations all consists of various types and amounts of stromatolites and oolites. The Kogelbeen Formation is represented by varying dolomite, limestone and chert lithologies (Eriksson *et al.*, 2001). The chert layers in the formation may attribute to the possible dolomite risk associated with a site. The Gamohaan and Tsineng Formations are microbial carbonates and cherts.

Formations of the Prieska Sub-basin

The Nauga Formation is composed of carbonates, and the Klein Naute Formation is composed of a thick sequence of shales, with some thick lateral extending chert (Eriksson, *et al.*, 2001).

2.3.5 Correlation between the Malamani and Ghaap Subgroups

The Table 3 illustrates the basic correlation between the lithologies of the Chuniespoort/ Malmani dolomite and the Ghaap/ Campbellrand dolomite:

Table 3: Transgressional interbasin correlation between the Chuniespoort and Ghaap Groups

AGE (Ma)	Transvaal Basin			Ghaap Plateau Sub-Basin			Prieska Sub-Basin			
	Group	Subgroup	Formation	Group	Subgroup	Formation	Group	Subgroup	Formation	
2420	Chuniespoort Group		Duitschland	Ghaap Group	Asbestos Hill	Danielskuil	Ghaap Group	Asbestos Hill	Danielskuil	
			Penge			Kuruman			Kuruman	
2500						Kliphuis			Kliphuis	
		Malmami	Friso		Tsining	Campbellrand		Gamohaam	Klein Naute	
					Kogelbeen					
					Papkuil					
					Klipfontein-heuwel					
					Fairfield					
2550								Eccles		Reivilo
								Lyttelton		Monteville
2600								Monte Christo		
								Oaktree		
										Schmidtsdrif
					Boomplaas	Boomplaas				
2650		Black Reef Formation			Vryburg Formation			Vryburg Formation		

Source: After Altermann and Nelson (1998)

2.4 Development and infrastructure on dolomite

Due to poor workmanship or use of inferior materials or due to deterioration of the materials, leakages often occur in water bearing services such as sewers, water pipes, storm water systems etc. These leakages increase in frequency as the water bearing services deteriorate (DPW, 2006). As described in Section 2.2 of this document, water infiltration is regarded as one of the major causes of sinkholes, therefore, as the frequency of leaks increases, so does the likelihood of sinkhole and subsidence formation. The main issue regarding infrastructure and dolomite is the fact that areas with high densities and amounts of infrastructure are usually also the most densely populated. This is also the case in Gauteng, which is the country's most populated province, of which 23% is underlain by dolomite (Buttrick *et al.*, 2011).

Buttrick *et al.* (2011) conducted a survey including the frequencies and amount of sinkholes induced by infrastructure over a 20 year period (1984 – 2004) across a 3 700 ha urbanized area located south of Pretoria. According to this study it was found that 643 out of the 650 sinkholes (99%) that were observed were found to be directly attributed to leaking services or humans' negative influences.

All residential developments depend on infrastructure for its existence. Yet on dolomite, it is the infrastructure that increases the risk of the development. Infrastructure designed for development on dolomite, such as infrastructure with a longer lifespan and infrastructure, which may be more tolerable to corrosion and ground movement, are more expensive than normal infrastructure. The development pressure in South Africa is mostly for low-income housing and not for high income housing. This has related negative impacts on cost, which if the site is underlain by dolomite, increases the development difficulty and in effect also the costs. It is therefore essential to characterise dolomite land before the development has taken place, and by doing so, eliminate areas which may require high infrastructure costs.

2.5 Legal Framework and standards

Due to the risk associated with areas underlain by dolomite and the extent of development on dolomitic land in South Africa, various legal frameworks and standards have been set up and implemented to regulate housing and infrastructure development. The most important of these are:

- Department of Public Works, 2006. Appropriate development of infrastructure on dolomite: Manual for Consultants;
- South African National Standards (SANS) 1936, Part I - IV;
- Geoscience Amendment Act, Act no. 16 of 2011. Department Of Mineral Resources. Governmental Notice. 7 September 2011.

- National Home Builders Registration Council (NHBRC), 1999. Home building manual Part 1 & 2.

Furthermore, according to the Constitution of South Africa (108 of 1996), a local authority has a responsibility towards the health and safety of its inhabitants:

Section 24 states: “Everyone has the right to an environment that is not harmful to their health or well-being” while section 152 (1(d)) states “the object of local government is to promote safe and healthy environments”

This is confirmed by the Local Government Municipal Systems Act (32 of 2000, Section 4(2) (i)) where the Council of a municipality ... has the duty to ... (i) promote a safe and healthy environment in the municipality”

It is also important to consider the legal implications and liabilities in terms of the following acts:

- The Occupational Health and Safety Act (Act 85 of 1993)
- Section 12 of Act 95 of 1998
- Act 103 (1977) National Building Regulations
- SANS 10400-B

2.6 Dolomite Risk Management

Due to the need for structure and guidance with regard to development on dolomite, the SANS and Geoscience amendment Act (16 of 2011) proposed the implementation of a Dolomite Risk Management Strategy (DRMS). This is a process which uses *“scientific, planning, engineering and social processes, procedures and measures to manage an environmental hazard, and encompasses policies and procedures set in place to reduce the likelihood of events (sinkholes and subsidences) occurring on dolomite land”*(SANS 1936, Part IV).

Dolomite risk management may take place at three levels. The principles are the same at all levels, with only some of the specific procedures and measures that differ. These levels are (SANS 1936, Part IV):

- Local authority level;
- Bulk service provider, utility organization and government department level;
- Individual development level.

The following requirements and standards have been outlined in the Geoscience Amendment Act (16 of 2011), in which state authorities with different situations at hand need to conduct different DRMS's:

- All state authorities that are directly considering new development of infrastructure of their own on dolomitic land;
- All state authorities that have existing developments or infrastructure of their own on dolomitic land;
- All state authorities that grant permission to develop on dolomitic land under their jurisdiction;
- All state authorities with decision making power by virtue of their jurisdiction through applicable legislation;
- All mining companies that operate on dolomitic land;

Table 3 represents the various components that need to be implemented in compiling a Dolomite Risk Management Strategy:

Table 4: Components of a Dolomite Risk Management Strategy

Component of Dolomite Risk Management Strategy	Entity responsible for compiling a Dolomite Risk Management Strategy							
	State Authority						Bulk service provider	Private Development
	New development	Existing development	Permission granting	Decision making power	Mining: Existing mine	Mining: New mine		
Dolomite Geotechnical Stability Investigation	x	x	x		x	x	x	x
Dolomite Risk Management Plan	x	x	x		x	x	x	x
Implementation Plan	x	x			x		x	x
Development Sensitivity Assessment		x			x			
Infrastructure and foundation assessment		x			x			
Land use assessment				x			x	
Preliminary development assessment		x			x			

Source: Own construction (2012) based on documentation listed in section 2.5

From this table it is evident that a DRMS is a strategic document focused on the alignment and management of all procedures and measures related to dolomite risk management so as to “manage the risk” related to dolomite and development on dolomite. This includes:

- Decision making;

- Management;
- Integration;
- Mitigation;
- Regional implementation; and
- Monitoring and evaluation.

The decision support system discussed in section 4 of this document will be based on the dolomite stability investigations (DSI) process, which is a subcomponent of a DRMS. It is important to understand that these are two separate independent procedures that take place simultaneously but support one another.

2.7 Dolomite stability investigation

The following section discusses various models of evaluation and reporting of dolomite land. This will be concluded by a final framework for a dolomite stability investigation which will be implemented in Chapter 3.

2.7.1 SANS 1936

According to SANS 1936 (Part II), a dolomite stability investigation is a geotechnical site investigation on dolomite land. Such a report must include:

- A site description and description of the investigation;
- An assessment of the basic geological and geomorphological features of the site, as well as any existing karst features within and in close proximity to the site;
- A geotechnical site investigation including a gravity survey and borehole drilling;
- Compilation of a geohydrological model of the site, including original ground water levels and fluctuations and assessment of the effect of the fluctuations;
- From the above mentioned, a geotechnical model must be developed for the site based on an assessment of the bedrock morphology, the subsurface profile from ground surface to dolomite bedrock, and the geohydrological conditions;
- The geotechnical model is then used to determine the inherent hazard class and dolomite area designation of the site.

From this information the following actions must take place:

- Evaluation of the appropriateness of proposed land usage on the site (in accordance with SANS 1936 part 1);
- Indication of what information is needed for identification of the precautionary measures and the DRMS;

- Identification of shortages in the current data if a design-level investigation is to take place;
- Identification and quantification of any hazard that might impact upon the development of the land.

Finally recommendations must be given regarding the selection and design of foundations, structures and infrastructure and the precautionary measures associated there with. This must be integrated in the DRMS so as to achieve and sustain a tolerable hazard rating.

2.7.2 Geoscience Amendment Act (16 of 2011)

According to the Geoscience Amendment Act (16 of 2011), a dolomite stability investigation is referred to as a dolomite geotechnical report. Such a report must include the following:

- Site location and site description, including a locality map and site map with contour lines;
- Coalition of all existing data from the study area, as well as of all adjoining sites;
- Conduction of a field survey, including research o previous work, relevant geological outcrops and survey for and sinkholes and subsidences;
- Conduction of a gravity survey;
- Conduction of rotary percussion drilling;
- Digging and inspection of trial holes and test pits;
- Soil sampling and testing;
- A description of the local and regional geological setting of the study area;
- A geohydrological description indicating and discussing the nature of the groundwater level fluctuations, compartmentalization, original groundwater level and how these affect the stability at and in the vicinity of the site;
- A stability evaluation and description of the evaluative procedures, including a final zonation map and a discussion of how the gravity and borehole results were interpreted to delineate the final results. This must be based on the following: a) receptacle development, b) mobilisation agencies, c) potential development space, d) nature of blanketing layer, e) mobilisation potential of blanketing layer and f) the bedrock morphology;
- The report must then be finalised with a conclusion and discussion of the relevant recommendations.

2.7.3 Council for Geoscience

The Council for Geoscience (CGS) is a semi-government organization and is the national custodian of all geoscientific information in South Africa (100 of 1993). It has compiled and developed “*a comprehensive and integrated collection of knowledge of geology...engineering geology... and geomagnetism*” (100 of 1993) within South Africa. It may also “*advise the Minister on research in the field of geoscience*” (100 of 1993). It is therefore appropriate that all DSI reports are sent to the CGS for review so as to ensure that the evaluations and recommendations are correct (NHBRC, 1999:23).

The Dolomite Section of the CGS has compiled the following document as a guideline for all dolomite related work in South Africa:

- Consultants Guide: Approach to sites on dolomite land. November 2007

According to this document the Geoscience Act requires the CGS to advise government institutions and the general public on the judicious and safe use of land (CGS, 2007:1). This document makes use of the term dolomite stability investigation and proposes the following structure:

- A site location and description indicating the exact location of the site and relevant information regarding the present and past use of the land, vegetation, slope/topography/contours;
- Research of existing information about the site and the surrounding area;
- Conducting of a field inspection;
- Conducting of geophysical surveys;
- Conducting of rotary percussion drilling;
- Evaluation of the regional geological setting and characterisation of the blanketing layer and the bedrock topography and morphology;
- A discussion of the original groundwater level, groundwater fluctuations and compartmentalization and how these affect the stability on and in the vicinity of the site;
- Conducting of a stability evaluation of the site, based on the following mobilising agencies: major groundwater level fluctuations (> 6m), ingress water, ground vibrations and gravity. The following evaluation factors must be considered: a) receptacle development, b) mobilising agencies, c) potential sinkhole development space; d) nature of the blanketing layer, e) mobilisation potential of the blanketing layer and f) the bedrock morphology;
- The report must then be finalised by a conclusion and recommendation.

The afore mentioned structure proposed by the CGS is in most areas identical to the structure

in section 2.8.2 as proposed in the Geoscience Amendment Act (16 of 2010). The main differences are:

Table 5: Comparison between Geoscience Amendment Act and CGS Guideline for Consultants

Geoscience Amendment Act	CGS – Guideline for consultants
Reference is made to the report as a dolomite geotechnical report	Reference is made to the report as a dolomite stability investigation
Digging and inspection of trial holes and test pits	Only percussion drilling
Soil sampling and testing	On-site characterisation
Description of local and regional geological setting	Description of the regional geological setting
No identification of the mobilizing agencies needed	Identification of mobilizing agencies necessary

2.7.4 Other stability investigation guidelines

The National Home Builders Registration Council’s Home Building Manual (NHBRC, 1999) is focused on recommendations and guidelines for developments. This includes contents and alignment with the DRMS of an area and to those of the surrounding area. They do not outline a specific dolomite stability investigation structure, but specifies that such a report must include the impact of the development (boreholes, storm water and water reticulation systems, swimming pools and gardening) on the underlying strata and in effect the hazard rating of the dolomite. As previously mentioned, the manual does specify that all DSI reports must be submitted to the CGS (NHBRC, 1999:23)

The focus of the guideline developed by the Department of Public Works also falls more on the appropriate development and risk management of infrastructure located on dolomite (DPW, 2006). It provides a comprehensive set of guidelines with detail designs and recommendations to insure the correctness and the correct installation of infrastructure on dolomite. This manual relies to a large extent on the NHBRC “D designation” of dolomite land. It stipulated the following general risk characterisation:

Table 6: Department of Public Works general risk characterisation

General Risk Characterisation	Inherent Risk Classes
Low	Class 1
Medium	Classes 2,3 and 4
High	Classes 5, 6, 7 and 8

Source: After Department of Public Works, 2006

All engineering and design details and recommendations in the DPW manual for consultants are based on the above mentioned general risk characterisation

2.7.5 Dolomite Stability Investigation framework (DSI)

From a coalition of all the above information it was determined that a DSI is an (geo-) investigation conducted to determine the geotechnical risk associated with the metastable dolomite underlying a future or existing development. The structure of such a report is formulated as follows:

- Introduction, specifying the background to the study and previous investigations and information that is available;
- Geo-environmental setting including the location and extent of the study area, the drainage and topography/contours and the vegetation and climate;

A full outline of the project is then given, detailing the fieldwork and data evaluation procedures that will be followed.

- Geological assessment of the regional and local geological setting of the study area, including an assessment of all existing instability features in the area and all possible structural information such as faults and folds in the area.;
- Geophysical surveys of the area;
- Percussion borehole drilling, based on evaluation of the structural geological setting of the area and the geophysical surveys of the area;
- Geohydrological assessment of the area on a regional and local scale so as to determine the geohydrological regime of the area, including groundwater fluctuation and water uses of the site and surrounding area. Geohydrological monitoring and modelling may also play a very important role.
- Final zonation based on the hazard characterisation and evaluation procedures. These are based on a) receptacle development, b) mobilisation agencies, c) potential surface manifestation development space, d) nature and mobilisation potential of the blanketing

layer and e) the bedrock morphology. This is evaluated in conjunction with the geophysical data and the geohydrological regime of the area;

- This is finalised by conclusions and recommendations based on the NHBRC classification and allowable land uses of the area.

This DSI process forms the basis of the study discussed in Chapter 3 and will be evaluated in terms of the decision support system derived from this study.

2.7.6 *Inherent hazard classification*

It is important to note that inherent hazard classification is a complicated process developed by Buttrick *et al.* (2001). This classification is based on the geotechnical model of each site. This process is discussed in detail in the following publication:

- Buttrick, D. B., van Schalkwyk, A., Kleywegt, R. J. & Watermeyer. 2001. Proposed method for dolomite land hazard and risk assessment in South Africa. *Journal of the South African Institution of Civil Engineering*, 43:2.

This process is based on the theoretical determination of the possible sinkhole and subsidence size, in relation to the probability that a feature may occur under the specific conditions of that site. These theoretical sizes are then interpolated over the entire site, based on and limited to the extent of the drilling information and gravimetric survey.

This theoretical classification process is based on the following contributing factors:

- Blanketing layer
- Possible receptacles
- Mobilisation and mobilisation agents
- Maximum potential development space

Based on the information gathered during the geotechnical drilling and geotechnical profiling, each individual borehole is characterised. This is done by determining the possible angles of draw of each layer from the sidewalls as well as its thickness. This in turn is used to determine the theoretical possible sinkhole size. These individual boreholes are then viewed spatially and correlated. Based on the maximum size of a potential feature to form and the probability of formation of that feature, the risk is allocated. This rating is based on a rating from one to eight, where one is the least risk and eight is the highest.

By means of this process an area may be zoned based on the various inherent hazard classes. These classes range from 1 to 8 based on the criteria in Table 7:

Table 7: Inherent hazard class rating (Buttrick *et al.*, 2011)

Inherent hazard class	Characterisation of the area
Class 1	Areas characterised as reflecting a low inherent susceptibility for feature formation of all sizes.
Class 2	Areas characterised as reflecting a medium inherent susceptibility of small-size feature formation.
Class 3	Areas characterised as reflecting a medium inherent susceptibility of up to medium-size feature formation.
Class 4	Areas characterised as reflecting a medium inherent susceptibility of up to large-size feature formation.
Class 5	Areas characterised as reflecting a high inherent susceptibility of small-size feature formation.
Class 6	Areas characterised as reflecting a high inherent susceptibility of up to medium-size feature formation.
Class 7	Areas characterised as reflecting a high inherent susceptibility of up to large-size feature formation.
Class 8	Areas characterised as reflecting a high inherent susceptibility of up to very large-size feature formation.

Source: After Buttrick *et al.* 2011

In the above mentioned table susceptibility refers to the susceptibility of a certain area for a feature to occur in a certain timeframe and feature refers to either a sinkhole or subsidence. The feature size is based on the following sizes:

Table 8: Feature size classification

Diameter of surface manifestation	Classification
< 2 meters	Small size feature
2 – 5 meters	Medium size feature
5 – 15 meters	Large size feature
> 15 meters	Very large feature

Source: After Buttrick & van Schalkwyk, 1995