An Independent Review and Summary of Geotechnical Information Pertaining to the Sidewall Stability of the Kimberley “Big Hole” Mine, with Specific Focus on the Weathering and Deterioration of the Kimberley shales.

By

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DECLARATION

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ABSTRACT

The Kimberley “Big Hole” Mine in the center of Kimberley experiences frequent small scale toppling and landslide slope failure events, which causes the sidewalls of the pit to slowly migrate outward towards surrounding businesses and infrastructure. The reason for slope stability problems and slope failures can be ascribed to the vast susceptibility of the underlying Kimberley shales to weather and deteriorate when exposed to the atmosphere and natural weathering conditions. This sets into motion a process known locally as “mine pit break-back”, where regression of the underlying shale unit causes the overlying dolerite cap to break off into large dolerite blocks or boulders, which eventually topples over and into the open mine pit as single block toppling slope failure events. In order to help combat this problem of undermining at the Kimberley “Big Hole” Mine, five different dust and erosion control liquids were identified on the basis of forming a waterproof and weather resistant base around the surface it is applied to. In theory, all five dust and erosion control liquids should prevent water ingress through the surface of the rock and create a protective layer that will increase rock durability and weathering resistance of the Kimberley shales. These products were tested by using various durability and weathering test techniques including absorption tests, cyclic wetting and drying tests, comparative accelerated weathering tests and slake-durability index tests. The ultimate aim of this project was to identify one of these dust and erosion control liquids as a viable solution towards the defined slope stability problem at the Kimberley “Big Hole” Mine and in turn stop the process of mine pit break-back by applying this product to the sidewalls of the pit.

In addition, many non-conventional techniques of measuring ground movement or displacement around large open pits, such as the Kimberley “Big Hole” Mine for example, were used to identify the entire extent of slope stability problems at the Big Hole Mine, as well as determine the migration pattern for the sidewalls over the past 46 years. These ground movement measuring techniques included a direct visual inspection of the slopes and sidewalls of the Kimberley “Big Hole” Mine as well as the remote sensing and pixel tracking of aerial photographs between the years 1968 and 2014.

The abovementioned procedures delivered significant result towards combatting the defined slope stability problem at the Kimberley “Big Hole” Mine and conclusions and recommendations surrounding further work at the open pit mine is worth further investigation. The Sasbind DECL product prevailed as the most successful and effective DECL product with regards to increasing the rock durability and weathering resistance of the Kimberley shales after each durability and weathering test, which lead to the conclusion that application of this product to the sidewalls of the Kimberley “Big Hole” Mine could prove to be highly successful in addressing the slope instability problem at the Big Hole Mine. Further testing in this regard is justified and recommended.

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CHAPTER 1: Introduction

1.1 Background

The small and historic mining town by the name of Kimberley, which is located in the dusty plains of the Northern Cape, owes its renowned existence to the commencement of diamond mining after the early discovery of the Kimberley Mine (also commonly referred to as the “Big Hole”). It is well documented throughout history that as soon as mining commenced at the Kimberley “Big Hole” Mine, which dates back as far as the year 1871, it resulted in a fast and ever growing mining camp with hundreds of primitive and permanent residences being raised daily around the pit. In fact, as mining operations flourished in the discovery of massive gem quality diamonds at the nearby Kimberley Mine, it did not take long for the town of Kimberley to be established around the Kimberley Mine as it still stands to this day. According to Preece et al. (2008), it only took about six years after the first discovery of diamonds in the area, before the town of Kimberley was proclaimed a municipality on the 27th of June 1877.

Equally well documented throughout many of the South African history books, was the first amalgamation and existence of the world-famous diamond mining company known as De Beers Consolidated Mines Limited (“De Beers”) in the year 1888, whom in only one year had managed to acquire the majority of all the claims in the Kimberley Mine and become a world-leading diamond production company in the year 1889. De Beers then became known as a colossal financial empire by single-handedly controlling the monopoly of diamond exploration and production in South Africa. It can be said that the history and legacies of both the Kimberley Mine and the De Beers company, goes hand-in-hand with one owing its existence to the other. Their paths to success being so closely intertwined as the streets of Kimberley today borders the outer fringes of the Big Hole Mine. Kimberley Mine was operated by De Beers from its existence in 1889 until its closure in 1914 and is still owned by De Beers to this day.

Considering the many years that have passed since the establishment of Kimberley as a town and the associated Kimberley “Big Hole” Mine, it comes as no surprise that many geotechnical and geological reports exists that pertain to the stability of the sidewalls of the Big Hole Mine. Seeing as the whole town was built narrowly surrounding the outer perimeters of the Big Hole, a single collapse of only one of the sidewalls of this deep open pit could lead to devastating consequences for the people and the town of Kimberley. Not only could such a failure lead to the loss of surrounding businesses and infrastructure, but it could also possibly lead to the loss of human lives. As a result, damages done by such an event could cost a fortune to rebuild or even just repair.

This project will therefore follow an integrated approach to focus on both the geological parameters and characteristics of the Kimberley “Big Hole” Mine, with the aim of assessing and understanding the overall stability of the Big Hole as it stands today, as well as on the application of an engineering method / technique which might prove valuable in combatting the existence of any slope instability problems which may have been found at the Kimberley “Big Hole” Mine. Up to date, no concerns around this matter have been raised and the only two available geotechnical engineering reports pertaining to the overall state and stability of the sidewalls of the Kimberley “Big Hole” Mine, were written to advise on the closure of Bultfontein Road rather than suggesting a viable engineering solution. Together, the integrated approach will ultimately be used to:

1. Determine whether the Kimberley “Big Hole” Mine does in fact show any signs of slope instabilities, which might later on lead to a possible slope failure or collapse and if so, does it pose an immediate threat or a long term problem?
2. Plan and propose an engineering solution that reflects the most economically viable and physically practical technique, which might help combat the identified slope stability problem at the Kimberley “Big Hole” Mine. The proposed engineering solution will include all engineering aspects including: viability, sustainability and limitations.

1.2 Motivation for Research

The Kimberley “Big Hole” Mine not only became world-famous in 1871 as one of the richest kimberlite pipes ever to be found on earth, but it is also still renowned for being one of the widest and deepest hand-excavated pits known to man. Due to the fact that the Kimberley “Big Hole” Mine played such a pivotal role in the financial and economic success of South Africa’s history and it still being one of the Northern Cape’s most visited and iconic tourist attractions, it is not difficult to see why the preservation of such an iconic South African landmark is of utmost importance. This thesis will therefore investigate the stability and safety of the Kimberley “Big Hole” Mine with the aim of endorsing its preservation and legacy for many years to come.

1.3 Aims and Objectives

Considering the practical importance of such a project and the use of a two-phased approach to determine its feasibility, it comes as no surprise that this project will consist of many chronological aims and objectives:

1. Phase One would be used to assess and determine the exact state and stability of the sidewalls of the Kimberley “Big Hole” Mine as it stands today in order to understand the extent of the problem.
2. The second phase of the two-phased approach would focus more on confronting the problem as defined by the first phase of this project in order to find or suggest a viable solution. It will involve the use various geological and geotechnical research techniques with the aim of providing and assessing a feasible solution. In order to propose such an economically viable and practical resolution towards the defined slope instability problem at the Kimberley “Big Hole” Mine, this project will:

2.1. Focus on micro analyzing the collected rock samples in order to better understand and interpret their molecular and chemical characteristics. The purpose of doing this is to classify the rock and to use the information to further investigate and determine its specific mineralogical properties.

2.2. Comprise an experimental phase in which a specific stabilizing technique will be tested and evaluated as to report on its viability at the Kimberley “Big Hole” Mine. The testing program will consist of a series of well-planned fieldwork and laboratory tests.

3. In conclusion, the final objective for this project would be to consider all available as well as any newly gained information and make an informative recommendation concerning any future work at the Kimberley “Big Hole” Mine as well as its surrounding area. This part of the project will only act as an informative conclusion to the findings of the research. It will act to either recommend the application of the proposed geotechnical solution in the light of it being viable to the encountered slope stability problem at the Big Hole Mine, or it would dismiss the significance thereof and encourage further research on the topic before such recommendations be made.

1.4 Limitations of Research

During the course of this project, a few problems arose which could not have been foreseen or dealt with. These unanticipated matters resulted in a change in the general data collecting process as well as in the overall analyses and interpretation of the obtained results.

The most significant limitation to the original scope of this project was the refusal of any sampling by De Beers at the Kimberley “Big Hole” Mine, which called for an alternative plan to be set into place. Therefore, instead of collecting samples directly from the Kimberley “Big Hole” Mine, a very similar mine (in terms of origin, structure and geology) was identified and utilized. The Bultfontein Mine, located only about 5 km north of the Kimberley “Big Hole’ Mine and owned by Petra Diamonds, was therefore used as a proxy for the Kimberley “Big Hole” Mine and all rock samples were obtained from the site visits to the neighbouring Bultfontein Mine. This could only be done due to a strong correlation between the general slope, geometry, structure and especially the geology of the two open pit mines (i.e. Kimberley “Big Hole” Mine & Bultfontein Mine).

Due to financial restrictions, only a limited amount of each dust and erosion control liquid (DECL) could be obtained and used for the necessary laboratory tests. A larger quantity of each product might have prompted a different scope of study as different test procedures would have been followed, especially with regards to the conducted laboratory tests.

The study is furthermore limited to only those aspects deemed critical to the overall state and stability of the slopes of the Kimberley “Big Hole” Mine, and not all aspects and risks were taken into consideration. The research was limited to the stability and safety of the mine pit slopes, with specific focus on the weathering of Kimberley shales and the methods of interpreting the degradation thereof under exposure to various elements and mechanical agitation.

1.5 Report layout and structure

This thesis consists of seven chapters, which include the introductory chapter, literature review, case study, a chapter defining the cause of instability at the mine, methodological procedures followed, and an evaluation of the results and interpretations followed by conclusions and recommendations. Each chapter will be described in short.

Chapter 2 and Chapter 3 constitutes a full desk study of all available literature, including any and all geological and geotechnical reports that pertain to the state and stability of the sidewalls of the Kimberley "Big Hole" Mine. Chapter 2 is specifically concerned with reviewing literature pertaining to the Kimberley "Big Hole" Mine, including information on the historical background of the pit, its origin and geological parameters and characteristics, whereas Chapter 3 describes a specific case study of the nearby located Bultfontein Road.

Chapter 4 concludes the first phase of this project and defines the slope stability problem at the Kimberley "Big Hole" Mine, including reasons therefore.

Chapter 5 introduces the second phase of this project by describing the various methodological test procedures that were followed in testing various solutions towards the defined slope stability problem at the Kimberley "Big Hole" Mine. It includes a very comprehensive step-by-step overview of the exact test procedures that were followed.

Chapter 6 discusses the results of the various test procedures. It analyzes and interprets the results of each durability and weathering tests, whilst Chapter 7 draws the whole project to a close with the necessary conclusions and recommendations towards the defined slope stability problem at the Kimberley "Big Hole" Mine. In the appendices, the extended calculations can be found as mentioned in the text.

Chapter 2: Literature Review

2.1 Introduction

As an introduction to the full scope of this project, which includes an in depth study on the state and stability of the sidewalls of the Kimberley “Big Hole” Mine, the following chapter will provide a brief overview of the most important aspects concerning the town of Kimberley, the Big Hole Mine and the related slope stability problem in the area. The chapter therefore starts with a brief discussion on the history of the Kimberley “Big Hole” Mine, including its discovery and exploitation by a company known as De Beers, which leads into an informative description of kimberlite pipes and their origin. The second part of the chapter deals more with the Kimberley “Big Hole” Mine itself, focusing mainly on its geological parameters, geotechnical aspects and associated safety implications. Finally, previous studies that have been conducted at the Kimberley “Big Hole” Mine and the significance thereof to the purpose of this project are briefly discussed.

2.2 Historical background

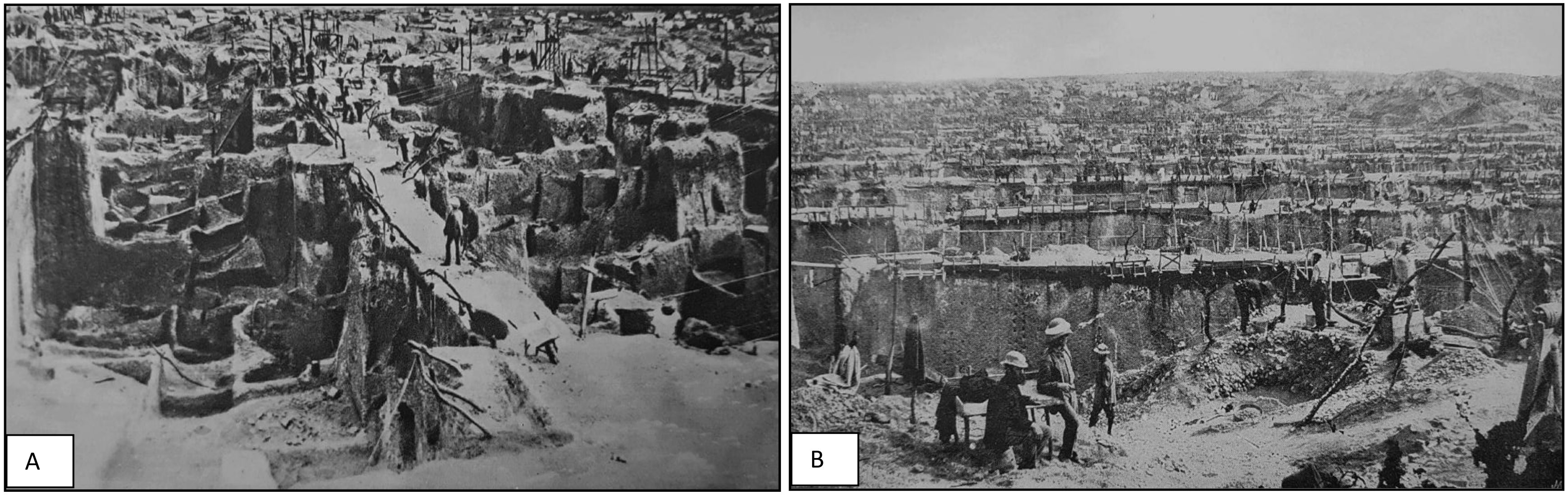
2.2.1 History of the “Big Hole”

A young man called Esau Damoense accidentally discovered the kimberlite pipe, which gave rise to the existence of the Kimberley “Big Hole” Mine, in July 1871. This happened after Esau was instructed to dig away a small kopje (known then as the Colesberg Kopje) as part of a punishment; where he unexpectedly discovered a few small diamond pebbles (Herbert, 1972). News of this remarkable discovery quickly spread and within a very short period of time, a second great diamond rush began in the diamondiferous fields of the Northern Cape Province on July 16th and 17th 1871, which famously became known as the “De Beers New Rush” (Chilvers, 1938).

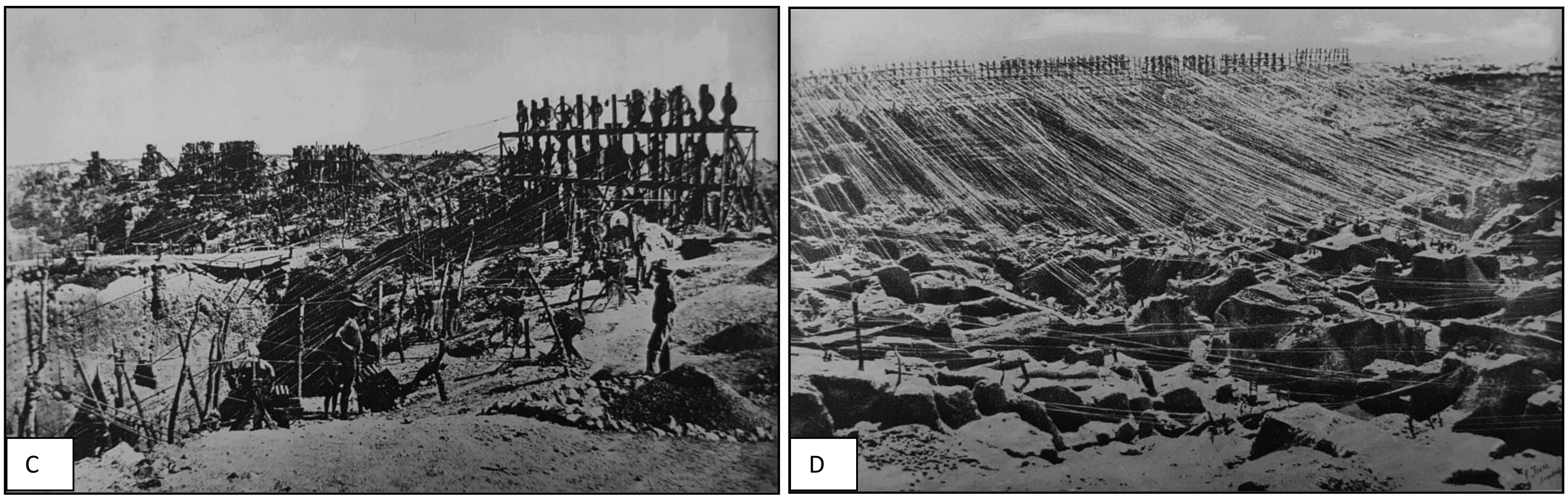
At first, individual claims at the Kimberley “Big Hole” Mine were limited to squares of approximately 10 meters, which tightly crisscrossed the “pipe” in all directions. As dozens of individual pits fell deeper and deeper into the center of the mine problems started to arise due to the fast developing honeycomb structure and overcrowding of the ever-growing “Big Hole” (Herbert, 1972). In order to reduce the number of mining fatalities and improve on the productiveness of the early mining operations at the Kimberley Mine, a newly found Digger’s Committee decided that 5-meter roadways had to be left right across the area every 15 meters as illustrated below in Figures 1 A and B.

However, from as early as the beginning of 1872 the roadways began to be unsafe and the occurrence of landslides had become so frequent that a new change in the system of working was needed (Theodore, 1893). The Diggers Committee once again came together to discuss the problem and came to the conclusion that the only solution which would allow miners to excavate further down this seemingly very rich diamondiferous “pipe” as well as ensure the safety of the workers, was to haul the unearthed material from the outer perimeters of the working area. This led to the erection of wooden platforms like scaffoldings on the outer edges of the “Big Hole” as illustrated in Figures 1 C and D (Herbert, 1972). These scaffoldings could be seen as the earliest foundations not only of a diamond fortune, but also of a South African empire (Theodore, 1893).

Understandably, as time went on, the once very prominent Colesberg “Kopje” which originally seemed to have burst out of the surface of the earth was now slowly disappearing and being mined into an enormous hole. Today its relict, the famous Kimberley “Big Hole” Mine (see Figure 2), is known as one of the greatest and most famous pits excavated by man without any sophisticated machinery (Herbert, 1972). It turned out that the Colesberg Kopje was merely one of several extinct diamond-bearing craters within the vicinity of the Kimberley area. These craters were described by Chilvers (1938) as immense pipes that rose from great depths with rims that exploded from the ground surface. “Kimberlite pipes”, as they are known today and named after the small mining town of Kimberley, were discovered to be filled with hard volcanic substances that contained an abundance of precious diamonds. The exact description, characterization and emplacement model for kimberlite pipes within the Kimberley area are discussed in Section 2.3.



Figures 1 A & B - An illustration of the 5 meter roadways that was used to increase safety and effectiveness of individual mining operations at the Kimberley "Big Hole" Mine back in 1871 (Chilvers, 1938).



Figures 1 C & D - This was the preferred method of mining before implementation of wooden platforms / scaffoldings (also commonly referred to as "staggings") (Theodore, 1893)

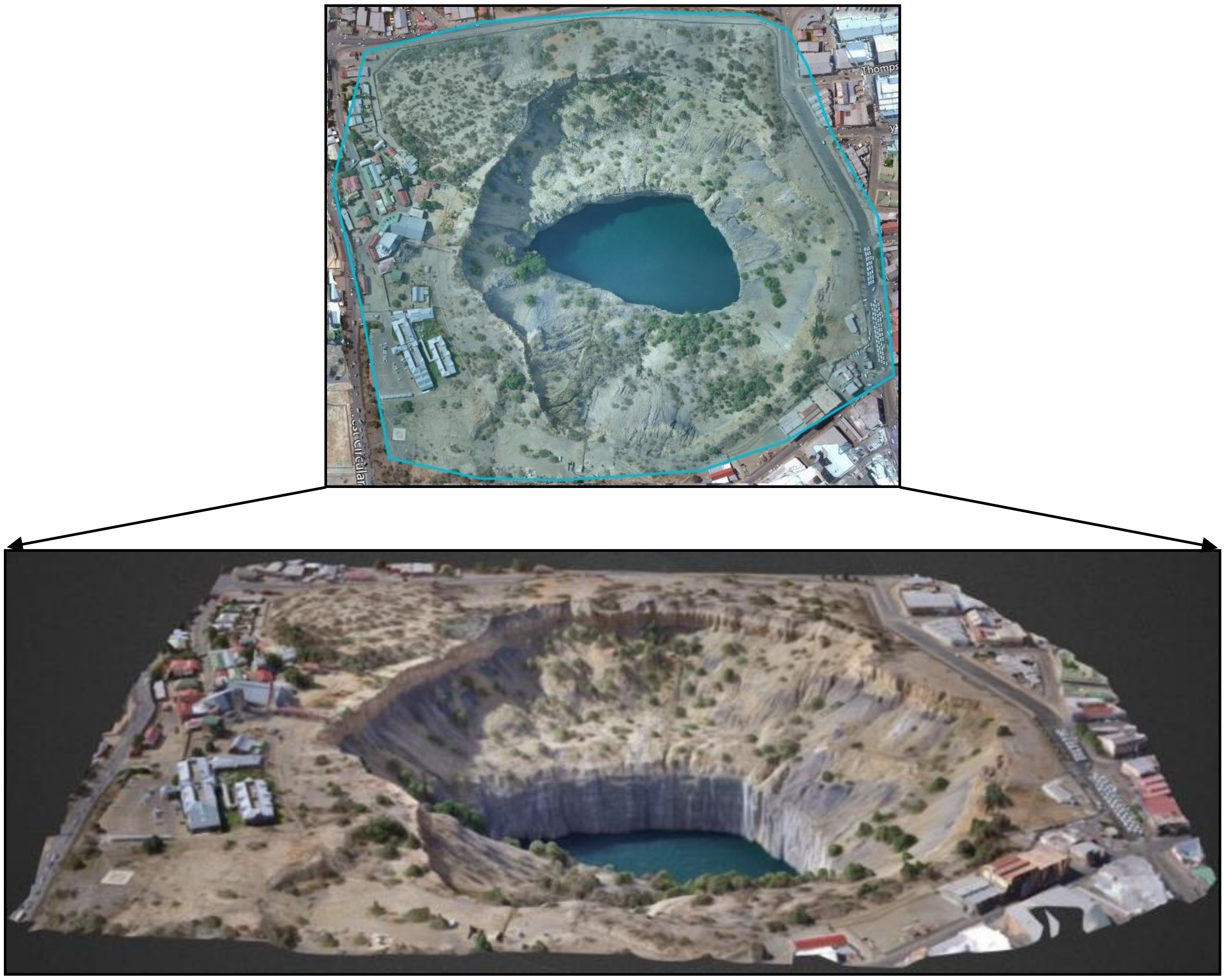


Figure 2 – Present day state of the Kimberley "Big Hole" Mine (drone images from Stellenbosch University).

2.2.2 History of De Beers

The start of De Beers Consolidated (Ltd) as a world-leading diamond mining company was a systematic process which only began when individual mining operations at the four surrounding major diamond mines including Kimberley, De Beers, Bultfontein and Dutoitspan, became too dangerous and difficult. Due to economic pressure at the time, individual miners and claim-holders were forced to either sell their claims or amalgamate with a neighbour, subsequently prompting the original rules, that limited claims to only two square claims per digger, to collapse and from as early as 1874 the limit was extended to up to ten claims per person. This marked the start of a whole consolidation process and it was during this time that the world saw rise of Mister Cecil Rhodes (Herbert, 1972 & Theodore, 1893). When the consolidation process began, Rhodes saw a potential opportunity and wasted no time in ceasing it. He slowly started taking over claims all around him as neighbouring diggers crumbled under the economic pressure and individual claims started to amalgamate (Herbert, 1972). Rhodes knew that whoever owned and controlled all four Kimberley Mines at the time, controlled the diamond monopoly of South Africa and had complete and utter control not only on diamond production from these four major mines, but also diamond marketing. In his book: *"The Diamond Diggers"*, Herbert (1972) claims that Rhodes's life-long dream and immediate target was a combination of all four Kimberley Mines where he would hold full control over the diamond monopoly of Southern Africa, because a monopoly alone could control the balance between the price of diamonds and the supply (Theodore, 1893). Therefore, after many schemes, financial loans, deals and negotiations, Rhodes finally managed to work his way into the shares of all four Kimberley Mines. After gaining full control of the four major diamond mines within the Kimberley area, as was his original plan, Cecil Rhodes finally had total control over the diamond industry of Southern Africa and he made sure that production could always be equated with demand (Herbert, 1972). Finally the new and historic company De Beers Consolidated Mines (Ltd) was formed as it remains to this day.

Rhodes had won his monopoly and started the mighty and world-renowned company, De Beers Consolidated, on 10 July 1889. The newly found company was valued at 24 million pounds at the time and controlled approximately 90% of South Africa's diamond output. It is stated by Herbert (1972) that during the first year of the company's trading, it yielded a net profit of about 1 million pounds which is why it is not so hard to see that the De Beers Company was a colossal financial success, even back in the day.

2.3 Kimberlite pipes

2.3.1 Discovery of kimberlite pipes

When diamonds were first discovered in areas other than alluvial deposits (such as the Vaal and Orange Rivers which had been the main prospecting ground for diamond diggers in South Africa at the time), diggers of the Kimberley area saw diamonds crop up everywhere without pattern or reason and it seemed that the new finds were all in "pans" or slight "depressions" as they are commonly referred to in South Africa (Herbert, 1972). It was only when they started digging deeper that the soil revealed diamonds in a layer of yellow clay of about 15 meters deep and the discovery of diamonds in a layer that was thicker than a few meters was revolutionary.

As a result, diggers continued digging even deeper than the yellow clay and unexpectedly came across the then-so-called "blue ground" (which is now famous as the matrix rock of South African diamond deposits, although it was originally thought to be barren bedrock) (Herbert, 1972). This constituted a second major discovery, which was that the yellow clay merely represented a layer of reworked and decomposed "blue ground" and that diamonds were still being formed at depths greater than 15 meters.

As the pits got deeper and wider, "blue ground" only seemed to appear as circular patches or "pipes" shooting up to the surface of the earth from great depths in vertical or near vertical shafts

(Herbert, 1972). Even though the first diamond mines in the Kimberley area were discovered by diamonds laying on the surface in the red sand of the Northern Cape, which subsequently caused a search that revealed numerous more in a very similar position, no diamonds were ever found in the surrounding country rocks immediately outside of the margins of the mines (Herbert, 1972). Evidence of a volcanic origin for the various Kimberley Mines was therefore regarded as complete and the "blue ground " material is actually known today as being diatreme facies kimberlites, which was soon after recognized as the primary source of diamonds (Mitchell, 1986; Theodore, 1893). In conclusion, the "blue ground pipes" as described by Theodore (1893) and Herbert (1972) actually represented massive kimberlite pipes.

2.3.2 Description of kimberlites and kimberlite pipes

In general, a kimberlite (named after the small mining town of Kimberley in South Africa) constitutes a very rare and highly alkaline igneous rock type, largely known to serve as a carrier of diamonds to the surface of the earth from deep within the earth's mantle (Le Roex et al., 2003). Today it is commonly accepted that kimberlites are derived from depths greater than any other igneous rock types on earth (at depths between 150 – 450 km) and that it forms from a unique and extreme set of magma compositions (Le Roex et al., 2003).

Janse (1964) on the other hand, first characterized kimberlite pipes (scientifically) as steep-sided cylindrical columns, which represent volcanic conduits of eruptive tuff that transport diamonds from deep within the earth's mantle to the surface via a series of volcanic actions. This characterization of kimberlite pipes follows the basic principle that the majority of kimberlites are usually found in vertical or near vertical pipe-like structures within the earth's crust, forming a cone shaped appearance towards the surface of the earth as shown in Figure 3. These structures are thus referred to as "kimberlite pipes", although it is worth mentioning that they could also sometimes appear as igneous dykes and sills, even though the latter is not as abundant.

2.3.3 A South African model for kimberlite emplacement

A paper written by Field and Smith (1999) suggests that kimberlite pipes in different areas have contrasting shapes and internal geological characteristics, with the three most common types of pipe geometries being: (1) deep and steep-sided pipes comprising three distinct zones (namely the crater, diatreme and root zones), (2) shallow pipes which comprise only one distinct zone (namely the crater), and (3) small but steep-sided pipes which comprise two distinct zones (namely the diatreme and root zones - see Figure 3). According to Field and Smith, the only reason for the formation of at least three different types of kimberlite pipes, must be a difference in the emplacement mechanisms of each individual pipe. The geological settings for the three different types of kimberlite pipes, as mentioned above, can respectively be described as follows: (1) country rocks, which are commonly very competent and contain some type of igneous rock, (2) poorly consolidated (loose) sediments, and (3) basement rocks, which are covered by a relatively thin layer of poorly consolidated sediments. Seeing that there are clear evidence of a relationship between the type of pipe formation and the geological setting under which it formed, the correlation suggest that the near-surface geological features play a major role in determining the emplacement process of each individual kimberlite pipe (Field & Smith, 1999).

However, when specifically focusing on the kimberlite pipe that constitutes the Kimberley "Big Hole" Mine, Clement and Reid (1989) was of the opinion that the most probable emplacement mechanism (taking into account the shape of the pipe as well as the geological setting in which it occurs) is that the pipe formed from an intrusive-extrusive magmatic eruption from a closed system in which the competent sub-surface country rock acted as a barrier for the build-up of juvenile volatiles in the magma, ultimately causing the eruption to explode and violently erupt from the surface of the earth. This is consistent with the findings of Field and Smith (1999), in that within the kimberlite pipe that constitutes the Kimberley "Big Hole" Mine (as with most of the kimberlite pipes within the Kimberley area), only the lower diatreme and root zone of the pipe is preserved with the upper portions having been removed through the process of erosion over the years.

Therefore, today the only real evidence of an eruptive volcanic origin for the kimberlite pipe, which lead to the existence of the Kimberley "Big Hole" Mine, is the great shaft that reveals where the diamondiferous pipe strikes downward (Herbert, 1972). As a result of its sheer volume and natural riches, the Kimberley "Big Hole" Mine became world-famous during the late 1800's and early 1900's and will subsequently also be the main focus area for the purpose of this project.

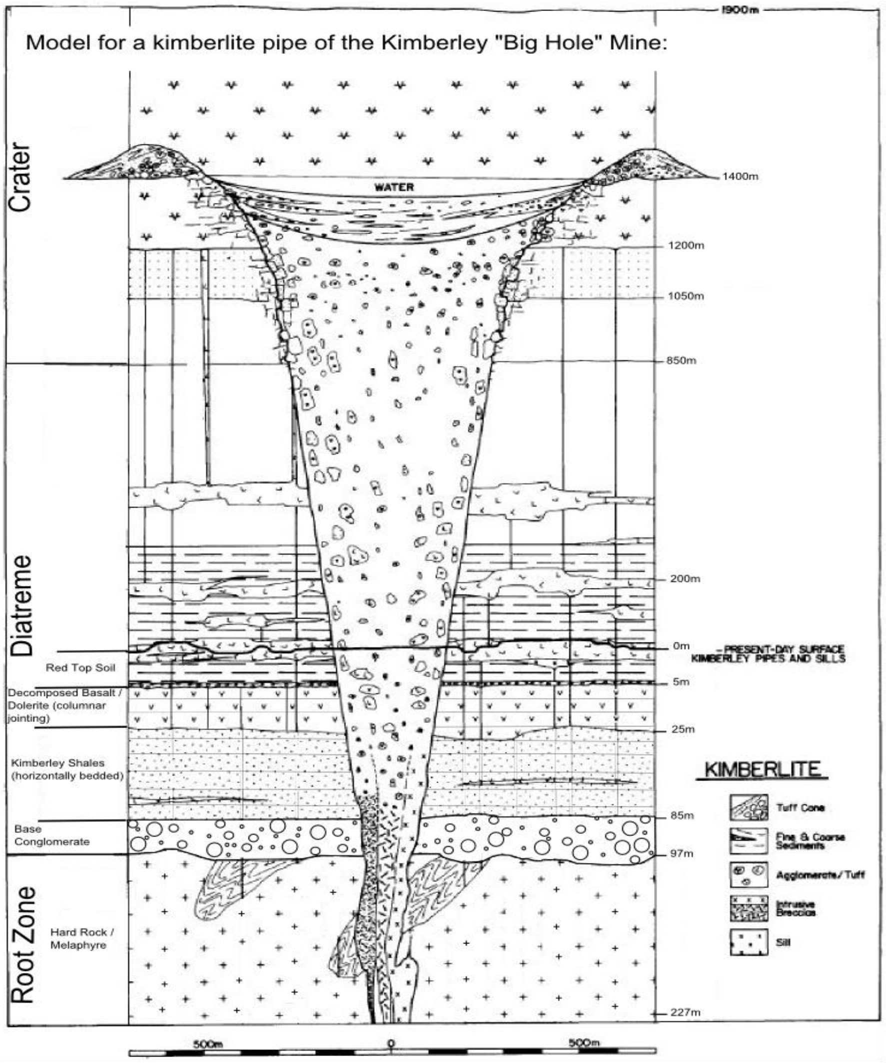


Figure 3 - A model for the kimberlite pipe of the Kimberley "Big Hole" Mine after sketches by Hawthorne (1975).

2.4 Kimberley “Big Hole” Mine

2.4.1 Weather conditions

The Northern Cape in general (and especially in the immediate vicinity of Kimberley) is characterized by a semi-arid climate with a mean annual precipitation (MAP) of approximately 280 mm (Kimberley Climate History, 2016). Figures 4 A and B, shows the yearly weather trends for the closest available data source to Kimberley, with information on the monthly weather averages and extremes over the past few years (Kimberley Climate History, 2016). It can be said that the climate around Kimberley is essentially, a continental one where during the months of November to February, the weather provides hot wet summers and during the months of June to August, it provides cold dry winters. It is also worth mentioning that the infrequent summer rains tend to take the form of occasional severe thunderstorms rather than prolonged soft showers (The Kimberley Climate, 2016), whilst it is not unusual at all for winter night-time temperatures to drop below freezing point.

Also evident from the charts, is that Kimberley experiences a wide range of temperature conditions and rainfall fluctuations during the time period of a year, which would subsequently not only cause an overall increase in the physical weathering of certain rock types (such as the *Kimberley Shales* for example), but it would also logically suggest an actively fluctuating water table. The undesired combination of weather conditions that are prone to encourage physical weathering of certain rock types and the effects of a continuously fluctuating water table, proves to be very significant in the overall state and stability of the slopes at the Kimberley "Big Hole" Mine. Therefore, it can be said that the weather conditions for the town of Kimberley plays a critical role in the scope of this project, both in defining the problem of slope instabilities at the Kimberley "Big Hole" Mine and in finding a proper solution.

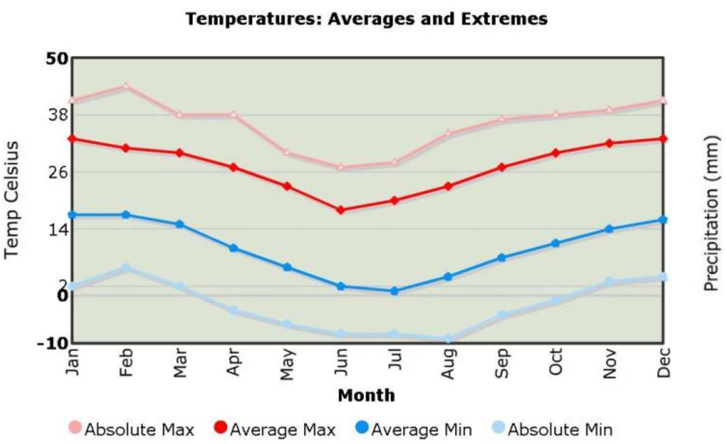


Figure 4 A - Average max and min temperatures for each month of the year, as well as the highest and lowest temperatures ever recorded (Kimberley Climate History, 2016).

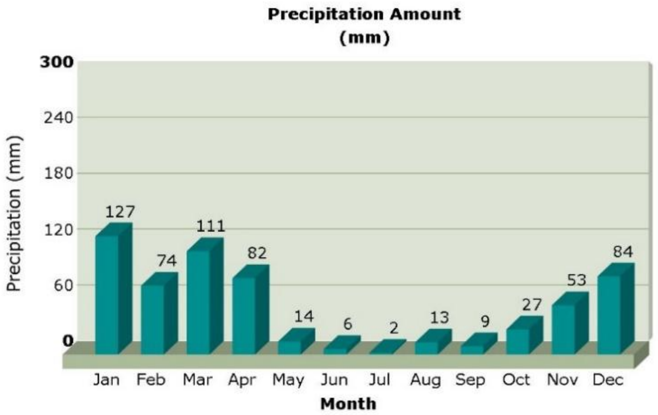


Figure 4 B - Average monthly precipitation (Anonymous, 2016).

2.4.2 Regional geology

In order to fully understand the local geology of Kimberley's diamond fields and especially that of the Kimberley "Big Hole" Mine, it will be necessary to refer briefly to the order in which the same rocks occur in other parts of South Africa. Please keep in mind that this section will only provide a brief and general overview of the most prominent geological features running through Southern Africa, with specific focus on the main geological strata that can directly be related to the local geology of the Kimberley area.

First, as a lower boundary, one will find the **Table Mountain sandstone**, which is a coarse grit sandstone of which Table Mountain and the various surrounding mountain ranges in the vicinity of Cape Town are formed. This relatively thick sandstone layer unconformably overlies a base of clay slates with intrusive granites, commonly known as the **Malmesbury shales**. This clay slate base can be traced all the way through to the Transvaal, where it reappears as the locally known, *Lydenburg Beds*. Above the Table Mountain Sandstone, lies a second series of interbedded slates and sandstones commonly known as the **Bokkeveld group**, which forms the base of the Witteberg, Zwarteberg and the Zuurberg mountain ranges. Conformably overlaying this is massive white **quartzites**, believed to be carboniferous in nature. Resting unconformably on the above-mentioned Quartzites, is a great belt of conglomerate known as the **Dwyka conglomerate**, running due east and west on the northern bases of the Zwarteberg and the Witteberg mountain ranges. Moving up north and inland is a thick deposit of sandy clay and quartzitic sandstones, commonly referred to as the **Ecca beds**. The Ecca Beds lie conformably with the underlying geological unit, being most prominently developed along its southern boundary, but gradually flattening out towards the north. Further north, one comes across the very important geological marker unit containing the diamond mines of Kimberley, known as the **Kimberley shales**. This very important geological marker unit occurs very prominently in all four of the major Kimberley diamond mines (i.e. De Beers, Bultfontein, Dutiotspan and Kimberley) and lie unconformably above the previously mentioned Ecca Beds. The above made summary on the regional geology of Southern Africa is represented graphically in Figure 5.

It is worth mentioning that there exists much difference in opinion as to the exact geological age of the very important Kimberley shales. Several well-known geologists have voiced their opinions, estimating an approximate age of 300 million years old, however it seems that no consensus around the matter have yet been reached. Another fact worth mentioning is that the Kimberley shales share a boundary in the north against the crystalline basement rocks of the Transvaal, separated only by a thin band of conglomerate, locally known as the basement conglomerates of the Kimberley shales.

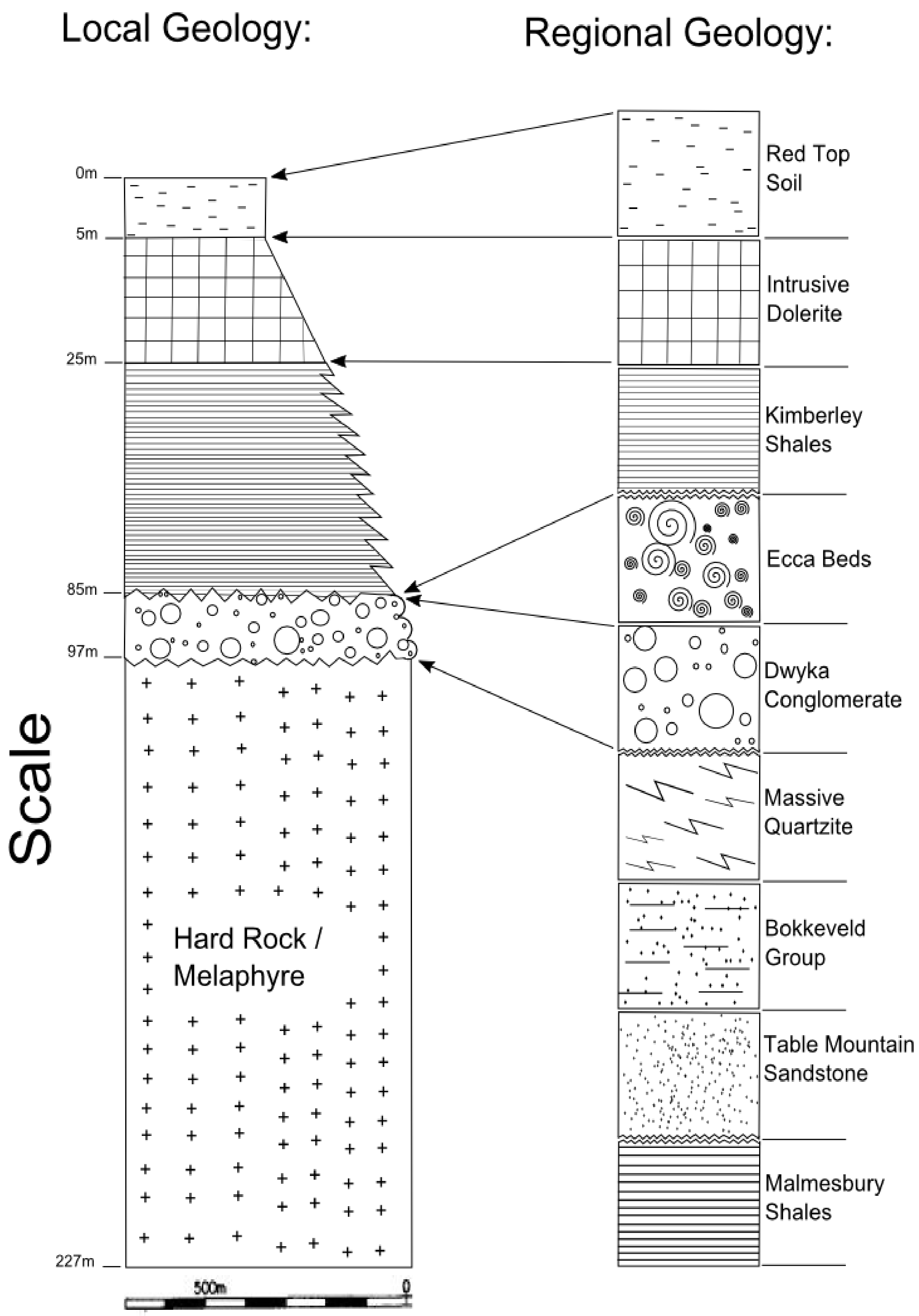


Figure 5 - Stratigraphic relationship between the regional geology of the Northern Cape Province and the local geology of the Kimberley "Big Hole" Mine. Images created with Inkscape software at Stellenbosch University.

Throughout the wide stretch of land that is covered by the Kimberley shales, a basaltic rock of more recent age is of constant occurrence and forms in a close relationship with the previously mentioned geological marker unit. Intrusive **dolerite**, as the basaltic rock is often referred to, generally appears in the form of massive dykes and intrusive sheets that cuts through and overlay the Kimberley shales (Theodore, 1893).

Finally, the wide-open plains of the Northern Cape Province is often also associated with a very characteristic **red ferruginous topsoil**, which is more often than not, accompanied by rounded stones and boulders which cover the slopes of all the hills. These were formed during the weathering of the above-mentioned dolerite traps, as these rocks tend to be a bit more competent than most of the surrounding rock types. However, in many of the nearby districts this characteristic red soil horizon is absent and rather seems to be replaced or underlain by a deposit of lime, which is thought to have been formed during the deposition of the underlying rocks (Theodore, 1893).

2.4.3 Local geology

The small mining town of Kimberley, which is situated within the heart of the Northern Cape Province of South Africa (28°44’30.84’’ S; 24°46’18.84’’ E), constitutes one of the oldest and most famous mining towns in the world. It is located approximately 110 kilometers east of the convergence of the Vaal and Orange Rivers and possesses a relatively simple geological history compared to most other terranes in Southern Africa. When looking at the historic mining operations of the Kimberley “Big Hole” Mine, which have been exploited to a depth of approximately 1097 meters, one starts to get a better sense of the local geology around the immediate area of the “Big Hole”. The shaft reveals the nature of the underlying strata and helps validate the succession of the rocks above.

Beneath the **red topsoil**, which varies from 1 to 5 meters in depth at the Kimberley “Big Hole” Mine, is a very large sheet of decomposed basalt (or more often also referred to as intrusive **dolerite**). This doleritic sheet / sill, typically varies in thickness from 6 to 20 meters and exhibits a very pronounced columnar geological structure due to the development of a strong orthogonal joint set. Underlying the dolerite (or in some cases immediately below the red soil), is the iconic and ever so important black shales of the country (locally known as the **Kimberley shales**), which varies in approximate thickness from 60 to 90 meters. It was noticed at the time by Theodore (1893) that the Kimberley shale unit had not yet bottomed at the Bultfontein and Dutoitspan Mines, meaning that it must have a greater thickness there than at the more northern mines of Kimberley and De Beers. In other words, the shale layer is thinning / pinching out towards the north. Some geologists, such as Theodore (1893), therefore voiced his opinion that the Kimberley Mines were situated at the northern-most rim of the saucer-shaped basin, which was once seen as the great freshwater lake of the Karoo.

The Kimberley shales are typically yellow, pink and brown for the first 9 to 15 meters, thereafter transitioning to black and almost perfectly horizontal beds (Theodore, 1893). Within the shale unit, one would occasionally find a combination of sheets and dykes of intrusive trap. Moving further down from the surface of the "Big Hole" Mine, the next geological unit beneath the Kimberley shales is a thin bed of conglomerate (also known as the **Dwyka conglomerate**) approximately 3 meters thick, which is dominantly composed of rounded pebbles and stones that are firmly cemented together. This thin conglomerate probably forms part of the basement conglomerates of the Kimberley shales. Underlying the conglomerate however, is 120 meters of what the miners referred to as the "hard rock", essentially almost the same as the bedrock. It generally consists of an amygdaloidal trap (or **melaphyre**).

The thick melaphyre bed is made up of very hard compact rock, with numerous nodules of agate and quartz, which made it exceptionally difficult and expensive to mine. Underneath the hard rock melaphyre, is a greenish **quartzite** also of hard and tough texture. It shares a similar thickness to the overlying unit, being approximately 125 meters from top to bottom. In his book: "*Diamonds and Gold in South Africa",* Theodore (1893) said that looking down the Kimberley Rock Shaft, at a depth of 350 meters from the surface of the "Big Hole", the above mentioned quartzite started transitioning into metamorphic slates, interlaminated with thin layers of sandstone. The local geological succession of the Kimberley "Big Hole" Mine (as discussed above) is represented graphically in Figure 5, together with the relationship thereof to the most important geological marker units of the regional geology of Southern Africa.

To conclude the local geology of the Kimberley "Big Hole" Mine, it is worth mentioning that shales (with specific reference to the Kimberley shales) will form a central theme in defining the overall state and stability of the sidewalls of the Kimberley "Big Hole" Mine, as such, the characteristics of shale, its weathering and swelling / shrinkage potential will be discussed in detail forthwith.

2.4.4 Geological structure at the Kimberley "Big Hole" Mine

According to Preece et al. (2008), a full structural review of the Kimberley "Big Hole" Mine was undertaken by De Beers early in the year of 2007, with the aim of more easily identifying the reasons for slope stability problems at the mine. As concluded and summarized in their report: *"A summary of geotechnical information pertaining to the stability of the sidewalls of the Kimberley Mine"*, Preece et al. (2008) reviewed that De Beers identified the following during their structural investigation of the mine, as also illustrated in Figure 6:

i. A single west-north-west (WNW), east-south-east (ESE) trending dyke.
ii. Two individual shear zones on the south-western side of the pit.
iii. Five different joint sets of which two appear to be of local nature and the other three matching regional trends.

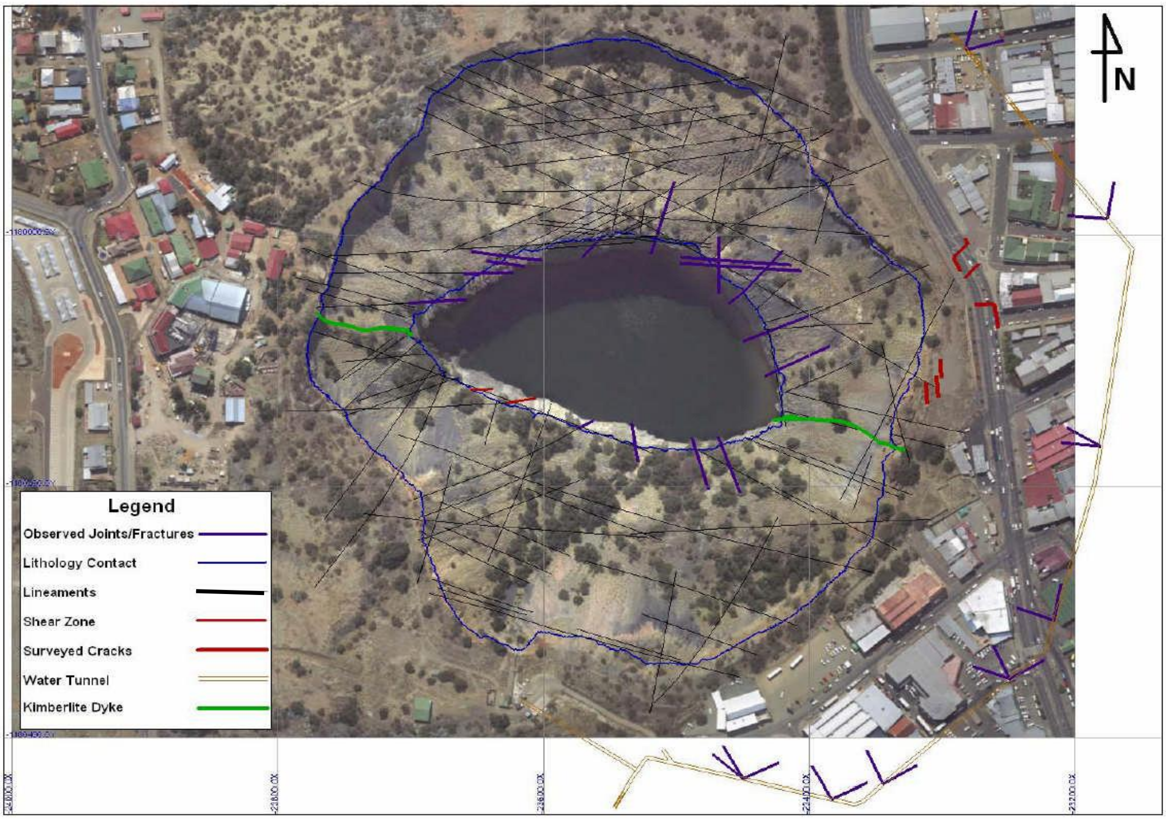


Figure 6 - Structural geology of the Kimberley "Big Hole" Mine according to De Beers geotechnical personnel and reviewed by Preece et al. (2008).

The two joints sets, which appear to be of local nature, occur orthogonal to one another and are clearly seen only within the near surface doleritic sheet. It is exactly these two orthogonal joint sets within the overlying dolerite unit, which creates the columnar geological structure of the rock and weakens the layer along certain angels. Consequently, an observation made by Croukamp (2008) was that *"stress relief"* due to the open pit and *"undermining"* due to regression of the underlaying shale unit, resulted in these orthogonal joint sets opening up and causing blocks of the dolerite rocks to become unstable. This observation proved to be very significant in terms of the scope of this project and held a lot of insight, which will only be discussed in more detail in later chapters. Furthermore, De Beers found very little structure in the underlying shale horizon during their structural review of the mine, whilst the bottoming melaphyre (andesite) only exhibited prominent near-vertical and horizontal jointing, which usually results in columnar geological blocks. The structural review of the Kimberley Mine, by De Beers, concluded that this is usually a stable joint configuration with no immediate dangers and that it can only give rise to toppling of large geological blocks (Preece, et al., 2008).

To conclude the structural review of the Kimberley "Big Hole" Mine, it is worth emphasizing the fact that the undermining property of the Kimberley shales (as desribed above) together with the toppling propensity of the overlying doleritic sheet, is deemed critical in understanding and defining the slope stability problem at the Kimberley "Big Hole" Mine and in constraining a proper solution. This will only be discussed in much more detail in later sections.

2.4.5 Pit geometry

According to Sjoberg (1996), the geometry of a pit significantly influences its own stability due to the associated stress conditions in the slopes. This is but only one of the many factors governing large scale slope stabilities of open pit mines (such as the Kimberley "Big Hole" Mine); including other factors such as:

- The effects of groundwater.
- The geological structure (in particular the presence of large scale features).
- The overall rock mass strenght.

As a result of the above mentioned factors, all modern day mine pits are the subject of exhaustive and detailed planning prior to the start of development and construction. Many modern day mines take years before they start operating as a response to many prefeasiblity studies and proper risk assessment analyses of the various risk factors involved and as mentioned above. The Kimberley Mine pit, however, was one of the first of its kind to be developed between the years 1871 and 1884 (before its acquisition by De Beers) and as a result of the initial disjointed amalgamation of numerous individual excavated claims into an eventual underground mining operation, no such planning or design was ever undertaken by the early claim holders to ensure total and utter safety (Preece et al., 2008).

In the same report written by Sjoberg (1996), he also mentions that in nature, the most stable (open) mine pit configuration is circular, due to the fact that a circular pit will always create the most stable regional stress regime around the outer perimeters of the mine. According to Preece et al. (2008) however, in the specific case of the Kimberley area, the principle regional stress regime is typically orientated north-north-east (NNE) to south-south-west (SSW), which generally explains the mishaped oval signature of the Kimberley Mine pit footprint as illustrated in Figure 7. This oval shaped structure that was adopted by the Kimberley "Big Hole" Mine, is not ideal for the most stable and safest mine slope configuration. In conclusion, it can be said that the overall geometry of the Kimberley Mine pit, is the reason for many of its slope stability problems due to the geometry of the mine creating a generally unstable regional stress regime around the outer perimeters of the "Big Hole". The oval shaped geometry of the Big Hole Mine, together with its unstable regional stress regime, causes many of the surrounding slopes to fall under an inbalance of pressure and stresses and leads to an increase development of the slope's natural angle of repose.

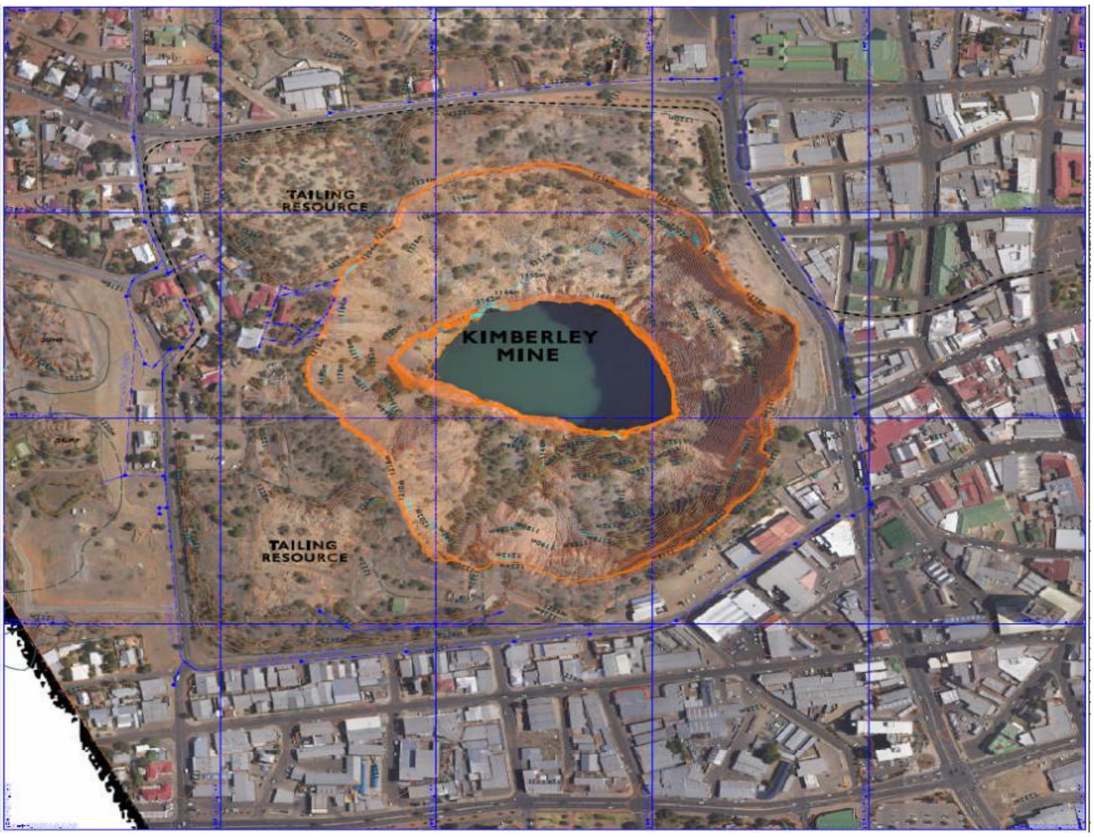


Figure 7 - Geometry and plan of the Kimberley "Big Hole" Mine showing the misshaped oval signature of the mine pit footprint (Croukamp, 2008).

2.5 Shales

2.5.1 Description and characteristics of shale

According to Stead (2016), shales form part of approximately 58% of all sedimentary rock records around the world and play a major role in the stability of both natural and engineered slopes. They are of particular interest when it comes to slope stability assessments, due to the wide variation in their engineering properties and their ever changing behaviour with time as a result of certain weathering processes (Stead, 2016). Although various terminologies have been developed to refer to these materials namely: argillaceous rock, claystone, siltstones and mudrock for example, the exact definition of a shale can be described as follows (Shaw & Weaver, 1965; Venter, 1980):

"A fine-grained sedimentary rock with compacted and hardened layers of either silt or mud and a clay content of usually more than 40%. They tend to have a well marked bedding plane fissility, primarily due to the orientation of the clay mineral particles that are present parallel to the bedding planes. Perpendicular to these bedding planes the rock usually breaks with an irregular, curving fracture. Finally, shales do not form a plastic mass when wet, although they may disintegrate when immersed in water (see Figure 8)".

Figure 8 - A classic field example of finely laminated shales with irregular weathered surfaces perpendicular to the bedding plane (Harvey & Tracy, 1996).

It is arguably the case however, that no universally accepted classification of shales exists today, and depending on the field of application, the terminology surrounding shales varies widely. Therefore, for the purpose of this project, a quick summary and classification of the different types of shales is given below in Table 1.

Table 1 - Classification of the different types of shales according to Stead (2016) and modified after Yagiz (2001).

Group	Name	Main Components
Compacted Shale	Clayey shale	Contain 50% or more clay-sized particles (< 0.002mm)
	Silty shale	Contain 25 - 45 % silt-sized particles
	Sandy shale	Contain 25 - 45 % sand-sized particles
	Black shale	Contain an abundance of organic-rich materials
Cemented Shale	Calcereous shale	Contain 25 - 35% $CaCO_3$
	Siliceous shale	Contain 70 - 85% silica
	Ferruginous shale	Contain 25 - 35% Fe_2O_3
	Carbonaceous shale	Contain 3 - 15% carbonaceous material (imparts toughness)
	Clay bonded shale	Welded by recrystallization of clay minerals

In terms of the engineering properties of shales however, there seem to be a bit more consensus on the matter and includes (Farrokhrouz & Asef, 2013):

- Very low compressive strength (< 100MPa).
- High sensitivity to water.
- Prone to swelling.
- High thermal conductivity.
- Very susceptible to weathering.

The propensity of shales to degrade and deteriorate with time due to certain weathering processes (both physical and chemical), has resulted in an ongoing attempt to try and classify shales according to their slaking, durability, swelling and softening properties (Stead, 2016). These properties are often highly variable and involves the use of many newly developed test methods, of which a few will be implemented throughout the course of this project.

2.5.2 Weathering of shales

It is in general agreement that the clay content of shales are responsible for much of their rock strength properties and more often than not: the higher the clay content, the poorer the engineering properties and the higher the susceptibility to certain weathering processes (Stead, 2016). According to Farrokhrouz and Asef (2013), the type of clay mineral present within the mineralogical structure of the rock, also plays a major role in its behaviour when exposed to various natural elements (such as water, wind or heat for example), with increasing problems being found in montmorillonite-rich shales. This is mainly because of the fact that some shales have limited cementation between individual grain boundaries, especially when it consists of highly compacted clays, whilst other shales may be well-cemented in nature with a stronger and more durable clay mineral, such as kaolinite for example (Stead, 2016).

According to Venter (1980), there are generally two varieties of breakdown / weathering phenomenon observed in common shale-type rocks in South Africa, although a gradation between the two processes seem to be inevitable. These two processes (shown in Figure 9) can be described as follows:

1.) The first breakdown process that ensues when a fresh shale sample is exposed to the atmosphere is **"disintegration"**. Disintegration involves the physical breakdown of the rock into smaller hard rock fragments (>2mm). It is a complex process that involves the formation of numerous microcracks on the surface of the rock, subsequently allowing for more water to infiltrate the material and in return, cause even further breakdown (Stead, 2016).

2.) The second weathering process, which usually follows after a certain degree of disintegration, is **"slaking"**. Slaking is considered to be a consequence result of disintegration breakdown and involves the weathering of shales into silt or clay sized particles (<0.06mm).

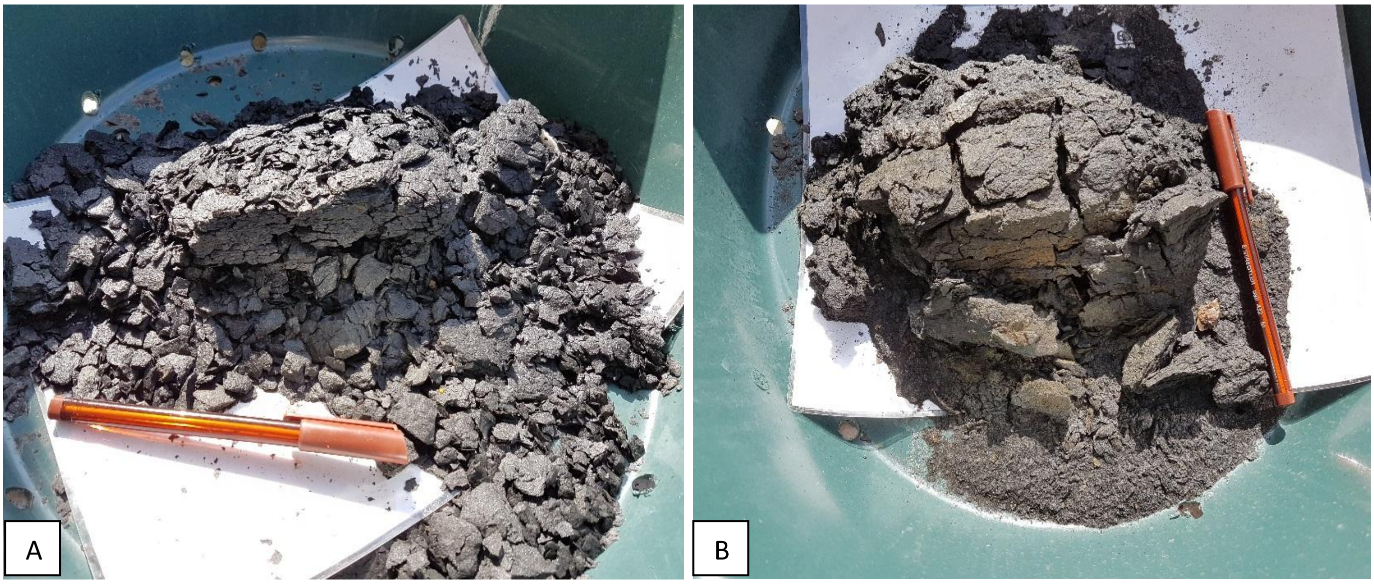


Figure 9 - Perfect example of the two types of breakdown / weathering patterns observed in shale-type rocks from South Africa. A.) Disintegration of shale material into smaller rock fragments; B) Slaking of shale material into finer particles. Both examples come from rocks that were studied for the purpose of this project.

Together with the two different classification types for the breakdown / weathering of shales, Venter (1980) was also of the opinion that they should be measured by means of different analysing techniques, seeing as it involves two different sets of processes. As a result, Venter (1980) suggested that: (1) disintegration breakdown be measured via a qualitative evaluation, by means of performing a five-cycle wet-dry test using water, whereas (2) slaking on the other hand, should only be measured by means of a slake durability index (SDI) test. Furthermore, the meaning of some of the terms used to describe the weathering of these rocks, needs to be specified as well (Venter, 1980):

- **Fissile:** Denotes the ability of shales to split approximately parrallel to their bedding planes (see Figure 10 A).
- **Flaggy:** Denotes the ability of shales to split in such a fashion that the length and the width of the slabs are much greater than their actual thickness (see Figure 10 B).
- **Flaky:** Denotes the tendency of shales to break into smaller chips, flakes, wedges or fragments (see Figure 10 C).

Figure 10 - Field examples of (A) Fissile; (B) Flaggy; and (C) Flaky- type weathering of shales (Edger, 2009; Millie, 2012; Oleinik, 2016)

2.5.3 Swelling / shrinkage potential of shales

When referring to any clay-rich rock mass (like shales for example), it is of critical importance to first try and quantify the swelling potential for that rock mass, as it may consequently have an adverse effect on the stability of tunnels, slopes and foundations if the swelling potential is mobilized (Pettersen, 2014; Bothma, 2015). However, in order to determine the swelling potential of a certain rock types, a study of the clay minerals is first and foremost required (Bothma, 2015).

According to Knappett and Craig (2012), the basic structural unit of most clay minerals are a silicon-oxygen tetrahedron and an alumimum-hydroxyl octahedron, which combine together to form different molecular sheet structures as illustrated in Figure 11. These tetrahedral units interact with the sharing of oxygen ions to form a silica sheet, whilst the octahedral units combine by sharing hydroxyl ions to form gibbsite sheets. The way in which the different layers are then formed, is by the bonding of a single silica sheet with either one or two gibbsite sheets. As a result, different types of clay mineral particles are formed by different stacks of these layered structures, which have different forms of bonding between them (Knappett & Craig, 2012; Bothma, 2015).

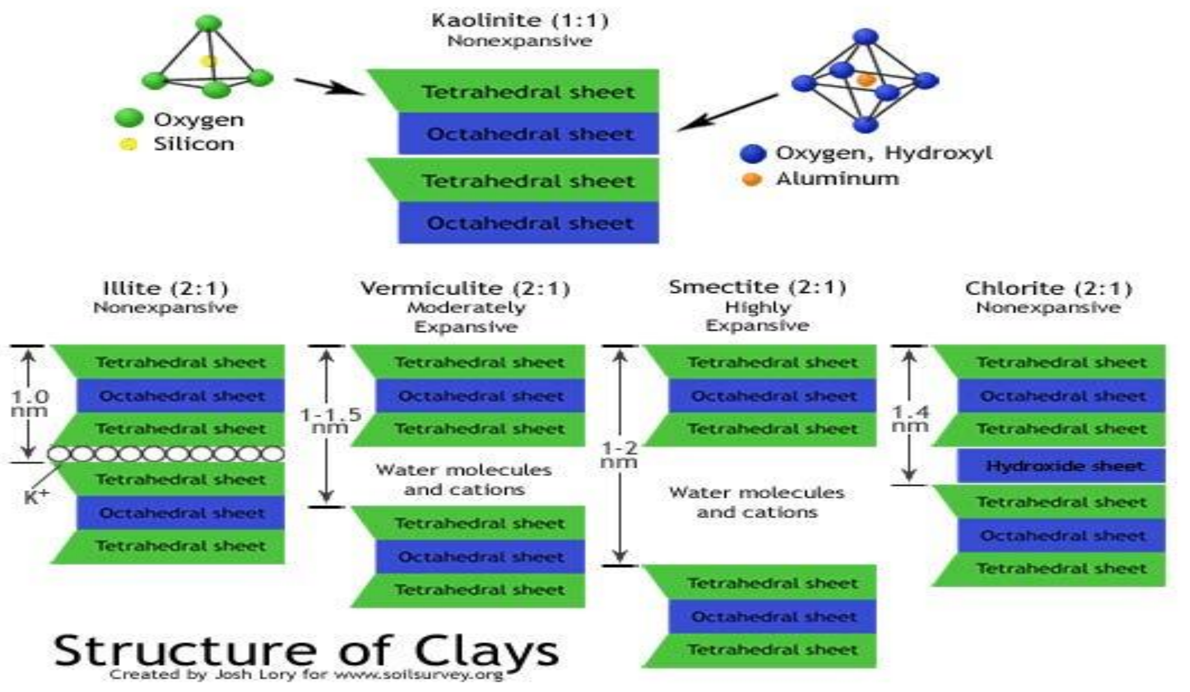


Figure 11 - Structures of the most common types of clay minerals in the world (Bothma, 2015; Lory, [S.A.])

In general, clays that are rich in montmorillonite (or smectite), may expand drastically when in contact with water, which means that the organic material subsequently has a great swelling potential. The swelling characteristics of the clay and the degree of overall expansion is highly dependent on (Pettersen, 2014):

- The material that is exposed to either an internal or external fluid source.
- The presence of swelling minerals in the clay.
- The amount of water accessible.

Any rock mass that is exposed to either an internal or external fluid source, can be de- and resaturated, which in turn results in the swelling and shrinkage of the internal clay minerals and more often than not, fracturing of the rock mass (Zhang et al., 2010). It is worth mentioning that the most commonly found clay minerlas in nature include montmorillonite, vermiculite, illite or kaolinite with the main difference between these being their varying sensitivity towards water. Montmorillonite is known to be one of the most expansive clay minerals when in contact with water, whereas vermiculite is only moderately expansive and illite or kaolininte the least or non-expansive (Knappett & Craig, 2012).

There are various ways of determining the exact chemical composition of clay minerals in a rock, which would subsequently also help to identify its internal structure (Zhang et al., 2010). The first and probably also the easiest method for determining the chemical composition of clay minerals, is by the study of thin sections, which is also known as a **petrographic analysis**. This entails both the description and classification of rocks, although this method of optical identification can sometimes be made extremely difficult when working with a very fine-grained rock mass (Bothma, 2015). Therefore the better and more accurate method of identification would be by means of an X-Ray examination. Generally there are two types of X-Ray examination techniques that can be used: the first is a **X-Ray diffraction (XRD)** technique, and the second is a **X-Ray fluorescence (XRF)** technique (Bothma, 2015).

The X-Ray diffraction (XRD)-technique can be used to determine both the presence and amount of mineral species in a sample, as well as identify the different phases. The X-Ray fluorescence (XRF)-technique however, will only allow you to determine the details of the chemical composition of a sample, but it will not indicate the different phases that are present. As a result, both techniques are used in the industry today, only depending on the information a person would want to obtain seeing as both techniques have their advantages and disadvantages.

In reference to the most common types of clay minerlas found on earth today (i.e. montmorillonite, vermiculite, illite and kaolinite), Table 2 below shows their unique corresponding and general chemical compositions (Bothma, 2015).

Table 2 - Chemical compositions of the most common types of clay minerals, showing both elements and chemical compounds (Bothma, 2015 & Pettersen, 2014).

Montmorillonite: $Na_{0.2}Ca_{0.1}Al_2Si_4O_{10}(OH)_2(H_2O)_{10}$				**Vermiculite:** $Mg_{1.8}Fe^{2+}_{0.9}Al_{4.3}SiO_{10}(OH)_2 \cdot 4(H_2O)$			
Element	**[%]**	**Chemical compound**	**[%]**	**Element**	**[%]**	**Chemical compound**	**[%]**
Sodium (Na)	0.84	Na_2O	1.13	Magnesium (Mg)	8.68	MgO	14.39
Calcium (Ca)	0.73	CaO	1.02	Aluminium (Al)	23.01	Al_2O_3	43.48
Aluminium (Al)	9.83	Al_2O_3	18.57	Iron (Fe)	9.97	FeO	12.82
Silicon (Si)	20.46	SiO_2	43.77	Silicon (Si)	5.57	SiO_2	11.92
Hydrogen (H)	4.04	H_2O	36.09	Hydrogen (H)	2	H_2O	17.87
Oxygen (O)	64.11			Oxygen (O)	50.77		
Illite: $K_{0.6}(H_3O)_{0.4}Al_{1.3}Mg_{0.3}Fe^{2+}_{0.1}Si_{3.5}O_{10}(OH)_2 \cdot (H_2O)$				**Kaolinite:** $Al_2Si_2O_5(OH)_4$			
Element	**[%]**	**Chemical compound**	**[%]**	**Element**	**[%]**	**Chemical compound**	**[%]**
Potassium (K)	6.03	K_2O	7.26	Aluminium (Al)	20.9	Al_2O_3	39.5
Magnesium (Mg)	1.87	MgO	3.11	Silicon (Si)	21.76	SiO_2	46.55
Aluminium (Al)	9.01	Al_2O_3	17.02	Hydrogen (H)	1.56	H_2O	13.96
Iron (Fe)	1.43	FeO	1.85	Oxygen (O)	55.78		
Silicon (Si)	25.25	SiO_2	54.01				
Hydrogen (H)	1.35	H_2O	12.03				
Oxygen (O)	55.06						

2.5.4 Durability of shales

In spite of their abundance in the rock record, shale type rocks have until recently received very little attention in terms of classifying them according to their durability and internal strength properties. However, recent studies have started to show a strong physical interdependence between the durability of shales and their rate of slaking. Therefore, researchers have started measuring the durability of shales with a variety and often interdependent set of slaking tests of which three of the more popular slaking tests include (1) the jar slake test, (2) the slake index test and (3) the slake-durability test (Erguler & Ulusay, 2009). All three slake tests include a similar test procedure, but differ in their obtained results. According to many papers, the slake-durability index test is still the most widely used slaking test for the evaluation of physical changes and / or slaking behaviour of rocks as a result of wetting and drying processes. Franklin and Chandra (1972), ISRM (1981, 2007) and Gamble (1971) suggested using the second cycle slake-durability index (I_{d2}) value as being the most effective way of assessing the slaking properties of a rock, which is why this testing program was included and followed within the scope of this project. In addition to the test methods as briefly mentioned above, some classification systems have also been developed and proposed to assess the durability of such rocks. One of these classification systems includes the durability–plasticity classification that was developed by Gamble (1971) and suggested by ISRM (1981). Gamble (1971) found some significant correlations between the properties of clay-bearing rocks such as water content, liquid limit, and dry density, which is why Gamble (1971) suggested that clay-bearing rocks are best classified on the basis of a relationship between the second cycle slake-durability index (I_{d2}) and their plasticity index, dividing the durability of shale type rocks into six different classes (see Table 3). This was subsequently also the classification system used and followed to classify shale rock material from the Kimberley "Big Hole" Mine according to their second cycle slake-durability index before and after applying the proposed solution as discussed in Chapter 5.

Table 3 - Slake-durability index (SDI) classification table, Gamble (1971)

SDI	30 - 60	60 - 85	85 - 95	95 - 98	> 98
Classification	Low	Medium	Medium -High	High	Very high

However, Gamble (1971) emphasized the importance of in-situ behaviour of clay-bearing rocks exposed to atmospheric processes, and concluded that more work is necessary to correlate laboratory test results with field behaviour to fully understand the slaking behaviour of such rock types. Taylor and Spears (1981) adopted Gamble's (1971) classification for less indurated types of clay-bearing rocks. For moderately strong to very strong clay-bearing rocks, Olivier (1979) developed a classification system that was based on the relationship between the swelling coefficient (free swelling from an oven-dry to saturated condition) and the uniaxial compressive strength (UCS) of similar materials. Franklin (1981) on the other hand, proposed a more quantitative shale rating system that includes both the second cycle slake-durability index (I_{d2}), the plasticity index (PI), and the point load strength index (Is_{50}) of the rock. The rating value (R) of the Franklin Shale Rating System can then be used to select certain safe slope angles for unsupported shale slopes by using two graphs as illustrated below in Figure 12 and Figure 13 respectively.

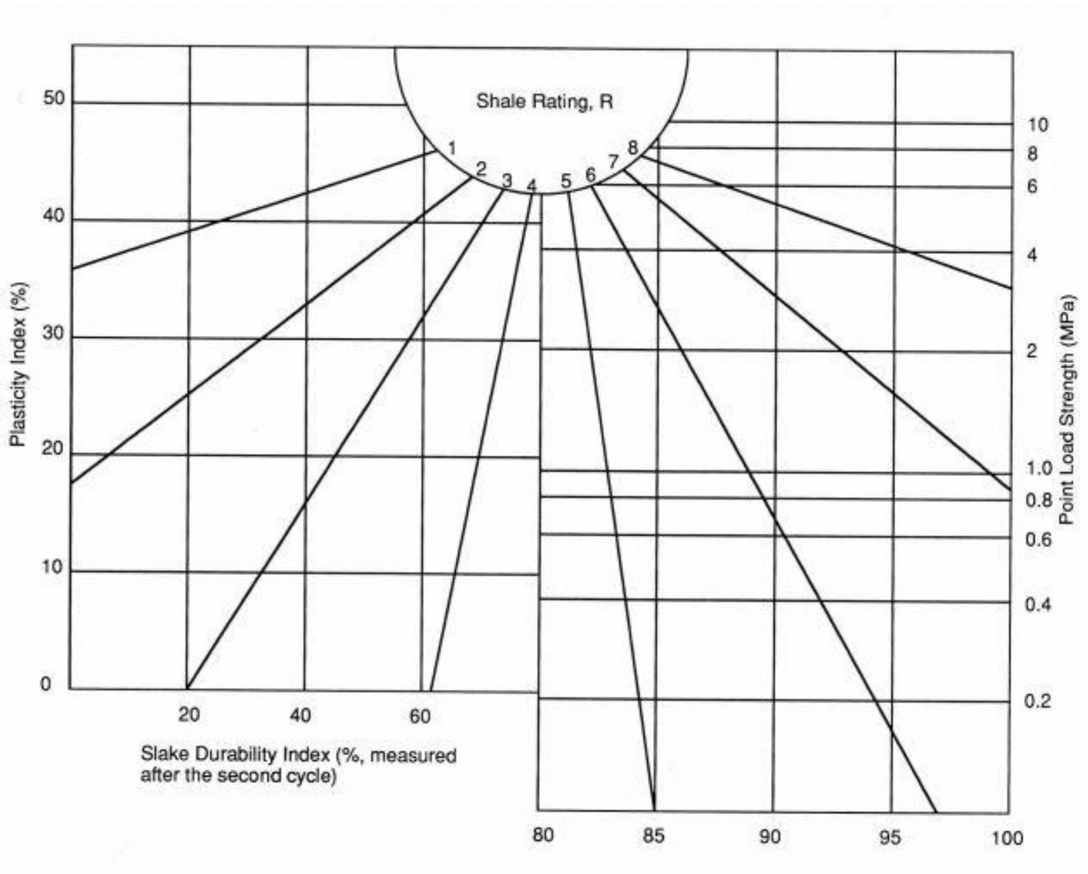


Figure 12 – Franklin's shale rating system (Franklin, 1983).

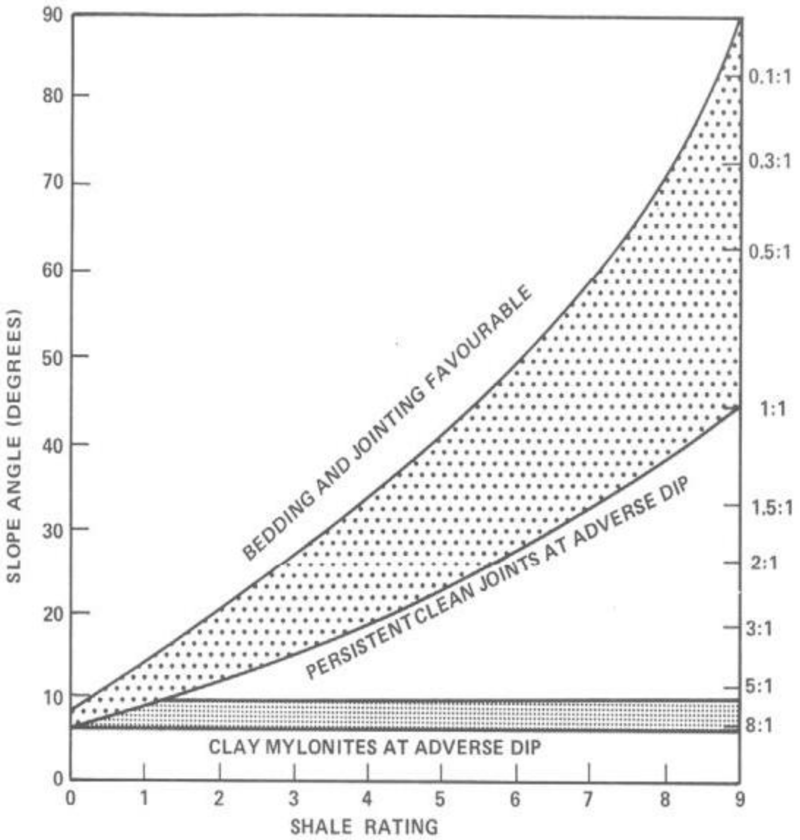


Figure 13 - Trends in safe shale slope angles as a function of shale rating (Franklin, 1983).

Using the Franklin shale rating system (as described above) Shakoor and Admassu (2016) determined the safe slope angles for weak rock units, which was based on the correlation between the second cycle slake-durability index (Id2) values of 24 shale rock samples and the safe slope angles as indicated by the shale rating system. Shakoor and Admassu (2016) generalized their results in order to propose the following safe slope angles for shale type rocks as seen in Table 4:

Table 4 - Safe slope angles of shale slopes according to the second slake-durability index (Id2)values of 24 shale rock samples (Shakoor & Admassu, 2016).

Second slake-durability index value (Id2)	Safe slope angle	Where:
<20%	Flatter than 2H:1V or less than 27°	H = Horizontal
20% - 60%	2H:1V or 27°	V = Vertical
60% - 85%	1.5H:1V or 34°	
85% - 95%	1H:1V or 45°	
>95%	0.5H:1V or 63°	

Other authors used the same method of thinking to apply the second slake-durability index (Id2) values of shale type rocks, to develop and predict the most likely engineering properties that would be associated with their in-situ material. The following table therefore predicts the most likely engineering properties of shale type rocks, according to their second cycle slake-durability index values as obtained from numerous slake-durability index tests (see Table 5) (Singh, et al., 2005):

Table 5 - Observed and predicted engineering properties of shale type rocks, according to their second cycle slake-durability index values (Singh, et al., 2005).

Observed slake-durability index value (Id2)	Uniaxial compressive strength (Kgf/cm^2)	Tensile strength (Kgf/cm^2)	Shear strength (Kgf/cm^2)
94.87	46.00	0.652	5.61
93.35	42.20	0.605	5.084
93.40	42.20	0.608	5.108
93.50	42.60	0.611	5.133
95.44	47.90	0.648	5.771
95.46	47.98	0.650	5.781
95.48	50.06	0.678	6.031
95.50	51.00	0.690	6.145
93.60	42.10	0.598	5.024
93.65	43.00	0.617	5.059

Dick et al. (1994) discovered some problems with the current literature and with the suggested classification systems of shale type rocks as is. He indicated that most of the classification systems (as mentioned above) are of limited application and that the reasons therefore be attributed to one or more of the following:

- The classification systems were developed for specific applications of mudrocks.
- The classifications were based on an insufficient number of samples and / or insufficient variety of mudrocks.
- The classifications did not distinguish between different types of mudrocks.

Nevertheless, the second-cycle slake durability index test is still widely used in evaluation and classification of shale-type rocks and the test as proposed by Franklin (1981) has been standardized and described in ASTM D-4644-87 (1992).

In addition, several researchers have also proposed durability classification systems based on slope stability evaluations that require on a number of other laboratory tests, including jar slake, rate of slaking, Atterberg limits, free-swell and point load strength tests. In the discussion of embankment slope designs by Franklin (1981), a figure was included and introduced a means of determining the internal friction angle (Ø) and cohesion (c) of the soil by using the shale rating of the rock mass in testing (see Figure 14).

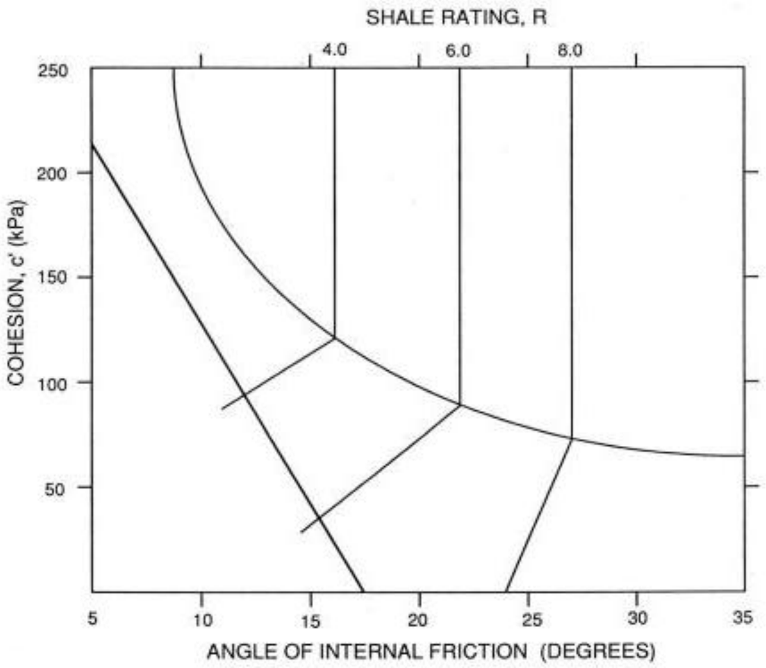


Figure 14 - General trends in the shear strength parameters of in-situ shales as a function of shale quality (modified from Strohm et al. 1978 and Franklin, 1981).

In other words, Figure 14 uses the shale rating, R that can only be obtained from Figure 12 to estimate a range of values for the cohesion and internal friction angle of the rock. However, in order to get a shale rating for the rock samples from the Kimberley "Big Hole" Mine, independent and additional plasticity index (PI) and point load strength index (Is_{50}) tests were required. Due to limitations associated with the scope of this project (i.e. cost and time constraints), these additional laboratory tests as required for further classification could not be completed and slake-durability index tests along with various other durability and weathering tests (i.e. absorption, cyclic wetting and drying and comparative accelerated weathering tests) were instead conducted with the aim of assessing the slake durability and weathering resistance of Kimberley shales against each other, with additional evaluation on the durability and strengthening effects of the applied solution on each rock mass.

According to Franklin and Chandra (1972), the slake-durability test describes an index test that is best used in comparing one rock sample with another. It will not predict in-situ rate of weathering and deterioration directly since factors other than the nature of the rock, for example the severity of climate, also influence weathering rate. A slake-durability test predicts deterioration due to climatic wetting and drying and the slaking-durability of a rock will therefore depend on the following (Franklin & Chandra, 1972):

- Permeability and porosity since these control the entry and retention of pore fluids and their mobility once inside the rock.
- The action of fluids once they have penetrated the rock must be considered. They may act by adsorption that results in surface energy changes, by solution of cement or disruption of bonds, or may set up disruptive forces by pore-pressure generation.
- The capacity of the rock to resist disruptive forces will decide the extent to which weakening, swelling or complete disintegration of the rock material will occur.

Hence a rock that is either impermeable, or non-reactive or has high intergranular strength will usually be more durable. According to Franklin and Chandra (1972), some indication of slake-durability can usually be obtained by studying the clay mineralogy and the microstructure of a rock, but it is quicker and more reliable to use a test. This must provide a means of causing slake-disruption, and a means of estimating its extent. Perhaps the most reliable means of causing disruption, if time is no object, is to leave a rock exposed to natural weathering, and much may be learned by examining naturally exposed surfaces at excavated rock slopes or quarry sites. Usually for convenience and greater control, an accelerated weathering process is employed that includes cyclic changes of environment such as drying and wetting. Franklin and Chandra (1972) states in one of their studies that there is a definite correlation between the rate of weathering of shales, the stable slope angle and the slake-durability index values obtained during testing, although such quantitative correlations have yet to be made. Gamble (1971) did however manage to produce a slake durability classification system that classifies the durability of shales according to “high”, “medium” or “low” durability as seen below in Figure 15.

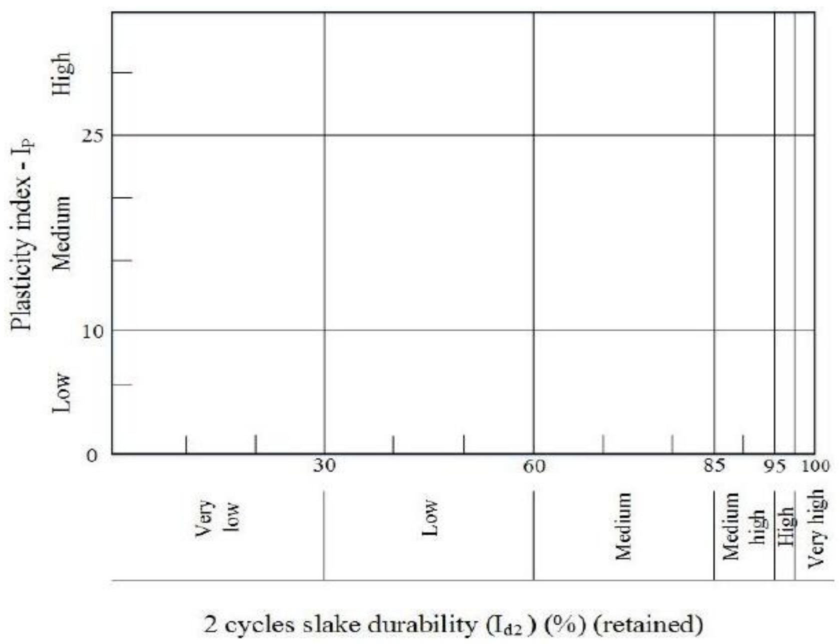


Figure 15 - Gamble's geotechnical classification of shales (Gamble, 1971).

With regards to Figure 15 above, the two categories of highest durability could be termed 'rock', and materials of lower durability 'soil'. A distinction between rock and soil is often required in engineering contracts, and the slake-durability index affords a possible quantitative method of discriminating between the two.

Following the abovementioned suggestions made by Franklin and Chandra (1972) and Gamble (1971), whom studied the slake-durability of shale type rocks for many years, this project included a variety of durability and weathering tests in order to assess the slake durability of the Kimberley shales. The abovementioned literature was the reason for conducting a full microscopic and geochemical analysis on the shales from the Kimberley "Big Hole" Mine. The testing program also allowed for a long-term durability test in the form of a cyclic wetting and drying test under exposure to the atmosphere and natural weathering conditions, as well as an accelerated weathering test that employed cyclic changes of environments as suggested by Franklin and Chandra (1972).

In conclusion, all authors are of the opinion that slake-durability index tests (in general), should only be used and interpreted in association with other rock index tests as an aid to rock classification, for selection and quality control of materials for rockfill, road and concrete aggregate, in predicting problems of excavation stability and rock support, and in selecting plant, equipment and techniques for rock excavation.

2.6 Slope stability

Over the past few years, slope stability assessments (or analyses) have become a very popular topic of interest amongst geologists and geotechnical engineers, which seemed to have evolved closely with the increasing developmental research of soil and rock mechanics as a whole (Abramson, et al., 1995). The reason for the sudden interest into slope stability assessments can be attributed to the devastating socio-economic effects that a slope failure or slip can have on humans when the delicate balance of natural soil slopes are disrupted in any way (Abramson, et al., 1995). Even though slope instabilities at the Kimberley "Big Hole" Mine do not necessarily constitute a typical slope stability problem in the sense that it does not require a full slope stability assessment / evaluation, the Big Hole Mine still represents a massive open-pit with steeply dipping to near vertical sidewalls and it is therefore worth considering the different types of slope failure mechanisms that are most commonly associated with steeply-dipping sidewalls and open pit mines.

According to Dr. Denis Kalumba (2016), a slope can be characterized as any inclined surface of which one end / side is at a higher elevation than the other. In other words, a rising or falling surface. Slopes such as defined above, can exist either through a set of natural processes or it can be engineered by humans to fulfil certain construction requirements (Abramson, et al., 1995). Slope instabilities as a topic of interest and for the purpose of this project, can thus be defined as the lack of potential of an inclined surface to withstand movement and resist failure without the aid of certain stabilisation techniques (Erasmus, 2016).

In order to fully understand the fundamental principles of various slope failure mechanisms, it is of critical importance to first distinguish between the difference in a slope instability and a slope failure. According to Knappett & Craig (2012) the term slope instability can be defined as the tendency of a slope to move, whereas a slope failure represents an actual mass movement event or a landslide. A general term used to describe all types of slope failures and instabilities however, is often referred to as a "slope movement".

Slope movements, as defined above, are most commonly caused by three forces of instabilities namely (1) the geometry of a slope, (2) gravity and (3) seepage which, in most cases, act together to induce a natural angle of repose for each individual slope. A natural angle of repose was described by Knappett & Craig (2012) as a phenomenon where, within all slopes there exists an inherent tendency for the slope to degrade to a flatter and more stable angle and ultimately move towards the horizontal. So in essence it can be said that slope movements are a direct consequence of slopes continuously wanting to develop towards their natural angle of repose, which in the case of the migrating sidewalls of the Kimberley "Big Hole" Mine, is no different.

More often than not, there is a direct correlation between a slope's natural angle of repose and the durability characteristics of the rocks it is made up of. In the specific case of the Kimberley Big

Hole" Mine for example, this project is hoping to find a unique correlation between the durability and weathering characteristics of the Kimberley shales and the rate at which the slopes are moving towards their natural angle of repose. In other words, it aims to draw direct correlations between the slake-durability index values as obtained from the testing program of this project, to the general safe slope angle as defined by the project and literature.

Due to the fact that the term "slope movement" is widely used as an all-inclusive term for almost all varieties of mass movement events including those that involve little or no true sliding, Varnes (1978) was the first person to classify the term and divide it into five different subcategories namely (1) falls, (2) topples, (3) slides, (4) spreads and (5) flows. The exact classification and processes of these subcategories are shown in Table 6 whilst Figure 16 illustrates them.

Table 6 - Abbreviated classification of slope movements and processes based on Varnes (1978) as modified by U.S. Geological Survey (2004).

TYPE OF MOVEMENT			TYPE OF MATERIAL		
				Engineering Soils	
			Bedrock	Predimonantly Course	Predominantly Fine
Falls			Rock fall	Debris fall	Earth fall
Topples			Rock topple	Debris topple	Earth topple
Slides	**Rotational**	**few units**	Rock slump	Debris slump	Earth slump
	Transitional	**many units**	Rock slide	Debris slide	Earth slide
Lateral Spreads			Rock spread	Debris spread	Earth spread
Flows			Rock flow (deep creep)	Debris flow (soil creep)	Earth flow (soil creep)
Complex			Combination of two or more principal types of movements		

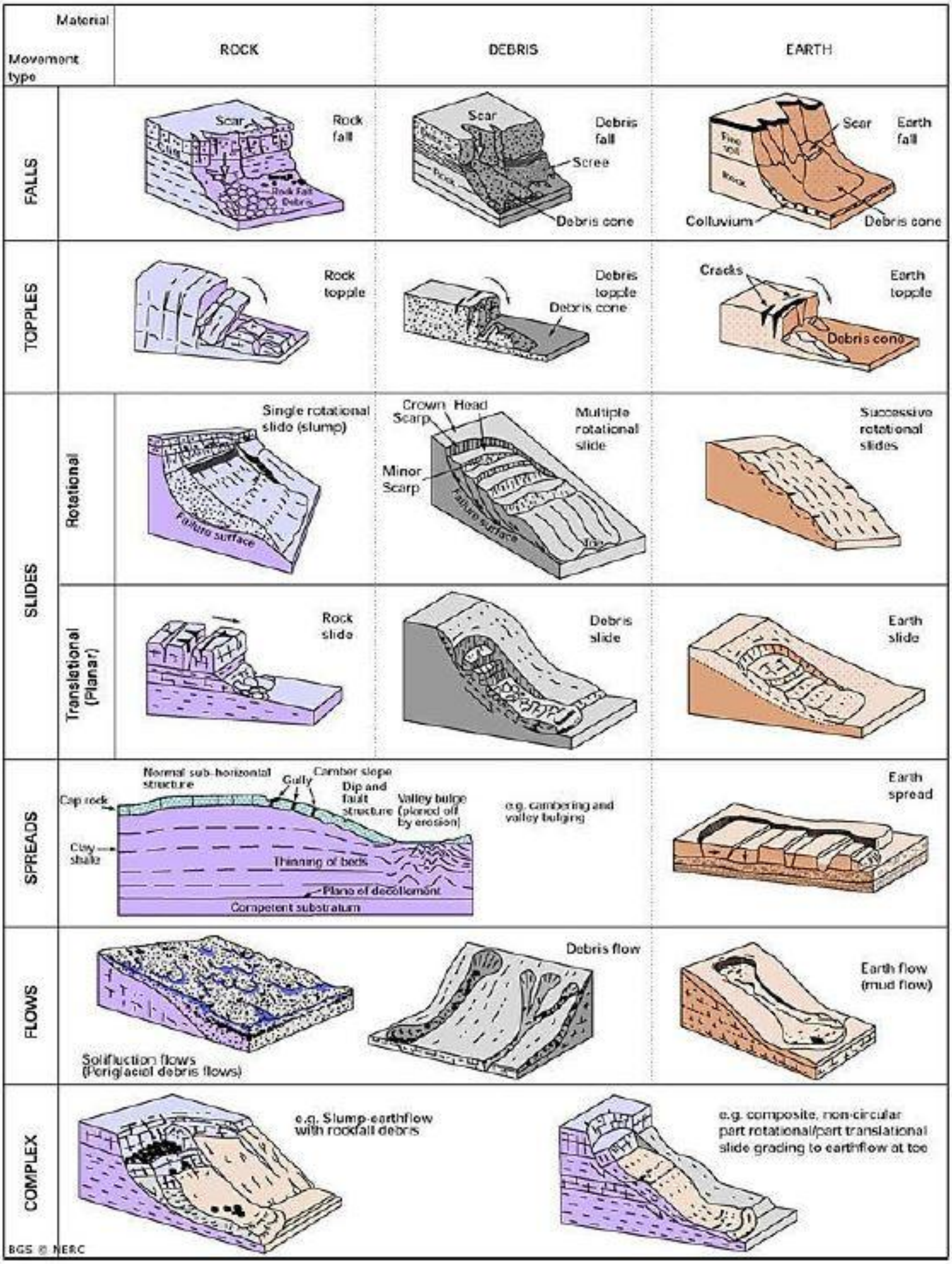


Figure 16 - Classification of slope movement processes (Bothma, 2015).

According to Tarbuck et al. (1998), there are numerous factors that could change the potential of any of the above illustrated mass wasting events. These factors include:

- Any short or long term changes in a slope's angle.
- The weakening of rock material due to weathering (i.e. refers to the defined slope stability problem at the Kimberley "Big Hole" Mine).
- A fluctuating water table / water content.
- Any short or long term changes in vegetation cover.
- Overloading of a slope.

All of the abovementioned information was used to describe the most common types of slope movement events along with their unique characteristics. The only reason for this comprehensive review was to introduce the different types of failure mechanisms that are most commonly associated with shale slopes around the world. Before describing each shale slope failure mechanism in detail however, Hunt (2005) suggested looking at the following key aspects of a slope, as a way of identifying the ensuing failure mechanism:

- The occurring history of slope failures in the area and the various factors that caused them.
- The geometry of the slope.
- The presence of any instability indicators near the surface of the slope (such as soil creep, tension cracks or landslides for example).
- The surrounding weather conditions including rainfall and temperatures statistics.

When considering a full slope stability assessment, mathematical formulas are normally used to calculate the most viable solution towards the defined slope stability problem however, these mathematical solutions can only be formulated once the shape of the slope's failure path is defined in some way (Hoek & Bray, 1981). Because slope failures such as avalanches, earth flows and rockfalls do not possess any indication of a slope failure path, it is generally accepted that they cannot be solved mathematically. In other words, they can be identified and categorized, but a viable solution would have to be inspired without the aid of using mathematical equations, which was exactly what was done for the defined slope stability problem at the Kimberley "Big Hole" Mine.

2.6.1 Failure mechanisms in shale slopes

Within every shale slope (or sidewall) that is exposed to the atmosphere and natural weathering conditions, certain failure mechanism exist that increase the potential for local slope instabilities. In other words, different types of slope instabilities are activated or mobilized by different types of failure mechanisms and according to Stead (2016), the most common type of failure mechanisms in shale slopes recorded today are the following:

- Translational failures.
- Earthflows.
- Rock falls.
- Toppling.

Each of these failure mechanisms lead to a different set of slope instabilities and whilst most are not applicable towards the defined slope stability of the Kimberley “Big Hole” Mine, a brief description of each is still provided below:

Translational failures are the most common type of shale slopes failures and can vary from simple planar failures along low shear strength weakness planes (usually found within engineered slopes) to extensive deep-seated multi-block landslides involving multiple and extensive shear zones (see Figure 17).

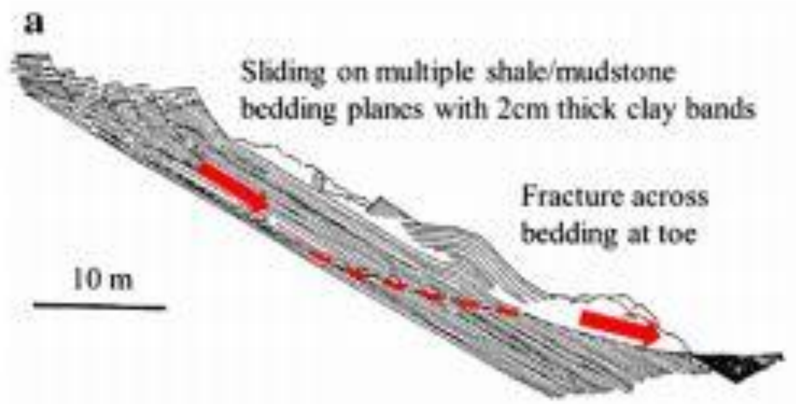


Figure 17 - An illustration of a typical translational shale slope failure (Stead, 2016).

According to Stead (2016), translational shale slope failures only tend to occur on sub-horizontal to slightly dipping shear zones. This is because rocks within a shear zone often exhibit very low shear strength parameters, which means that an active driving force, such as gravity for example, in combination with the lubricating effect of high pore water pressures is often enough to cause a massive slope slip or failure. Stead (2016) further goes on the suggest that there is a direct correlation between the behaviour and the rate of movement as a function of the depth of the clay shale shear surface, which in the case of the Kimberley “Big Hole” Mine, is inapplicable. There are only two recorded shear zones on the sidewalls of the Big Hole Mine, both of which have no correlation to the defined slope stability problem of the pit. Slope failures experienced by the sidewalls of the Kimberley “Big Hole” Mine exhibit no features or components of a planar or circular slip (as found with translational failures), but rather the regression and degrading of surface shale material as a result of extensive weathering.

Earthflows on shale slopes most commonly occur due to the softening of shale debris material after a preceding landslide event. It involves a downslope viscous flow of fine-grained materials that have been saturated with water and mover under the pull of gravity (see Figure 18).

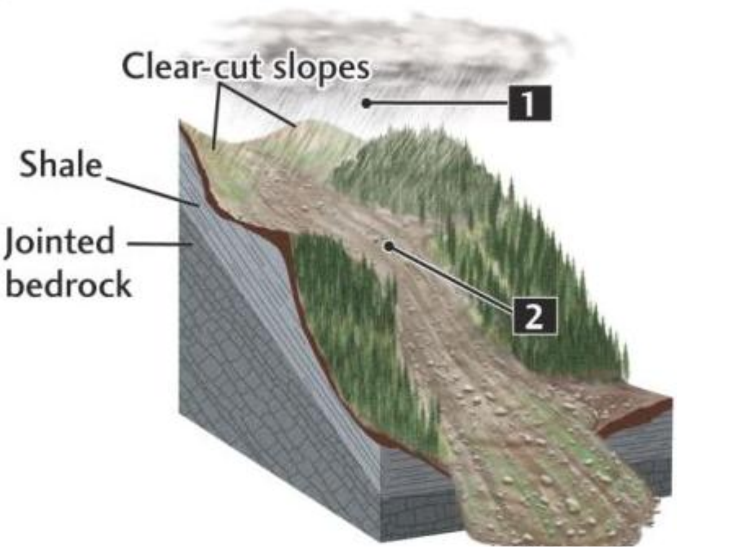


Figure 18 - A typical example of an earthflow event on a shale slope surface (USGS, 2004).

According to Bovis (1985), in order for the earthflow of a shale slope to take place, a landslide or some form of a landslide event must have preceded to earthflow failure. The reason for this is that a preceding landslide event often results in the formation of weaker clay shale material on the surface of the slope, which upon further weathering and deterioration start to exhibit softening behaviour. This softening behaviour of shales is activated by the disruption of their original form and structure causing fissuring, dilation and the development of a negative pore water pressure within the internal structure of the rock. These types of failures however, are mostly found within tropical areas and require a large amount of rainfall usually within a very short period of time and was therefore discarded as a possible failure mechanism for the shale slopes of the Kimberley "Big Hole" Mine. Also, the few landslide events that have been on the slopes of the sidewalls of the Kimberley "Big Hole" Mine are the result of a block toppling slope failure event which causes degraded material to slide down the slope. In other words, the landslide event does not precede the defined slope failure mechanism at the Kimberley "Big Hole" Mine, but rather follows as a consequence thereof (Stead, 2016).

Rockfall failures have become much more recognized over the past few years as the effects of weak rock masses, such as shale for example, that underlie more competent rock beds have become a critical geotechnical consideration in rock fall hazard rating systems due to the dangers thereof to surrounding infrastructure and human lives. Rockfalls occur when fragments or blocks of rock detach by sliding, toppling or falling along a vertical of sub-vertical cliff as seen in Figure 19 (Marzorati, et al., 2002). Rockfalls in shale slopes are much more concerned with the weathering control on durability and degradation of the shale rock mass as opposed to the kinematic sliding factors along adverse planes such as described above for translational failures. Rockfalls in shale slope environments often occur due to support loss or undermining of a shale unit, which causes the overlaying and more competent rock mass to fail. In other words, these failures often occur along steep-sided slopes where one rock unit, usually lower down in the geological succession, weathers and deteriorates much faster than the rock mass above. Weathering-induced recession of weak shale rock masses at the toe of a slope could lead to a variety of different types and scales of rockfall failures including toppling failures, wedge failures and spreading failures (Stead, 2016). However, because the later defined slope stability problem at the Kimberley "Big Hole" Mine (as discussed in Chapter 4) can best be described through the process of toppling, the toppling slope failure mechanism as a type of rockfall failure is described and discussed below.

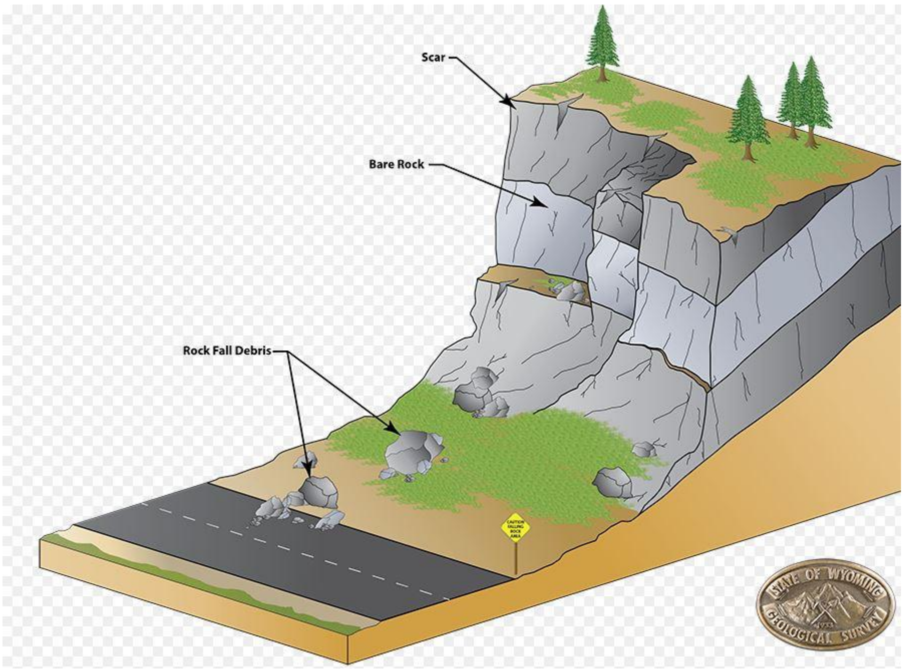


Figure 19 - An image depicting a rock fall slope failure event (Marzorati, et al., 2002).

Toppling slope instabilities in shale slopes form part of the rockfall slope failure mechanism and constitutes only one of the many slope failure mechanisms of shale that lead to slope instabilities. According to Goodman (2012), the growth of a toppling root zone is controlled by the presence of hard and weak rock strata with the presence of weak anisotropic shales within a sedimentary sequence being an important control on toppling instability. In other words, the location of the shale formations whether at the toe of the slope, mid slope or near the slope crest will influence the overall failure mechanism that occurs and is the subject of ongoing research. Toppling is one of the five major types of slope movement failures that occur commonly in nature and in all rock types, although recently much more associated with shale type rocks (Varnes, 1978). According to

Duncan (1980), whom studied the case histories of three separate toppling slope failure events around the world, toppling can generally be subdivided into two subcategories namely (a) flexural toppling and (b) block toppling, both of which occur very commonly in nature but initiates due to different failure mechanisms. Schematic examples of flexural and block toppling are shown in Figures 20 A and B.

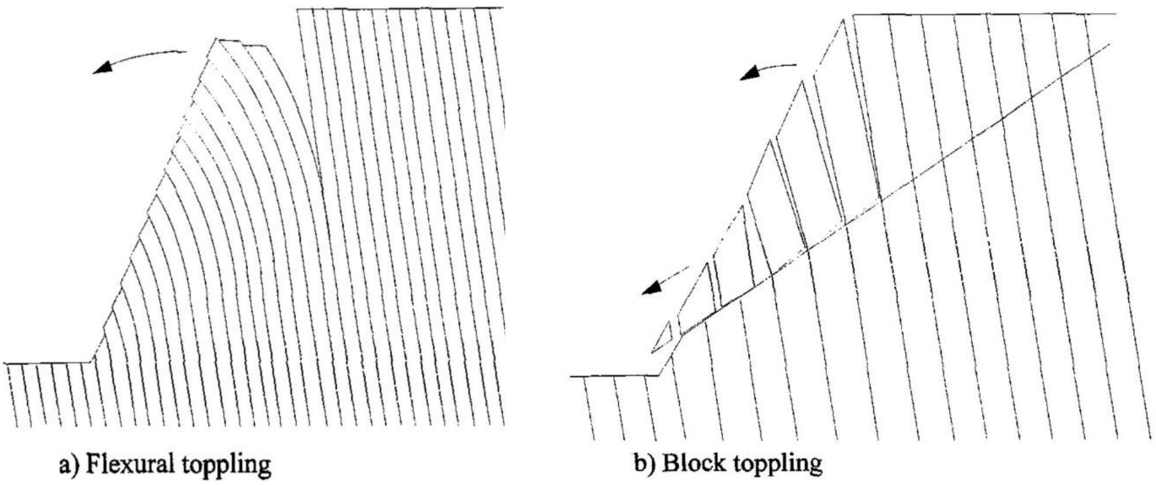


Figure 20 - Schematic examples of (A) Flexural Toppling and (B) Block / Direct Toppling (Adhikary et al., 1997).

According to Duncan (1980), block toppling occurs when the centre of gravity lies outside the outline of the block and topples over, due to the rock mass having a big overturning moment. Flexural toppling on the other hand, occurs when a layered rock mass outcrops against a steeply dipping slope and the principle stresses acting parallel to the slope triggers a slip between the layers and causes the intact rock to subsequently fracture and overturn (Adhikary et al., 1997; Bothma, 2015). The stability of toppling, as a slope movement failure, can be analysed both mathematically and via the use of physical models. However, it is also worth mentioning that these types of stability analyses can often be very time consuming with the necessary facilities required to do such an analysis not always being accessible (Duncan, 1980). When looking at the defined slope stability problem at the Kimberley “Big Hole” Mine (as discussed in Chapter 4) it becomes clear that block toppling as a slope failure mechanism explains the process of regression on the sidewalls of the pit best and is therefore considered the shale slope failure mechanism responsible for slope instabilities at the Big Hole Mine. As the underlying shale unit weathers and deteriorates, the overlying dolerite block shifts its centre of gravity to the outside of the outlined block and topples over and into the open mine pit as a single block toppling slope failure event. This subsequently also leads to small-scale landslides on the surface of the slopes, which causes further degradation and weathering.

Looking the four most common types of shale slope failure mechanisms as discussed above (i.e. translational failures, earthflows, rockfalls and toppling), it can be argued that rockfalls, with specific reference to block toppling as a slope failure mechanism, is the main reason for slope instabilities at the Kimberley “Big Hole” Mine. Weathering-induced recession of weak shale rock masses at the crest of the slope is what leads to toppling rockfall failures at the Kimberley “Big Hole” Mine. Logically, it is also assumed that the more toppling slope failure events occur, the less durable the underlying shales become due to more of the surface area being exposed to the atmosphere and natural weathering conditions.

2.7 Geotechnical considerations

2.7.1 Natural angle of repose

According to Carrigy (1970) and Van Burkalow (1945), all geological materials on earth have what is known as a **“natural angle of repose”**, which can be defined as the angle at which material in nature will form a stable slope. This fact was noted by Preece et al. (2008) in their report, as they seemingly understood that the same principle applied to the stability of the slopes at the Kimberley “Big Hole” Mine. As part of their studies conducted on the ground conditions of the mine and the geomechanical properties of the rocks, Preece et al. (2008) found that for the shale zone of the pit, the natural angle of repose would be between 20° and 30° as oppose to the current slope angle of 38°.

This means that there will come a day when mine pit break-back at the Kimberley “Big Hole” Mine will eventually start to slow down and reach natural equilibrium when a balance between the vertical sides of the inner pit and the slope of the outer rim is reached, rendering the Kimberley “Big Hole” Mine in its most natural and stable form. According to Preece et al. (2008), the continues effects of seasonal rainfall and time, will eventually reach a point where progressive erosion of the outer perimeters of the pit will decrease and establish a more stable profile. However, trying to equate a precise time limit for natural equilibrium to occur at the Kimberley “Big Hole” Mine, would prove near impossible as there are currently many human factors that are contributing to the frequency and occurrences of slope failures at the mine including:

- Nearby construction sites (causing massive vibrations, which encourages loose material and cracks to become even more unstable and have the propensity to increase the risk of slope slips or failures).
- Heavy traffic along main roads immediately next to the outer fringes of the mine (in some cases even as close as 22 meters from the outer edge of the eastern side of the pit, case in point: Bultfontein Road).
- Nearby businesses and heavy infrastructure surrounding the “Big Hole”, which ultimately adds to the load and regional stress regime of the surrounding area.

2.7.2 Water table

In addition to the calculation of the natural angle of repose at the Kimberley "Big Hole" Mine, it is also worth mentioning that the data collected during the study by Preece et al. (2008) indicated a generally shallow (close to the surface) groundwater table around the pit, which if allowed to infiltrate the shale zone, would cause the weathering process of the rocks to accelerate rapidly. However, according to Preece et al. (2008), De Beers had already been aware of this problem and had therefore already constructed a precuationary measure to effectively mitigate the negative effects of a shallow water table on the mine pit slope, by developing a massive dewatering tunnel (see Figure 21) some 60 meters below the surface and some 200 metres back from the outer edge of the pit. As a result of clever construction on behalf of De Beers, ground water in the vicinity of the Kimberley Mine is effectively drained into the strategically placed dewatering tunnels via a series of intersecting boreholes and as a successful result, since its development these tunnels have effectively kept the shale slope dry and away (for the most part) from an accelerated weathering process (except during times of heavy rainfall in the summer months of Novemeber to February) (Preece et al., 2008).

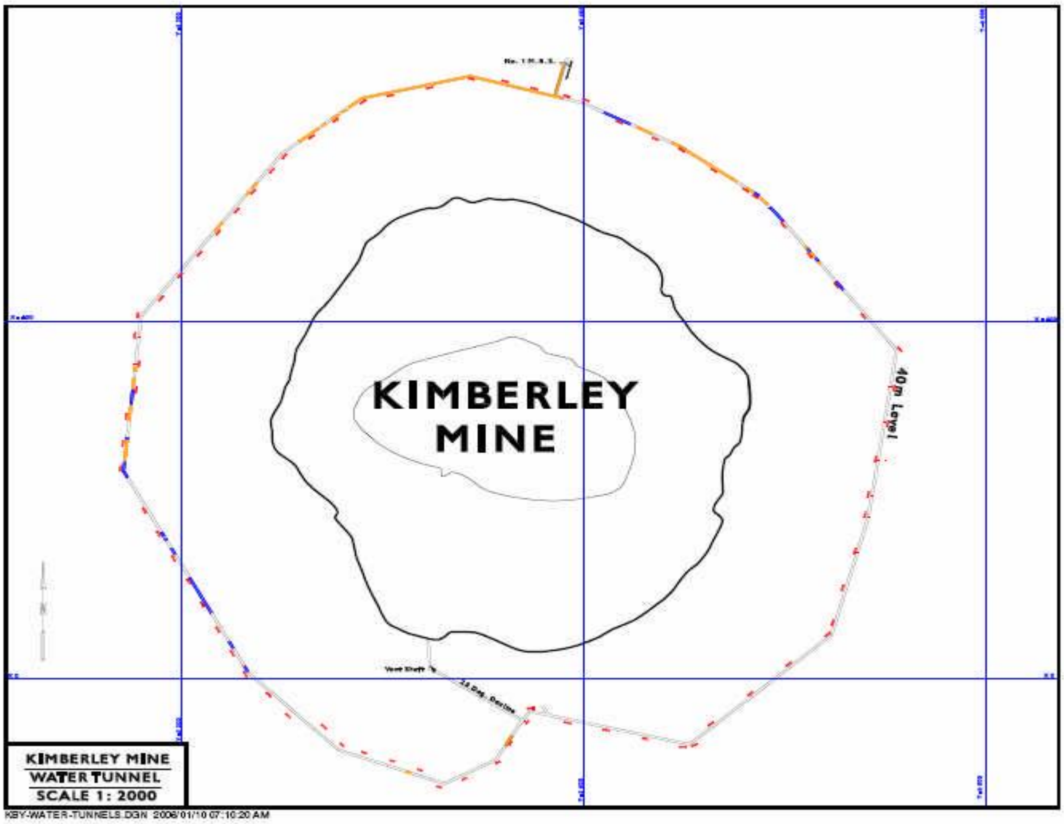


Figure 21 - Layout of the Kimberley "Big Hole" Mine water tunnel (Preece et al., 2008).

2.8 Safety at the Kimberley "Big Hole" Mine

2.8.1 Seismic activity

South Africa is generally not known for a frequency of large seismic events, even though some seismic activity has been recorded over the past few years. However, due to the fact that even the slightest seismic activity can cause a slope failure process (especially toppling for example) to activate (Kijko et al., 2003; Bothma, 2015), it is worth investigating the average seismic activity rates around the area of Kimberley and the Big Hole Mine. As illustrated by Figure 22, a seismic-hazard map was created by Kijko et al. (2003) for the whole of South Africa. The seismic-hazard map indicates that the town of Kimberley lies exactly wtihin the yellow to orange transition zone with an approxiamted peak ground acceleration (PGA) of 0.14 g. Fortunately, in terms of seismic activity and physical dangers of seismic events, this value is fairly low and poses no immediate threat. This is subsequenbtly also the value that is being used in calculations when slope stability problems are being investigated (Kijko et al., 2003).

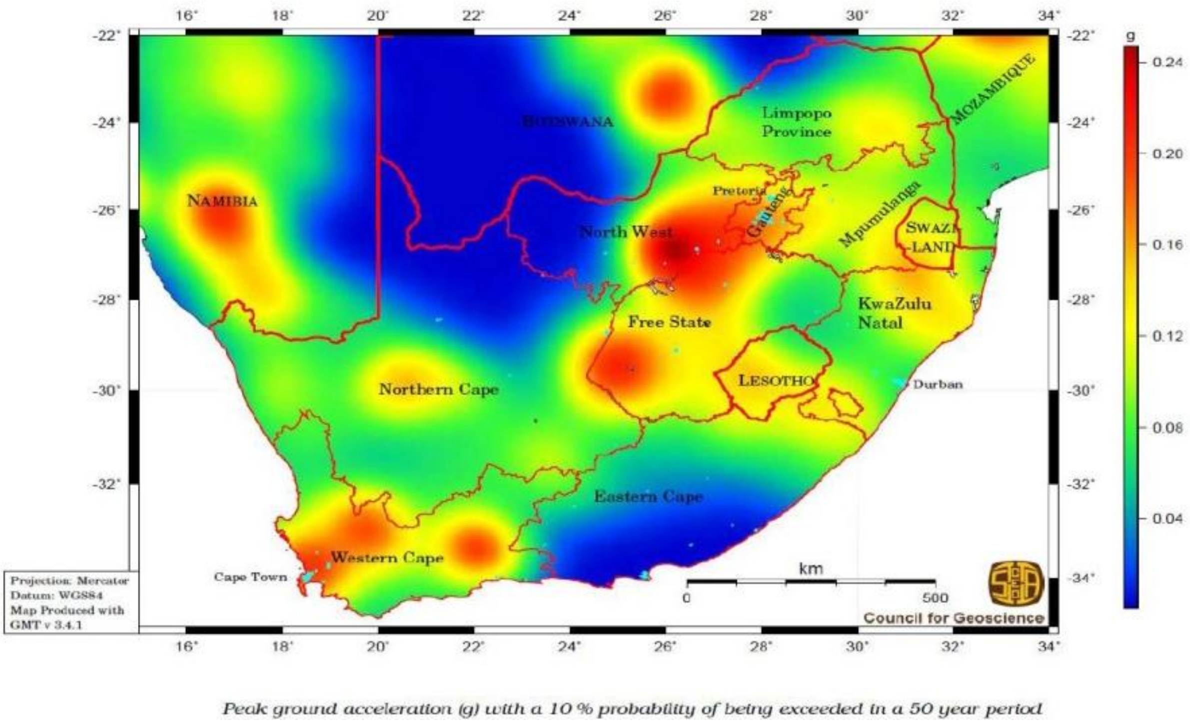


Figure 22 - Seismic-hazard map of South Africa (Kijko et al., 2003)

2.6.2 Monitoring and management

Following on from the investigative studies done by Preece et al. (2008), the report included the fact that De Beers managed to implement a comprehensive monitoring strategy, which is still presently being adhered to. As at the date of publication of their report, Preece et al. (2008) made a summary of exactly what the monitoring strategy of De Beers entails:

1. Weekly visual inspections of the mine pit that are conducted by De Beer's geotechnical personnel. At these inspections obvious visual changes are looked for, for example the opening of old cracks or the development of new cracks that are not shown on the current mine plans.
2. The installation and maintenance of a remote / continuous geotechnical monitoring system that records discrete movements at defined points, which are in close proximity to the actual mine pit. Figure 23 shows the three types of movement monitoring equipment installed and used by De Beers for the Kimberley "Big Hole" Mine to track any ground displacement around the pit.
3. Precise surveys that are conducted quarterly by the De Beers Kimberley Mine's Survey Department. These surveys aim to monitor any and all movements that have occurred along the defined radiating survey lines that cover a wider zone around the entire mine pit perimeter.
4. From time to time, aerial surveys of the mine pit are also conducted in order to accurately determine and update the entire mine pit profile for comparison with previous mine pit profiles. Up until the time of publication of the report written by Preece et al. (2008), data that had been collected by these infrequent aerial surveys indicated an ongoing movement pattern around the northern half of the mine pit, with the north-eastern area of the pit being the most active at the time.

According to Preece et al. (2008) the entire monitoring system of the Kimberley Mine (as described above) is an on-going process which have been conducted by De Beers for many years. So in conclusion, Preece et al. (2008) was of the opinion that the slope stability problem at the Kimberley "Big Hole" Mine was being managed as far as is reasonably possible by the De Beers company, firstly by: (1) maintaining the dewatering tunnels around the shale zone of the slopes of the mine pit and secondly (2) by ensuring that the ground movement monitoring strategy (as referred to above) is in place, working and being reviewed.

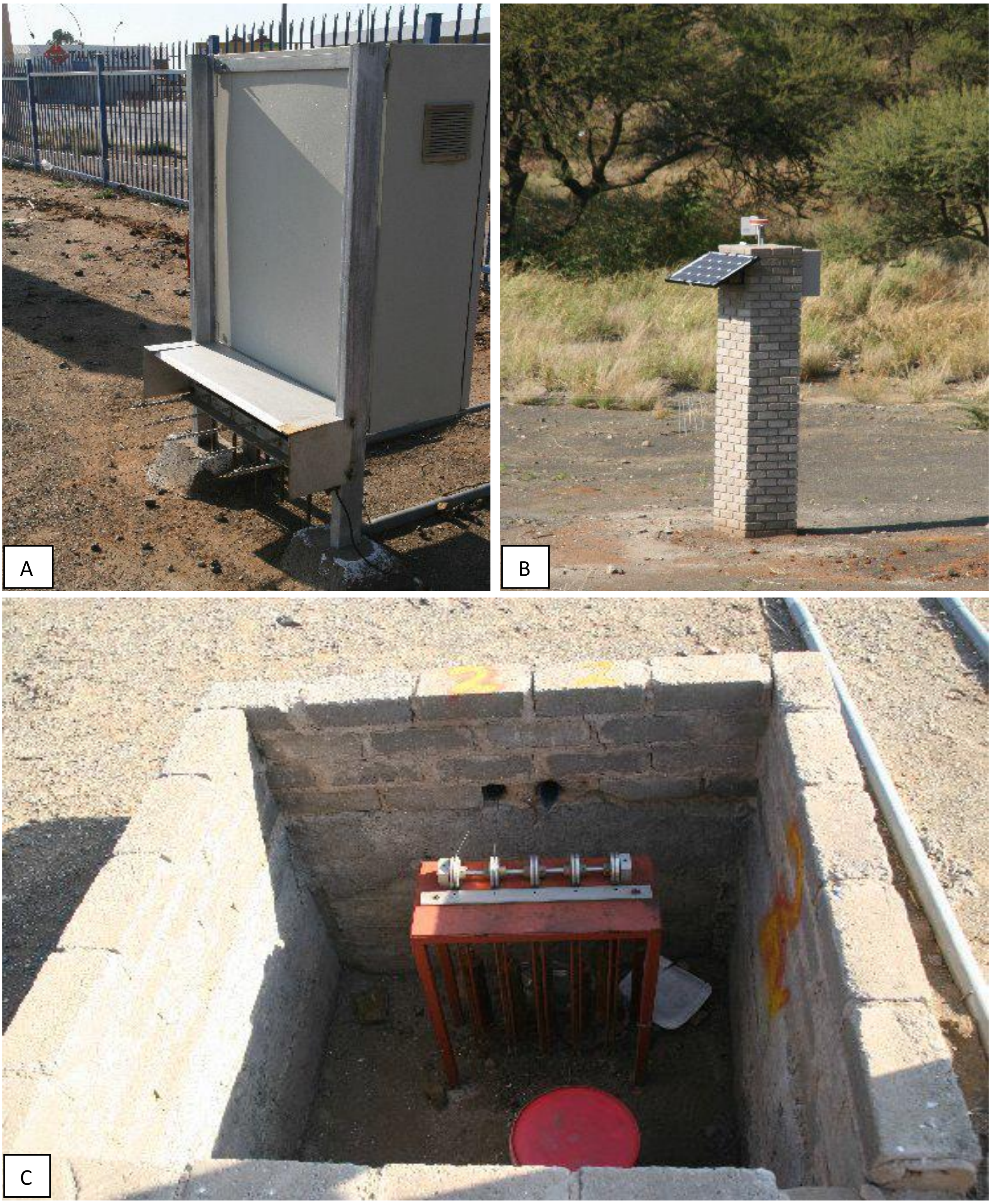


Figure 23 - A.) Continuous Type Extensometer, which constantly records movement; B.) Modern GPS automated levelling system, which automatically sends data to the main office at De Beers; C.) Manual Type Extensometer, which involves measurements being taken via manual inspection on a bi-weekly basis (Croukamp, 2008).

2.9 Previous studies

In the past there have been numerous studies conducted at the Kimberley "Big Hole" Mine that pertain to the overall state and stability of the sidewalls of the open pit mine. These studies covered a whole range of topics and experiments including: slope stability analyses, site investigations, joint surveys, estimation of break-back patterns, precise level surveys and aerial surveys to only name a few. These studies were not only conducted by De Beers officials and geotechnical personal, but also included independent review reports from outside companies and institutions such as the Sol Plaatje Municipality and the Council for Geoscience. The relevant topics discussed, are all included within the reports that were reviewed for the purpose of this project, which includes:

- *"A summary of geotechnical information pertaining to the stability of the sidewalls of the Kimberley Mine (commonly referred to as the Big Hole) located in Kimberley, Northern Cape Province, Republic of South Africa and the relevance thereof to the adjacent Bultfontein Road", complied by CA Preece, AD Wilson and Dr. AR Guest, 27 February 2008.*
- *"Sidewall stability of Kimberley "Big Hole" Mine", compiled by The Council for Geoscience, 30 June 2008.*

These studies also included a few case studies that relate to recent slope failure events at the Kimberley "Big Hole" Mine, further supporting evidence of an unstable and continuously weakening slope configuration. An example of such a case study is discussed in the following chapter.

2.10 Conclusion

After carefully reviewing all available literature on slope instabilities, shales and the geological and geotechnical components of the Kimberley "Big Hole" Mine, a brief summary of the most important aspects justifying further research in this project is highlighted below.

Even though there are many durability and weathering tests that deal with the strength and slaking characteristics of shales, a standard shale classification system has yet to be developed as all available literature suggest limitations to each existing classification chart. Several authors are in agreement that the slake-durability index test is best utilized in comparing one rock or shale sample to another, which is why the testing program conducted within the scope of this project, follows the same argument. Furthermore, slope instabilities surrounding shale slopes are mobilized due to different failure mechanisms, although toppling as a rock fall shale slope failure is generally considered as the best described failure mechanism on the sidewalls at the Kimberley "Big Hole" Mine. This failure mechanism is mobilized due to weathering and durability problems with the Kimberley shales (as discussed in Chapter 4), which is why a viable solution includes the potential of decreasing the weathering and deterioration rate of the Kimberley shales, whilst testing the effects thereof by means of a variety of durability and weathering tests.

Chapter 3: Case study

In order to prove the entire extent of slope stability problems at the Kimberley "Big Hole" Mine and the damaging effects thereof on the adjacent infrastructure of the town of Kimberley, a specific case study was undertaken by Preece et al. (2008) during conduction of their report that pertains to the sidewall stability of the Kimberley "Big Hole" Mine, which particularly focused on the rapid degeneration and cracking of the nearby Bultfontein Road.

According to Preece et al. (2008), Bultfontein Road runs to the east of the Kimberley Mine pit in a general north-south direction. The main concern and reason for choosing Bultfontein Road as the focal point of their study, was that this road seems to fall exactly within the break-back zone of the Big Hole Mine (as referred to in Chapter 4) and showed the most potential for a possible slope slip / failure. This is subsequently also why the eastern edge of the Kimberley Mine pit became the subject of continuous and focused monitoring by De Beers. To predict a slope failure for the eastern edge of the Kimberley Mine, or at best to determine the average rate of deterioration of the slope, Preece et al. (2008), in accordance with De Beers, used Figure 24 as a guideline for the predicted break-back perimeter of the eastern edge of the pit.

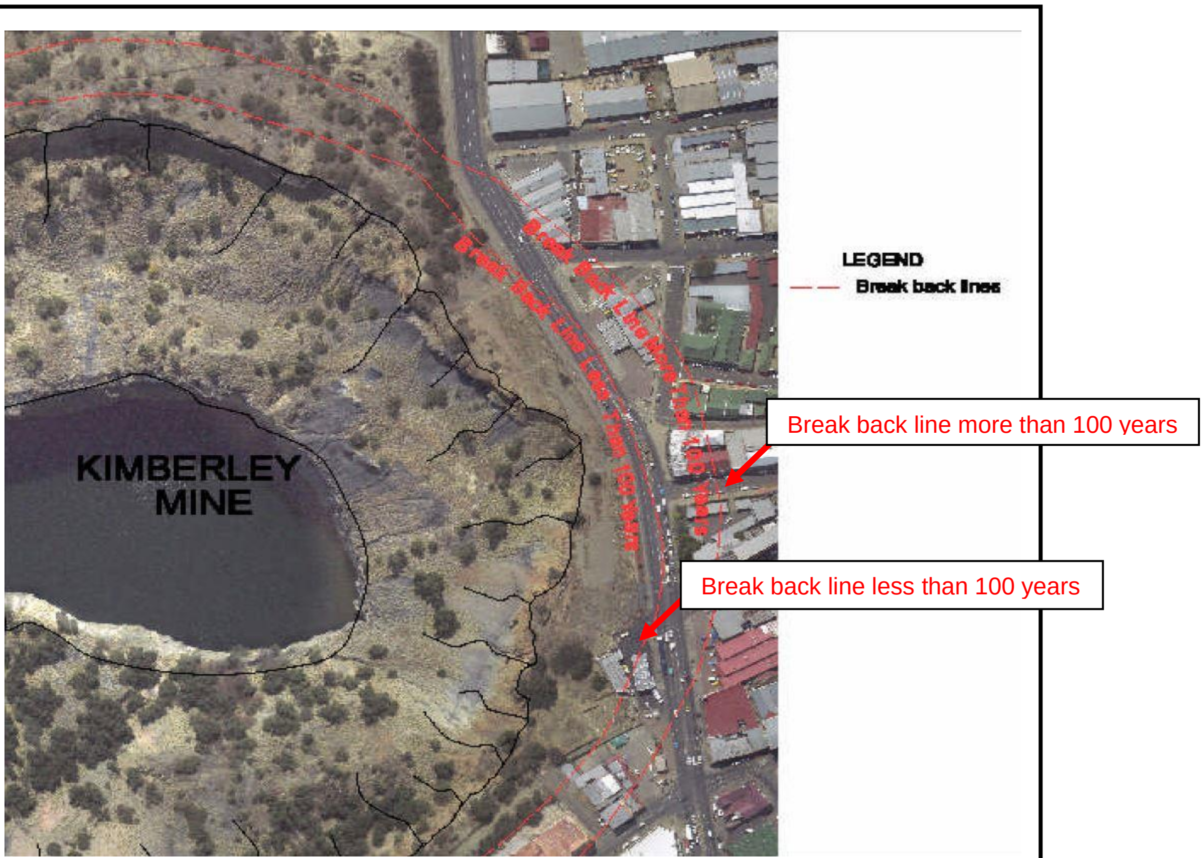


Figure 24 - Limits for potential mine pit break-back near Bultfontein Road (Preece et al., 2008)

Preece et al. (2008) also used all obtainable information from remote monitoring equipment surrounding the Big Hole, as well as any information obtained from precise level surveys, to ultimately calculate the relevant lateral deformation of the slope. Figure 25 is therefore an indication of the tensional (horizontal) movement creeping towards the open mine pit.

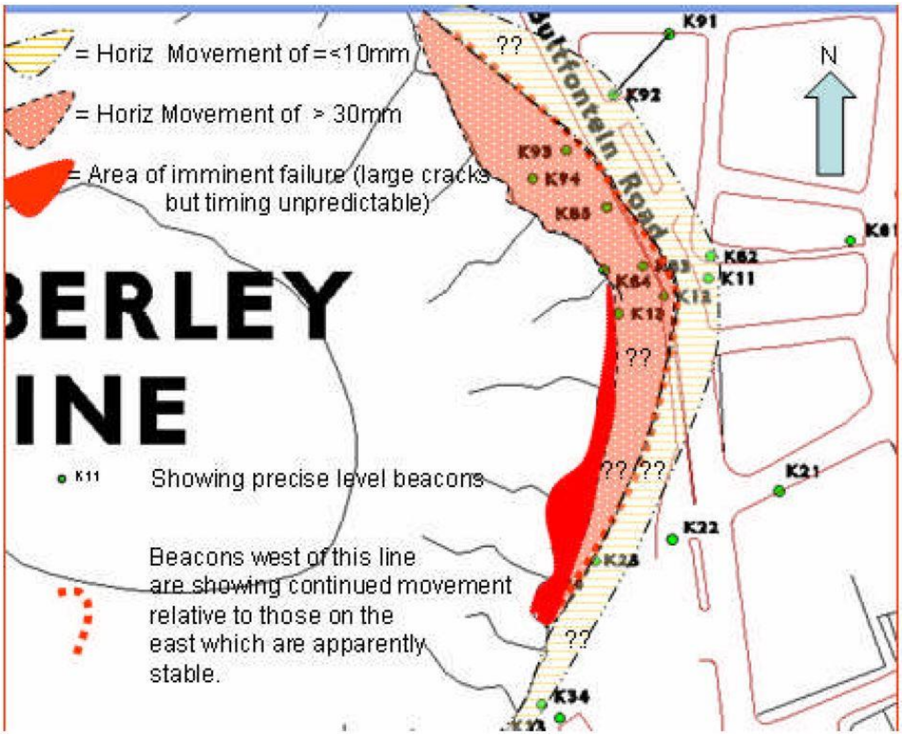


Figure 25 - The relative degree of tensional horizontal movement towards the Kimberley Mine pit (Preece, et al., 2008).

By doing this, it was proved that on-going movement was still being registered by monitoring beacons west of Bultfontein Road and that they were becoming much more significant. With reference to Figure 25, Preece et al. (2008) was also of the opinion that the zone demarcating the area of relative movement, seemed to fall between the east and west beacons on either side of Bultfontein Road, causing the actual location of the failure plane(s) to be somewhat masked, although a pattern of cracks in the road can be considered to coincide with the columnar jointed nature of the dolerite capping. The zone of imminent failure on the outer perimeters of the mine pit edge, exhibited well-defined tension / toppling cracks that were up to a few meters wide in some places.

Preece et al. (2008) further elaborated on the existence of many small-scale tension cracks in the tarred surfaces of Bultfontein Road, suggesting that (by their relative location and orientation) it has a close relationship with the loosening of the dolerite caps in the area. Relatively minor movement of these cracks (equating to <10mm since 1980) however, were registered by the precise level surveys in the area and seemed to be perfectly aligned with the degree of cracking seen in the tar of Bultfontein Road (Preece, et al., 2008). According to Croukamp (2008), even though these cracks strike such that they can be projected to almost coincide with some of the cracks along the eastern boundary of the mine pit, the risk of an instantaneous failure should be mitigated by virtue of the fact that:

- Jointing in the overlying dolerite caps are sub-vertical.
- There are no apparent low-angle wedge-forming features daylighting on the mine pit face.

At the time of publication of their report, Preece et al., (2008) had concluded that during the conduction of their studies, there had been no real evidence that would suggest a fault-slip failure between any of the units on either side of the tar cracks, but that it simply had a tensional relationship. On review of the visual inspections that were undertaken by the De Beers's Geotechnical Department in the underground storm water drains, running to the east of Bultfontein Road, Preece et al. (2008) also claimed that it did not reveal any form of surface failure or cracking, which further supports the above made statement.

The exact same beacons located on the eastern side of the Big Hole Mine that were used to monitor movement by completing precise level surveys of the area thought to be most in danger, were also used to calculate the vertical displacement of the slope as illustrated in Figure 26. However, according to Preece et al. (2008), the beacons west of Bultfontein Road seemed to exhibit the most vertical movement. The combined effect of resultant vertical and horizontal movement was considered by Preece et al. to be a consequence of progressing deformation of the underlying shale and the fact that movement was still continuing, is thought to suggest a certain risk factor to the Bultfontein Road area that is only escalating.

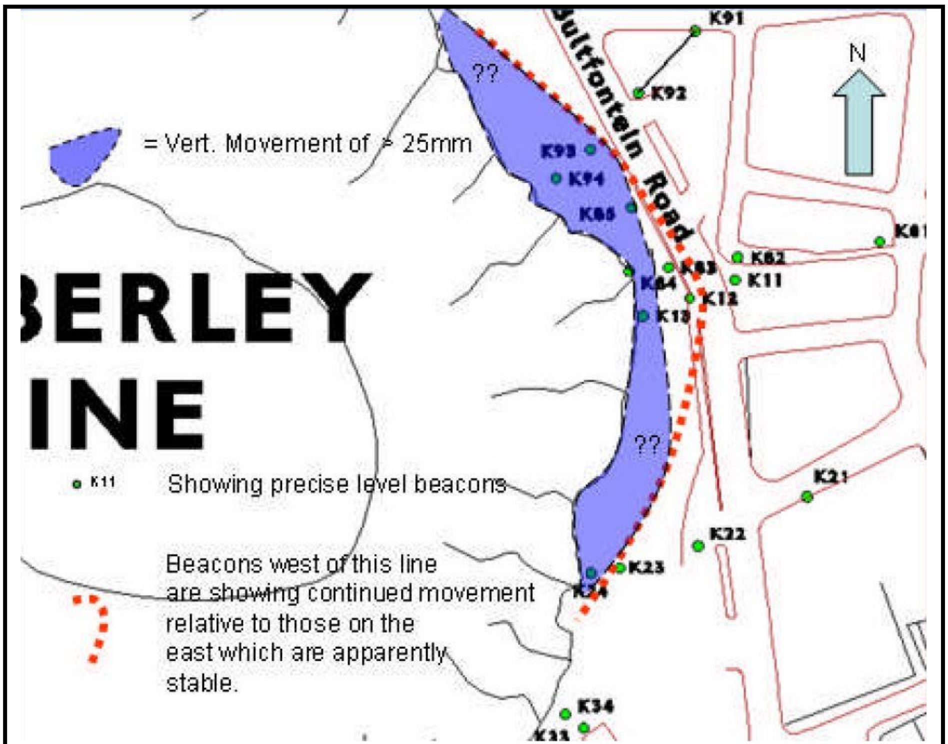


Figure 26 - The relative degree of vertical (downward) movement west of Bultfontein Road (Preece et al., 2008)

Considering all of the above-mentioned information, with specific focus on the evidence for vertical and lateral displacements over the past few years at the eastern edge of the Kimberley "Big Hole" Mine, Croukamp (2008) made the following conclusions:

- A slope failure is almost always preceded by visible cracking and significant opening / displacement in close proximity to where the failure usually occurs. In accordance with this statement, large failed areas usually also take a long time to fall, whereas smaller zones fall within a much shorter period.
- Slope failure at the Kimberley "Big Hole" Mine, seems to be linked to areas where there is significant height of the vertical scarp dolerite / shale face and it is therefore very important to recognize the exact location of (especially) the <100 year old break-back zone of the outer perimeters of the pit and limit work to just outside / behind it.
- The unstable zone adjacent to Bultfontein Road is an escalating risk, because there is no clear failure-point model to work to for the Kimberley Mine pit. In other words, it is not possible to predict when a slope failure will occur.

In summary of the above-mentioned case study, Preece et al. (2008) felt the need to summarize the three most important points regarding slope stability problems at the Kimberly Mine:

1. There is a significant risk that the east side of the Kimberley Mine pit could break-back or fail with segments of Bultfontein Road collapsing into the mine pit as a result;
2. Although De Beers employed a remote monitoring system in order to monitor any and all movement of the sidewalls of the Kimberley Mine pit, not even De Beers can predict with a great amount of accuracy when any major sidewall slippage will occur;
3. The sidewalls of the Kimberley Mine pit will inevitably fail someday, until a natural angle of repose is reached; i.e. slope failure is inevitable.

3.1.1 Two examples of recent slope failures near Bultfontein road

1. Slope failure – 5th April 2007

On this day, a relatively large-scale slope failure occurred on the eastern side of the mine pit in the exact area as depicted in Figure 27 A. Preece et al. (2008) estimated that the size of the failure amounted to a wedge of dolerite approximately 10 meters long, 4 meters wide and 15 meters down. At the time of publication of their report, Preece et al. (2008) was of the opinion that the remainder of the wedge, as indicated in Figure 27 B was likely to fail shortly due to the existence of more cracks along the side of the slope, indicating an overall increase in slope instabilities. In their report, several other images depicting further cracks and possible future failures along the eastern boundary of the mine was shown as reviewed in Figures 27 C, D and E.

2. Possible new slope failure – 24th January 2008

Preece et al. (2008) used their report to review and acknowledge the fact that during routine monitoring activities, De Beers Geotechnical personnel had identified the existence of a new tension crack on 24 January 2008 that had developed on the eastern side of the Kimberley Mine pit (see Figure 27 F). According to Preece et al. (2008) the identification of these cracks by competent De Beers personnel, only constituted a further indication that there are instabilities in the area closest to Bultfontein Road, which are likely to result in a block of ground slipping into the mine pit at some point in the near future.

3.1.2 Conclusion

In nature, there is a general tendency for the sides of any excavation in the earth to recede to a point where a natural angle of repose is achieved and many factors can contribute to the sidewall instability, which ultimately influences or dictates the entire extent and rate of recession.

As a result of the case study that was undertaken by Preece et al. (2008), a valid conclusion was made about the overall state and stability of the Kimberley "Big Hole" Mine as it stood in the year 2008. In the reviewed report of Preece et al. (2008), the opinion was that even though De Beers had managed to implement various monitoring systems around the Big Hole in order to track any ground movement activities, it was still not possible for anyone to accurately predict the exact time frames within which parts of the edge of the mine pit may collapse.

As a worsening effect to the risk factors already involved in the overall stability of the sidewalls of the mine pit, sustained periods of rainfall (especially during the summer months of November to February) affects the level of the ground water table immensely. During the extensive studies of their report, Preece et al. proved that a rise in the immediate water table surrounding the Big Hole exerts an immense pressure on the sidewalls of the mine pit, which can easily influence and encourage slope slippages.

For all the above-mentioned reasons and with a specific reference to the discussed case study, Preece et al. (2008) was of the opinion that the loss of the section of Bultfontein Road, adjacent to the eastern side of the mine pit, is inevitable.

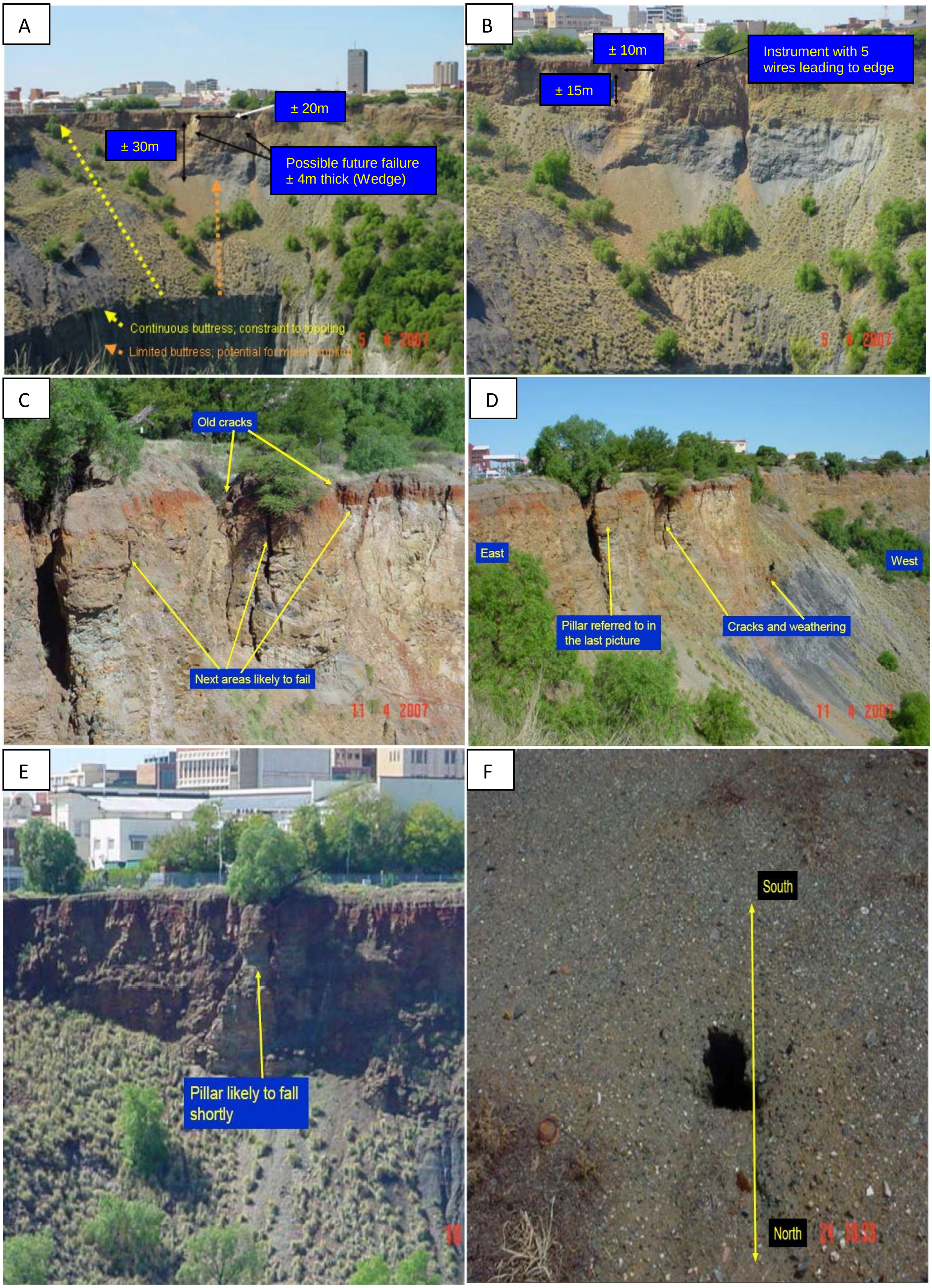


Figure 27 - Images depicting a few local failures of the cracked dolerite capping at the Kimberley "Big Hole" Mine, as well as areas where more imminent failures are likely to occur (Croukamp, 2008 modified from Preece et al., 2008).

Chapter 4: Defining the problem

After reviewing all available literature and reports that pertain to the overall state and stability of the sidewalls of the Kimberley "Big Hole" Mine over the past few years, an evaluation was made on the most likely cause of slope instability problems at the Kimberley "Big Hole" Mine and it seemed to go hand-in-hand with the local geology of the pit.

4.1 Local Geology

To summarize and simplify the local geology of the Big Hole Mine (as described and discussed in chapter 2 above), a brief review of the most important geological features with respect to the slope stability problem at the Big Hole Mine is given below (Croukamp, 2008):

- Near surface strata dominantly consisting of 15 to 20 meters of well-jointed dolerite. It is worth highlighting the fact that this layer exhibits a very pronounced columnar geological structure due to a strong presence of orthogonal joint sets in the rock, making it very prone to toppling.
- This is subsequently underlain by a 60 meter thick, near horizontally bedded black shale (commonly referred to as the Kimberley shale), which is considered to bear a large swelling and shrinkage potential, making it highly susceptible to weathering and accelerated deterioration under natural conditions. Understanding the regressive characteristics of this brittle geological marker unit is key in defining the slope stability problem at the Kimberley "Big Hole" Mine.
- The shale is sitting on a 12 meter thick horizon of dwyka tillite, described as a thin conglomerate bed that forms the basement conglomerate of the Kimberley shales.
- Finally, a 140 meter thick hard rock layer commonly known as melaphyre, which is significantly more competent than the surrounding host rocks and forms the vertical sided profile of the Big Hole Mine.

Looking at the simplified geology of the mine pit itself, it is clear that there are two very specific problems that are contributing towards the overall slope stability problem at the Kimberley Big Hole Mine: The first and most important concern being owed to the susceptibility of the underlying shale horizon to weather and deteriorate when exposed to the atmosphere. In their specific reports, Preece et al. (2008) and Croukamp (2008) explained this overshadowing effect of slope stability problems at the Kimberly Big Hole Mine as follows: *"The main culprit behind slope instabilities and failutres at the Kimberley "Big Hole" Mine, can be ascribed to the susceptibility of the shale horizon to weather and degrade as a result of surface exposure to various elements and extreme weather conditions".*

This undesired effect of undermining due to regression of the underlying shale unit, is exactly what gives rise to the second succsessive slope stability problem at the Kimberley Big Hole Mine, namely the propensity of the overlying doleritic sheet to break off into large blocks and undergo mass toppling failures. In other words, the strong columnar geological structure of the overlaying dolerite caps (due to an abundance of orthogonal joint sets in their structure) tend to loosen when encountered with "support relief" from the underlying shale horizon. As a result, many of the orthogonal joint sets open up to such an extent that large blocks of dolerite become unstable and eventually topple over into the mine pit.

However, the propensity of the Kimberley shales to rapidly weather and deteriorate under exposure to various natural elements and extreme weather conditions (especially during the hot, wet summer months of November to February), is still considered to be the main cause of in-pit slope instabilities at the Kimberley "Big Hole" Mine and the reason for the resulting gradual migration of the mine pit rim outwards. This gradual migration of the slopes of the Big Hole Mine outward, is commonly referred to as **"break-back"** and is concerned with the weathering process that is continuously resulting in an ongoing removal of shale material from the sidewalls of the mine.

4.2 Mine pit break-back

Mine pit break-back at the Kimberley "Big Hole" Mine can be described in very simple terms and the following will serve as a quick explanation of the process:

- the underlaying shale horizon (with its variable clay content) weathers and decomposes rapidly during seasonal wetting and drying (mainly by means of disintegration);
- as a result of rapid disintegration of the underlaying shale unit, slaking of the shales seem to further undermine the overlaying doleritic blocks, which due to the well developed joint sets, break off and topple into the mine pit.
- the gradual removal of the overlaying doleritic blocks from the outer rims of the mine pit, in turn exposes more fresh shales to the process of seasonal wetting and drying and as a result, the cycle is constantly repeated.

In terms of mine pit break-back at the Kimberley "Big Hole" Mine, it is considered to be a very fast and ongoing process that is repeated every few years. The effects of seasonal wetting and drying on shales at the mine, is also exacerbated by the heavy rainfall during the summer months of November to February, which is often accompanied by very hot and humid climatic conditions, which means that temperatures reach extremes on a daily basis. This, as a result, causes extreme fluctuations in the moisture content of the rocks, accelerating the process of mine pit break-back and the effects of slope instabilities and failures at the Kimberley "Big Hole" Mine. Because of constant weathering and deterioration of the shales, the mine pit perimeter has started to develop a very wide and flat angled break-back pattern as illustrated in Figure 28, which can ultiamately be attributed to the slope's natural angle of repose.

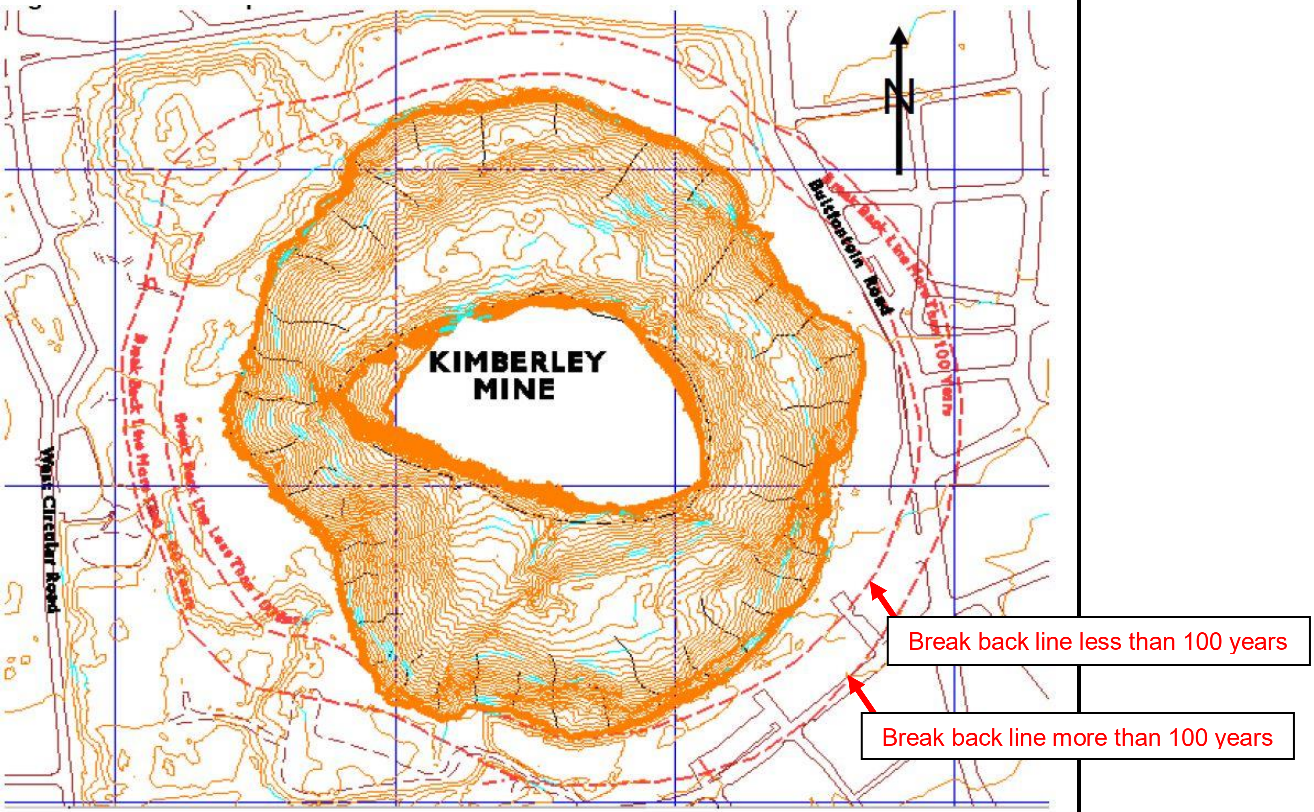


Figure 28 - Limits for potential mine pit break-back at the Kimberley "Big Hole" Mine according to Preece et al. (2008).

After carefull consideration of (1) the local geology of the pit, (2) the natural angle of repose, (3) the level of the groundwater table and (4) the geometry of the pit with its resulting stress regime around the Kimberley Mine, it is safe to conclude that the biggest threat to the stability of the sidewalls of the Kimberley “Big Hole” Mine is not that of a true slope stability problem (in the sense that it requires a complete slope stability assessment, as would have been required when working with a translation slope slip failure for example), but that it is rather concerned with the break-back perimeter of the open-mine pit as a result of the extensive weathering and deterioration of the underlying shale, as well as the rate at which this process ensues. In other words, the identified slope failure mechanism at the Kimberley “Big Hole” Mine is not concerned with the development of a planar or circular slip failure plane, but rather a toppling (rockfall) slope failure mechanism that initiates due to undermining / regression of the underlying Kimberley shales. This would subsequently prompt the investigation to move from a complete slope stability assessment to a weathering analysis, where the solution would have to address the vast susceptibility of the Kimberley shales to resist weather and deterioration when exposed to the atmosphere and natural weathering conditions.

4.3 Summary

This summary will emphasize the most important aspects of the slope stability problem at the Kimberley “Big Hole” Mine as well as conclude the first phase of this project, which was to “define the problem”.

The problem statement encapsulating the slope stability problems at the Kimberley “Big Hole” Mine, thus reads as follows (see Figure 29):

A fast and ongoing removal of shale material from the underlying geological marker unit, due to its intense susceptibility to rapid weathering and deterioration, which is generally exacerbated by extreme weather conditions such as heavy rainfall periods during the summer months of November to February every year. This regressive process in turn causes the overlying dolerite cap to weaken along its orthogonal joint sets and break off into sizeable blocks, which eventually topples over and into the open-mine pit, giving rise to a process which is locally known as mine pit break-back. Mine pit break-back can therefore be seen as the end result of a ongoing weathering process that is responsible for the sidewalls of the Kimberley “Big Hole” Mine to expand and slowly widen, causing many socio-economic issues for the town of Kimberley.

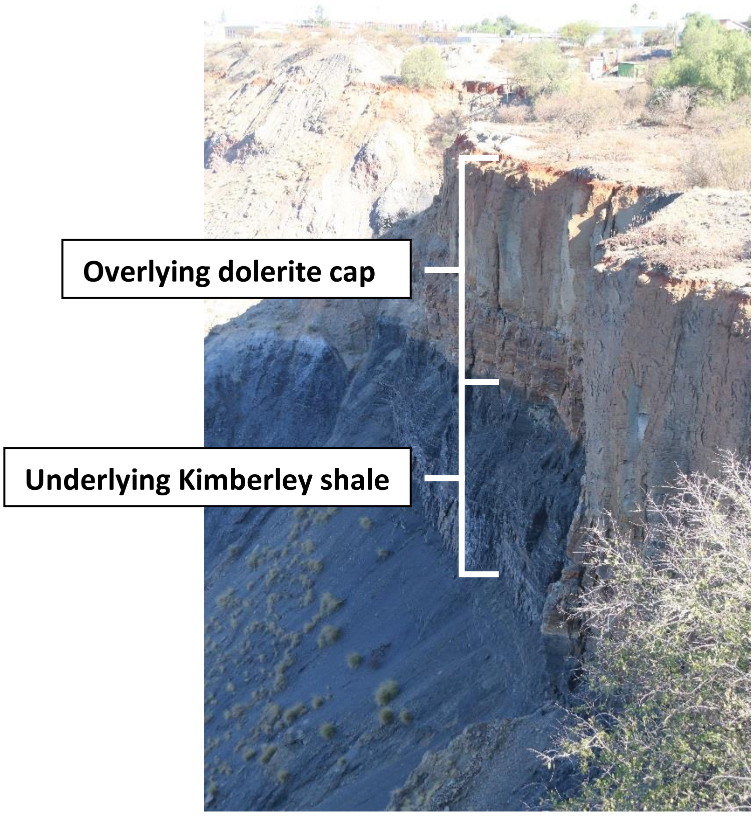


Figure 29 - Photograph depicting the two most important geological marker units concerning the slope stability problem at the Kimberley "Big Hole" Mine.

As a contributing factor to assist in combatting the process of mine pit break-back at the Kimberley “Big Hole” Mine however, it is worth mentioning that up to date the single biggest contributing factor to the relatively stable state of open pit mine, was the dewatering of the shale slopes by the development and maintenance of water tunnels and associated drain holes as implemented by De Beers in 2000. As a result, the relatively stable water table surrounding the Big Hole does not seem to pose such a big threat to the stability of the sidewalls of the mine, as that of the high annual influx of water during the summer months over the town of Kimberley. Annual flooding of the subsurface shale horizon continuously exposes fresh shales to the surface of the slopes at the Big Hole Mine, beckoning the start of a new weathering cycle and continues removal of more and more shale material.

Thus, in order to find the most appropriate solution in terms of effectiveness and economic viability when discussing the slope stability problem at the Kimberley “Big Hole” Mine, the following questions might act as a useful guideline to finding and assessing a proposed solution:

- **What is the internal structure and chemical characteristics of the shale and can this be classified?**
  By knowing the internal structure and chemical characteristics of the Kimberley shales, one can start to identify the most common types of clay minerals present within the chemical construct of the rock, which directly relates to its swelling and shrinkage potential. From literature it is known that some clays are much more expansive than others. Clays rich in montmorillonite for example, have a much greater swelling and shrinkage potential when in contact with water than does kaolinite-rich clays. If this swelling potential is mobilized through a constant ingress of water, it may consequently have an adverse effect on the stability of the slopes at the Kimberley “Big Hole” Mine. According to literature, the best way to determine the internal structure and exact chemical composition of clay minerals in a rock, would be by means of a petrographic analysis with the additional aid of a geochemical analysis (i.e. X-Ray diffraction and X-Ray fluorescence analyses) to ensure accuracy.
- **To what extent does surface water infiltrate the shale (i.e. the permeability) and how can it be reduced?**
  If clay rich rocks, such as shales for example, are exposed to either an internal or external fluid source, it drastically increases its potential to weather and deteriorate as water is one of the most dominant weathering agents of rocks and soils. Any rock mass that is accessible to the inflow of water, can be de- and resaturated, which in turn results in the swelling and shrinkage of the internal clay minerals and more often than not, fracturing of the rock mass. Thus, knowing the permeability of the Kimberley shales would automatically indicate (to a certain degree) its weathering potential. According to literature, one way of measuring the permeability of a rock is to test its absorption capacity. Various literature suggest that there is a direct correlation between the absorption rate of a rock mass and its permeability. An absorption test would therefore provide the necessary insight into the permeability characteristics of the Kimberley shales and a method or measure of reducing it.
- **What is the weathering rate for the shale and how can it be slowed down / decreased?**
  According to literature, testing the weathering rate of shales against an international standard is very difficult as each test should ideally be conducted according to its own application. In fact, many of the existing durability and weathering tests on shale type rocks lack the application of a workable classification system for scale and measure. Literature suggests conducting more than one durability test on the same sample, as to collect as many variables

as possible before making an accurate durability classification. Literature also briefly describes the various durability and weathering tests that exists in practice today, along with the different durability classification systems and their associated limitations. Due to the various limitations associated with the durability classification of shales, literature suggests rather testing the durability of shale type rocks by means of using more than one weathering test and using the obtained results as a comparative measure against each other. Understandably, the significance of different durability aspects could also have an effect on the engineering properties.

- **Is the proposed solution effective and economically viable?**
  Due to the different types of slope failure mechanisms in shale slopes, different slope instabilities exists with various mechanisms of initiation and mobilization. The key in finding a viable solution towards the defined slope stability problem at the Kimberley "Big Hole" Mine, is understanding the mechanics behind the slope failure and finding a workable solution that would directly address the source of instability. The best way to evaluate the effectiveness of a solution, is to test it.
- **Can the proposed solution be implemented at the Kimberley "Big Hole" Mine?**
  Seeing as the Kimberley "Big Hole" Mine still represents one of South Africa's most historic landmarks and tourist attractions, various criteria exists surrounding the implementation and application of a possible solution. The proposed solution still needs to be aesthetically pleasing, whilst not damaging the slopes any further upon implementation / application and not adding to the overburden of the slopes as is. All these factors need to be considered and brought into account when deciding and proposing a possible solution.
- **Can a safe slope angle or natural angle or repose for the sidewalls of the Kimberley "Big Hole" Mine be determined through testing?**
  One of the main goals for this project is to use the ensuing slake-durability index test as a direct measure to try and determine a safe slope angle or natural angle of repose for the sidewalls of the Kimberley "Big Hole" Mine as it stands today. If a safe slope angle can be deduced from the second cycle slake-durability index value of an untreated Kimberley shale sample, then various predictions can be made with regards to the rate of weathering, amount of regression still needed to take place and the predicted safe horizontal ground distance from the current mine pit perimeter.

Chapter 5: Methodology

This chapter will describe the exact methodological procedures that were followed during the collection of samples and undertaking of both the fieldwork and laboratory experiments in detail. It includes a meticulous discussion of the respective sample preperation and outputs for each individual test, as well as a detailed discussion on the exact procedures followed in order to ensure the successful outcome thereof. Fieldwork experiments and tests were mainly conducted with the focus being on assessing the state and stability of the Kimberley "Big Hole" Mine as it stands today. It not only includes a direct visual inspection of the evidence for slope stability indicators, but also a comprehensive desktop study in the form of aerial photography, drone modelling and satellite interferometry inspections. Laboratory work on the other hand, were more concentrated on the direct reason for slope stability problems at the Kimberley "Big Hole" Mine (i.e. the rapid weathering rate of the Kimberley shales) and includes a variety of different tests to classify and characterize the (shale) rock as well as to define the rock strenght parameters of the Kimberley shales. But first, a brief overview of the research plan is described and discussed below. It provides the full process of the project including the step-by-step development, testing, analysing and after-calculating stages with an overview flowchart acting as visual aid (see Figure 30).

5.1 Research plan

The first stage of the research plan consisted of a developmental phase, where all available literature, including the incorporation of previously written geological and geotechnical reports pertaining to the sidewall stability of the Kimberley "Big Hole" Mine, were reviewed independently and utilised in the form of a full desk study. This was done to gain a comprehensive background of the Kimberley "Big Hole" Mine and gather sufficient evidence to synthesize a valid problem statement for the defined slope stability problem as it stands today.

The second stage was concerned with defining the problem as identified by the first phase of this project. In order to find a viable solution towards the defined slope stability problem at the Kimberley "Big Hole" Mine, a comprehensive problem statement first needed conceptualizing. This still formed part of the developmental process and included the introduction of a case study, as well as various site visits (fieldwork) to the Kimberley "Big Hole" Mine. To define the exact extent of the problem, the second stage of the research plan also included a full desktop study in the form of aerial photography, drone modelling and pixel tracking using various software packages. The desktop study was performed with the purpose of assessing the rate of sidewall migration over the past few years and indicate whether the defined slope stability problem still issues an ongoing process.

After conceptualizing and defining the slope stability problem at the Kimberley "Big Hole" Mine, the third stage of the project was introduced and included research into finding a viable solution. By completing a whole literature review, case study and site visits to the Kimberley "Big Hole" Mine, the exact slope failure mechanism behind slope instabilities was modelled and familiarized. Knowing the exact mechanism behind the slope failure that causes slope instabilities on sidewalls of the Kimberley "Big Hole" Mine, the third stage of the project mainly focussed on proposing a viable solution that would effectively decrease slope instabilities or failures and that could easily be implemented.

After deciding on a possible (or experimental) solution towards the defined slope stability problem at the Kimberley "Big Hole" Mine, the experimental / data collecting process of the research project comenced with the introduction of a full testing program. The testing program included enough time for both fieldwork and laboratory tests and aimed at producing data and results. The exact methodological procedures followed for laboratory testing / laboratory activities however (i.e. absorption tests, cyclic wetting and drying tests, accelerated weathering tests and the slake-durability index test), is meticulously described below in Section 5.2.

This lead to the fifth stage of the research plan, which included the data analysis and interpretation part of the results as obtained from the previous stage. This part of the research project demanded a lot of time and attention, as all of the obtained results needed to be reworked, calculated and discussed in detail, which probably formed the bulk of the work as set out by the researcher.

Finally, the last stage of the research project was concerned with drawing a scientific and valuable conclusion towards the experimental findings. The aim of this stage was to satisfy the problem statement as set out by the researcher during the second stage of this project. This chapter also includes a justified recommendations section for any future research that might possibly be undertaken on the subject matter. The brief research plan overview, as discussed above, is graphically illustrate below in Figure 30.

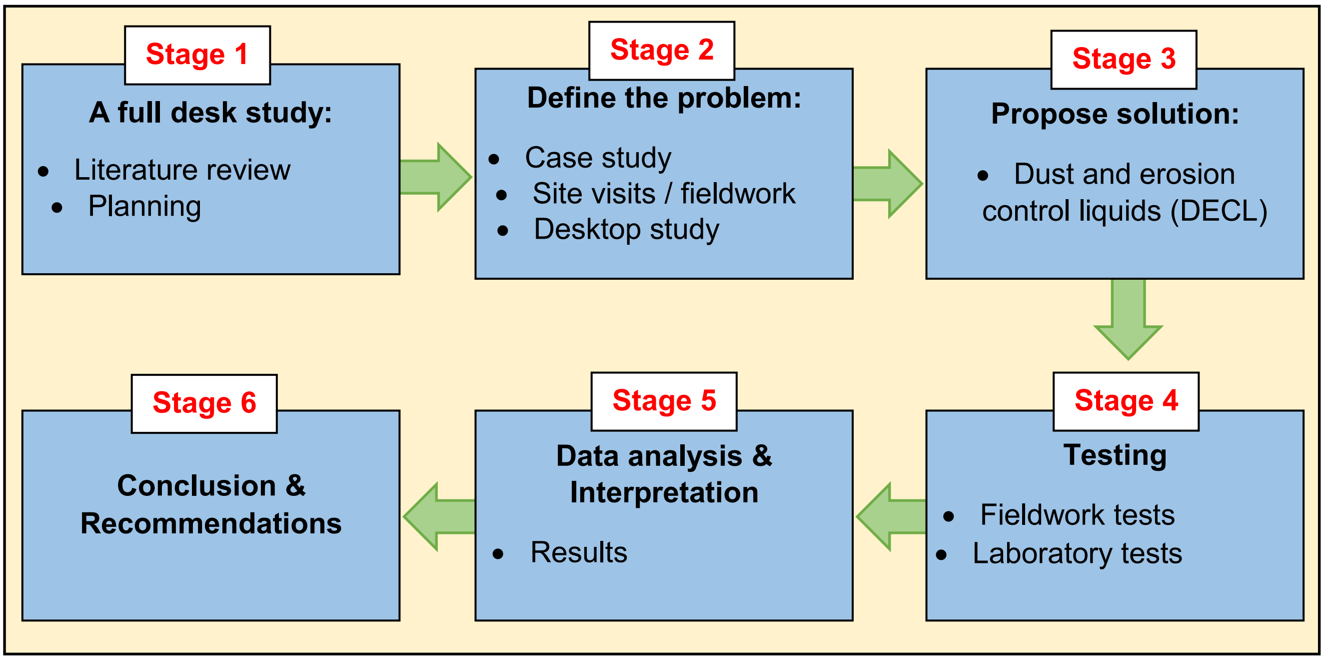


Figure 30 - A flow chart depicting an overview of the full research plan as conducted for the purpose of this project.

5.2 Data collection (fieldwork)

After defining the slope stability problem at the Kimberley “Big Hole” Mine (as described in Chapter 4), site visits were undertaken on two separate occassions to both the Kimberley “Big Hole” Mine in October 2016 and the neighbouring Bultfontein Mine in February 2017, with the aim of: (1) assessing the state and stability of the Big Hole as it stands today, (2) creating a 3D-model of the open mine pit, and (3) collecting the necessary rock samples for the proposed fieldwork experiments and laboratory tests. These site visits were not only conducted with the aim of better understanding the defined slope stability problem, but also for producing a more suitable and effective solution.

5.2.1 Current state and stability of the Kimberley “Big Hole” Mine

In order to fully assess the current state and stability of the Kimberley “Big Hole” Mine as it stands today, visual inspections were undertaken, aerial photopgraphs were analysed and pixel tracking of remote sensed images were carried out.

5.2.1.1 Visual inspection (slope stability indicators)

The first site visit to the Big Hole Mine (11 – 14 October 2016) was conducted with the sole purpose of assessing the modern day state and stability of the sidewalls as it stands today and comparing it to that of previously written and reviewed geological and geotechnical reports. The aim was to visually determine whether slope stability problems at the Kimberley “Big Hole” Mine had worsened since conduction of the last written report from 2008 and if so, to what extent? Specific focus was therefore given to surface stability indicators such as:

- Tension cracks on the surrounding tarred surfaces (with specific reference to Bultfontein Road).
- Evidence of fresh landslides along slope surfaces of the sidewalls.
- Occurrences of soil creep around the outer perimeters of the pit.
- Development of toppling structures in the overlying dolerite caps.

The on-site walkover was completed over a total period of three days spent at the Kimberley “Big Hole” Mine and consisted of daily manual evaluations and visual inspections in and around the pit. Tools used to document and assess the evidence of slope stability indicators included:

- A DJI – Inspire 1 drone.
- A digital (Canon) camera with a high lens zoom.
- Measuring tape.
- A notepad.

In essence, the drone as seen in Figure 31 was used to assess the current state and stability of the sidewalls of the Kimberley “Big Hole” Mine from an aerial view (or plan view), whilst tension cracks on surrounding tarred surfaces and fresh landslides on the slopes of the sidewalls were directly documented and photographed by means of using the digital (Canon) camera. A measuring tape was essentially used to measure the various lengths of tension cracks found in the surrounding tarred surfaces of Bultfontein Road for example and the notepad was used as an additional aid for sketches and notes. Figure 32 illustrates a typical walkover evaluation as conducted for one of the sidewalls of the Kimberley “Big Hole” Mine and depicts an actual visual inspection of one of the surface slope stability indicators in the form of an occurring tension crack.

Figure 31 - DJ1 – Inspire drone used for aerial assessments.

Figure 32 - A walkover evaluation on the sidewalls of the Kimberley "Big Hole" Mine.

This specific site visit proved to be very fruitful in providing enough visual evidence of newly formed tension cracks and landslides in and around the sidewalls of the Kimberley “Big Hole” Mine as illustrated in Figure 33 for example. Figure 33 depicts evidence of an approximately 8 meter long and still propagating tension crack running through multiple pavement stones on the sidewalls of the Kimberley “Big Hole” Mine, with a propagation direction that is parallel to the sidewalls and developing toppling structures of the nearby pit. Most of the documented images showing the modern day state and stability of the sidewalls of the Kimberley “Big Hole” Mine however, will only be included within the results chapter (Chapter 6) of this project.

Figure 33 - A single tension crack on Bultfontein Road.

5.2.1.2 Aerial photography

A sequence of aerial photographs over the Kimberley "Big Hole" Mine, ranging from as old as 1975 to 2014, were obtained from the Department of Rural Development – National Geospatial Information (NGI) in Mowbray and used in cooperation with a geospatial software program called ArcMap10. This software was used to visually track and trace the migration of the outer perimeter of the sidewalls of the Kimberley "Big Hole" Mine over the past 39 years and the results proved to be very insightful. It helped in visualizing the migration pattern of the sidewalls of the pit as a function of time and gave a good representation of the ground movement events associated with the defined slope stability problem at different areas of the mine.

In order to track and trace the migration of the outer boundaries of the Kimberley "Big Hole" Mine by means of using a sequence of aerial photographs however, the photographs first needed to be georeferenced against a master image as to ensure that they precisely overlay one another. In ArcMap10 software, a base map (or image) that have already been georeferenced (in other words already contained the correct spatial information with regards to its real-world location) was used as the master image and all other aerials were subsequently georeferenced to the same image. In other words, each aerial photograph ranging from 1975 to 2014 was independently georeferenced as a raw / slave image towards the same master (base) image in ArcMap 10 software.

The process of georeferencing included the following steps:

- Each aerial was independently uploaded into ArcMap10 software and re-projected with the “define projection tool” as to ensure that both images (i.e. master and slave) have the same projection / datum (WGS 1984) to begin with.
- Next ground control points (GCPS) were selected on both the master and slave image as to accurately warp and overlay the two images on top of one another. GCPS can be defined as definite points on both images that are known to be the same point or have the same location irrespective of the time difference between them. Classic examples of GCPS include physical structures such as the corner of a building, the intersection of a street or a trig beacon for example.
- In order to ensure the most accurate outcome / results for the georeferencing procedure, 30 GCPS were selected on each image pair and a second (2^{nd}) polynomial algorithm was used to warp and overlay the two images.
- If after the first georeferencing attempt (as described above) the two aerial photographs still did not overlay each other precisely, more GCPS were chosen and the process repeated until a satisfactory result was achieved.

In theory, after each and every aerial photograph was independently and successfully georeferenced to the same master (base) image, they should also overlay one another precisely to pixel-scale accuracy. A full record of the evolution and migration of the sidewalls of the Kimberley “Big Hole” Mine in the form of overlaying aerial photographs from the year 1975 to 2014 can now successively be viewed, tracked and traced in ArcMap10 software. This was used to digitize and map the boundaries of the Kimberley “Big Hole” Mine for each time frame / period since 1975 to 2014 as to visually illustrate the migration and evolution of the sidewalls outward. The whole process of georeferencing and using aerial photography as a means of monitoring slope movements at the Kimberley “Big Hole” Mine over the past few years is graphically illustrated below in Figure 34.

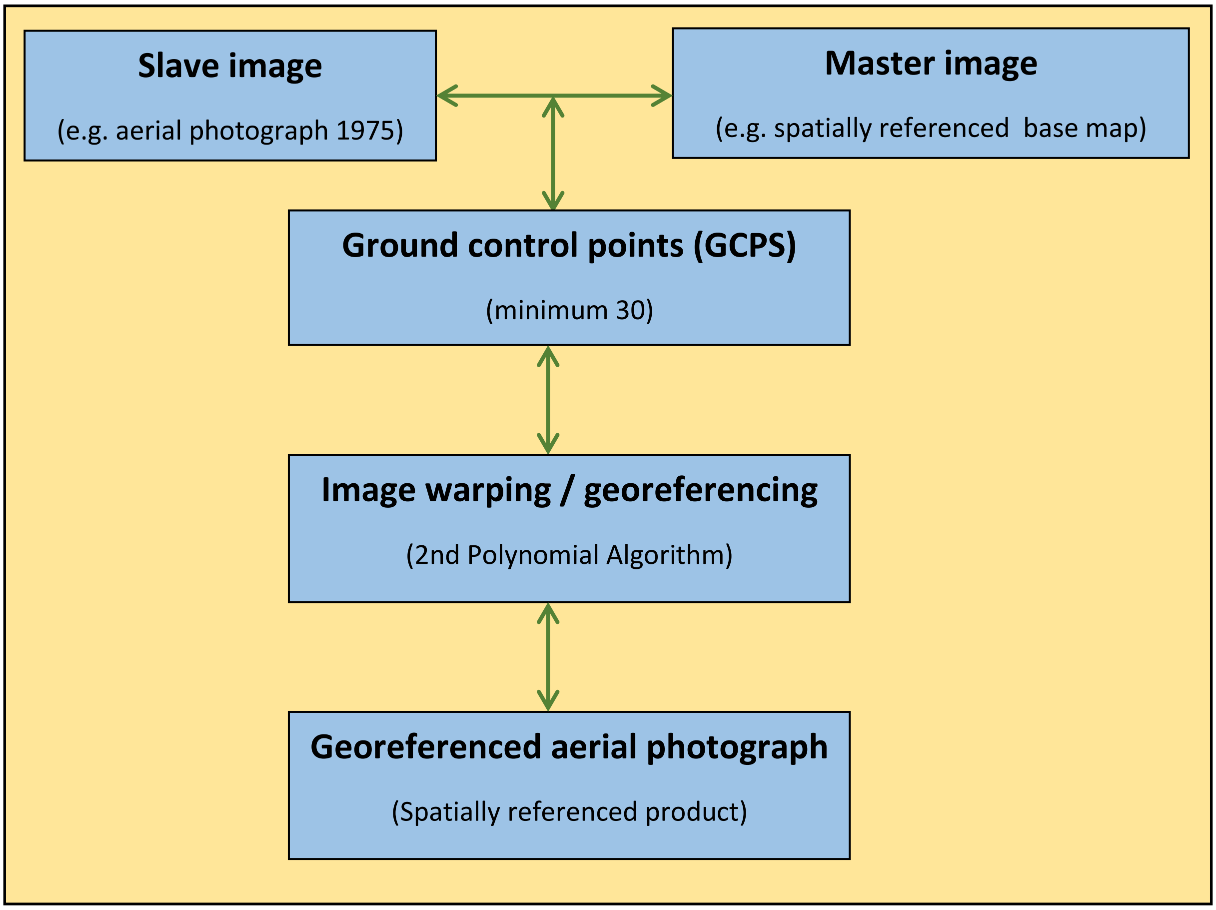


Figure 34 - Georeferencing process chain of aerial photographs.

To summarize the process, each individual aerial photograph (i.e. 1975, 1997, 2001, 2014) was georeferenced independently to an already georeferenced (i.e. containing real-world spatial information) master base image. These images were then stacked on top of one another in chronological order so that the boundaries of the sidewalls could be digitized and visually analyzed to track the migration of the sidewalls of the open pit mine over the past 39 years.

5.2.1.3 Pixel tracking

By means of using a different approach to the already implemented and manually monitored ground movement equipment at the Kimberley “Big Hole” Mine (as referred to in Chapter 2), a new and modern day technique was used to analyze ground movement events (such as landslides and toppling failures) at the Big Hole Mine. This technique has never been done before. It involved the combination of remote sensed aerial photographs together with image correlating and pixel tracking software named Cosi-Corr, to measure and track ground deformations around the open pit mine down to a pixel size width between the years 1968 and 2014. In order to produce a typical output displacement vector map in COSI-Corr software however, certain preparations was first required to ensure the most accurate ground movement measurement outcome and these can be categorized as two phases namely: (1) image pre-processing and (2) image processing.

For the first phase (image pre-processing) six aerial photographs of the Kimberley "Big Hole" Mine, covering a collective time span of 46 years, were collected from the Department of Urban Development – National Geospatial Information (NGI) in Mowbray and include the following dates: 1968, 1975, 1997, 2001, 2008, and 2014. Pre-processing of these aerials involved:

- **Orthorectification:** Each photograph was orthorectified individually to a *Landsat 8* master image (which already contained a spatial reference - *Datum: WGS84 Universal Transverse Mercator Zone 35S*) and a digital elevation model (DEM) (which corrects for topographic elevations). The *Landsat 8* image was obtained from Google Earth's public domain, whilst the digital elevation model (DEM) came from The Centre for Geographical Analysis (CGA) at Stellenbosch University. Orthorectification was done on a software program called PCI Geomatica and it involved the collection of at least 30 ground control points (GCPS) as well as a root-mean-square (RMS) error of less than eight meters (< 8m) for each individual photograph.
- **Georeferencing:** After orthorectification of all six aerials, each photograph was further georeferenced to its successive follow-up aerial. For example: 1968 was georeferenced against 1975, 1975 was georeferenced against 1997 and 1997 was georeferenced against 2001 etc. This was done to minimize any distortions or discrepancies, which might have propagated through during the orthorectification process, and a *2^{nd} Polynomial Algorithm* was used to successfully execute the georeferencing process.

After all six aerial photographs were orthorectified (in other words, now containing a real-world spatial reference and an elevation correction) and georeferenced (in other words, overlaying each other precisely up to a single pixel size scale), the second phase, which involves image processing, commenced in COSI-Corr software at CSIR's offices in Stellenbosch and included:

- **Co-registration:** Each pairing of successive georeferenced aerials were co-registered to map and match each individual pixel from the pre-deformation image to the same pixel in the post-deformation image.
- **Correlation:** The paired pre- and post-deformation images were correlated mathematically to produce a displacement field where the convention *"eastward and northward positive"* is used. The displacement field represents a horizontal ground displacement file, which uses an East/West and North/South band to subsequently construct a correlation file.
- **Displacement measurements:** The correlation file uses displacement measurements of each individual pixel from the pre-deformation image to the post-deformation image to construct a displacement vector map. Individual displacement vector maps were also created for each successive pair of aerial photographs, as a means of tracking and monitoring ground movement patterns around the Kimberley "Big Hole" Mine in a timeline series.

As a result, after completion of image pre-processing and image processing, the final output product is a deformation vector map, with vectors (or arrows) indicating both the degree of deformation as well as the direction for each corresponding pixel from the pre-deformation image to the post-deformation image.

5.2.2 Drone footage (3D model)

Another modern day method was used during the execution of this project to map and visualize the real-world parameters of the Kimberley "Big Hole" Mine as it stands today and it involved the creation of a three dimensional (3D) model of the sidewalls of the Kimberley "Big Hole" Mine by means of a DJI-Inspire 1 Drone.

Upon the first site visit to the Kimberley "Big Hole" Mine in October 2016, the drone was flown into and across the Big Hole Mine via a specific pre-programmable flight path as illustrated in Figure 35.

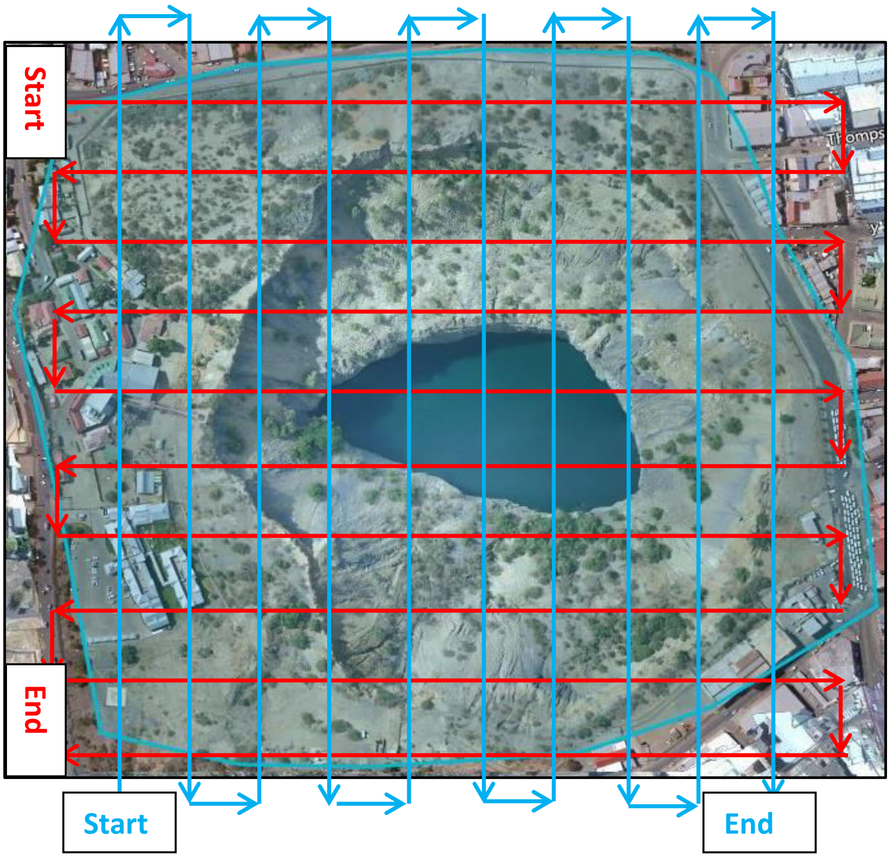


Figure 35 - Pre-programmable drone flight path.

The flight plan captured every square meter of the Big Hole Mine and allowed for all of the captured images to be stitched together in a software program called *DroneDeploy*, which was subsequently also used to create the following maps and a 3D model of the Big Hole:

- A high-resolution two dimensional (2D) map.

- An elevation map - showing the different elevations in and around the slopes of the Big Hole Mine.
- A contour map - showing the different contour lines in and around the Big Hole Mine and
- A three dimensional (3D) model of the Big Hole.

➢ **High-resolution two dimensional (2D) image**

The 2D map of the Kimberley "Big Hole" Mine represents a high-resolution image that can be zoomed in to meter scale resolution. As a result of its high-resolution status, it was not only used as a base map for the successive elevation and contour maps, but it was also used to identify newly formed tension cracks and toppling structures in and around the sidewalls of the Kimberley "Big Hole" Mine as it stands today.

➢ **Elevation maps**

Outside and inside perimeter elevation maps were created for the Kimberley "Big Hole" Mine. The outer perimeter map was created by using the red band (or band 1) of the multispectral image in order to better identify tension cracks and examples of soil creep on the surrounding pit surfaces. It therefore focused more on elevation differences of the surrounding area than elevation parameters of the actual mine pit slopes.

The inner perimeter map was created by using the blue band (or band 2) of the multispectral image in order to identify fresh landslides and toppling slope failure events on the inside slopes of the Kimberley "Big Hole" Mine as it stands today. It therefore focused more on the elevation parameters of the actual mine pit slopes, than the elevation values of the surrounding mine pit surfaces.

A combined version of the outer and inner perimeter maps were created (in other words, band 1 – red & band 2 – blue) and underlain by a high-resolution 2D base map to illustrate the overall extent of elevation differences and values in and around the sidewalls of the Kimberley "Big Hole" Mine.

➢ **Contour map**

A contour map showing 1.5 meter contour lines in and around the slopes of the Kimberley "Big Hole" Mine was created to better understand and visualize the elevation profile of the sidewalls of the pit. The original contour map (black and white insert) was first created in *DroneDeploy* software, after which it was underlain by the same high-resolution 2D image as used for the elevation maps as discussed above.

➢ **Three dimensional (3D) model**

The main reason for flying the DJ1 – Inspire drone over the Big Hole Mine of Kimberley was to create and capture a 3D model of the open pit as it stands today, which could subsequently be used in *DroneDeploy* software to visualize and monitor the sidewall properties of the pit from all different angles including volume, area and perimeter calculations. Not only did the 3D model aid in building a small-scale digital model of the Kimberley "Big Hole" Mine, but it also aided in finding a proper solution towards the defined slope stability problem.

Unfortunately, due to license restrictions, *DroneDeploy* software does not allow the 3D model to be exported or viewed in any other accessible software programs at the University of Stellenbosch, as such only screenshots of the actual model, as produced and viewed in *DroneDeploy*, will be presented.

5.2.3 Rock sampling

Rock samples were collected during the second site visit to the neighbouring Bultfontein Mine on 10 February 2017. Bultfontein Mine (28°45'46.66"S; 24°47'31.22"E) is located approximately 5 kilometers southeast of the Kimberley "Big Hole" Mine and was chosen as a suitable site locality for sampling due to its similar geological structure to the Big Hole Mine and its easy access to fresh shale samples via a series of underground water tunnels.

Fresh shale samples (i.e. Kimberley shales) were obtained from underground water tunnels, approximately 50 meters deep, via a simple process of manually collecting them, putting them in air tight plastic bags and tagging the bags with appropriate collars as illustrated in Figure 36.

Figure 36 - Sample collection.

In total 45 shale samples ranging in weight from 3 to10 kg each and in size from 20 to 30cm were collected from the sidewalls of the underground tunnels and placed into air tight bags as to preserve their natural moisture content as much as possible. These samples were then wrapped and sealed, only to be reopened on the day they were tested. The aim was to keep the samples as consistent as possible in terms of structure, size and shape and to keep them in their most natural state before testing.

5.3 Testing program

After completing the necessary fieldwork analyses that was set out for the purpose of this project and discussed in the previous section, the samples collected during the second site visit to the neighbouring Bultfontein Mine in February 2017, were analyzed and tested by means of both microscopic and macroscopic laboratory work. Shale samples underwent various tests to determine the presence and abundance of clay minerals within the rock as well as to quantify its: (1) permeability; (2) slake index / resistance; and (3) it's internal strength parameters, all with the ultimate aim of increasing its durability against natural weathering conditions.

5.3.1 Petrographic analysis

For the purpose of better understanding the microscopic structure and chemical characteristics of the Kimberley Shales (as the problematic focal point for this project and the reason why slope stability problems occur at the Kimberley "Big Hole" Mine), two rock samples were cut into polished thin sections at the University of Cape Town (UCT) and investigated petrographically. Thin sections of both rock samples were obtained by cutting the rock into thin slices with a power saw and placing them on a small (2 x 5cm) glass cover. The cover is then capped with another polished glass piece to ensure the preservation of the sample as shown in Figure 37 A. The subsequent petrographic analysis involved the inspection of these thin sections under a normal laboratory microscope with a maximum zoom lens of 20 X/ 0.45 (see Figure 37 B).

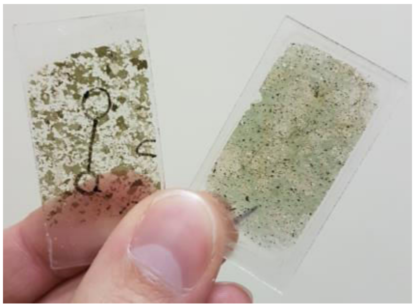


Figure 37 A - Two thin sections.

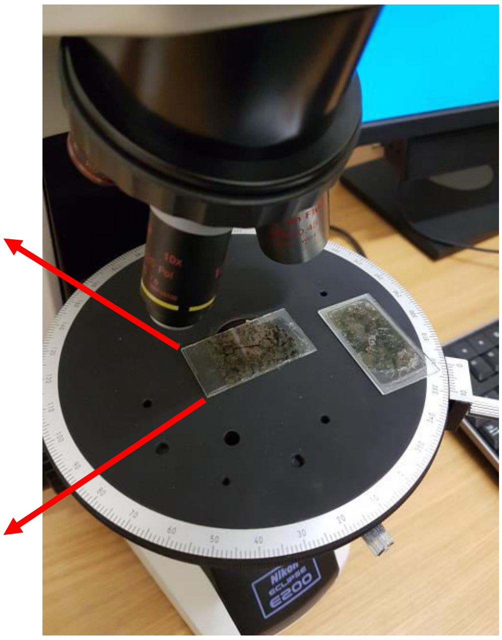


Figure 37 B - Laboratory microscope with two thin sections on its rotation stage.

The thin sections were rotated on a stage with light transmitting through the glass cover and through the thinly sliced rock sample itself. Samples were investigated under cross polarized light (XPL) as well as plane polarized light (PPL) in order to more accurately identify the different minerals present within the rocks. Different minerals display different crystallographic characteristics under the microscope such as colour, cleavage, relief and extinction angles to only name a few. The fact that each mineral has its own unique set of mineralogical properties makes it possible to identify different mineral phases within a rock. The petrographic analysis therefore served as a good guideline to characterize and classify the Kimberley shales according to Stead's (2016) classification table of different types of shales (refer to Table 1):

Table 1 - Classification of the different types of shales according to Stead (2016) and modified after Yagiz (2001).

Group	Name	Main Components
Compacted Shale	Clayey shale	Contain 50% or more clay-sized particles (< 0.002mm)
	Silty shale	Contain 25 - 45 % silt-sized particles
	Sandy shale	Contain 25 - 45 % sand-sized particles
	Black shale	Contain an abundance of organic-rich materials
Cemented Shale	Calcereous shale	Contain 25 - 35% $CaCO_3$
	Siliceous shale	Contain 70 - 85% silica
	Ferruginous shale	Contain 25 - 35% Fe_2O_3
	Carbonaceous shale	Contain 3 - 15% carbonaceous material (imparts toughness)
	Clay bonded shale	Welded by recrystallization of clay minerals

5.3.2 Geochemical analysis

5.3.2.1 X-Ray Fluorescence (XRF) analysis

In order to more accurately determine the most dominant clay mineral constituent present within the Kimberley shales, as well as to better understand the chemical composition of the rocks, a major element XRF analysis was done on two powders (or crushed rock samples) at the Central Analytical Facility (CAF) at the University of Stellenbosch.

XRF (X-Ray Fluorescence) is a non-destructive analytical technique used to determine the elemental composition of materials, such as rock or soil samples for example. It determines the chemistry of a sample by measuring the fluorescent (or secondary) X-ray emitted when the sample is excited by a primary X-ray source (Kalnicky & Singhvi, 2001). Every single element on earth produces a certain set of characteristic fluorescent X-rays, almost like a "fingerprint", that is unique for that specific element. According to ThermoFisher (2016), this is the reason why XRF is most suitable for a qualitative and quantitative chemical analysis of any material composition.

In preperation for the XRF analysis at Stellenbosch University, both samples were first crushed into smaller rock fragments (< 2kg) by means of using a jaw crusher and then subsequently milled to a powder form with a swing mill. In order to ensure that the most representative sample of the bulk rock was used during the XRF analysis, each powdered sample was quartered. Finally, the major element XRF analysis was carried out on a 3kWatt, Rh Tube, XRF spectrometer by means of using a wide range of international (NIST®) and national (SARM®) standards during the calibration procedure and quality controls (precision and accuracy) for major elements. The detection limit was set to 0.5 parts per million (ppm) and a loss on ignition (LOI) test was run at 1000°C in order to include the total volatile content of the rock.

5.3.2.2 X-Ray Diffraction (XRD) analysis

In correspondence with the abovementioned XRF analysis, which ultimately revealed the chemical composition of the Kimberley shales by completing a major element analysis on two crushed shale samples, an XRD analysis was also undertaken with the aim of determining the various mineral phases present within the same two samples. In other words, the XRF analysis (as discussed above) provided results giving the most dominant compositional elements of the Kimberley shales, whereas the following XRD analysis will aid in defining the different mineral phases to which these various elements belong to.

In short, an XRD analysis is a primary, non-destructive tool for identifying and quantifying the mineralogy of crystalline compounds in rocks or soils (Kemp, 2017). It works in very much the same way as the abovementioned XRF anaylsis in terms of the fact that every mineral compound on earth has a “fingerprint profile” that can be matched against a database of over 250 000 other record phases. It is especially an essential technique for identifying and characterizing the nature of clay minerals in a rock and provides information which cannot be determined by means of any other analytical method.

An XRD anaylsis was therefore undertaken at iThemba Labs in Cape Town, South Africa, where laboratory personnel used the same two crushed and milled shale samples from the XRF analysis (for consistency purposes), to complete a phase identification of the associated rocks. Sample preparation included the same procedure as described for the XRF analysis above and the actual analytical procedure was carried out by iThemba Labs personnel on a 2-Theta, 30kV, 1-dimensional LYNXEYE, XRD spectrometer with a detection limit of one to fifty degrees (1 - 50°) and a step size of 3000 steps on a 0.5 second time interval. The analysis was run for approximately 20 minutes per sample.

5.3.3 Absorption tests

The rate at which mudrocks (and with no exception to the Kimberley shales) absorb water, is a critical parameter with regards to its permeability and a very important engineering property when considering the stability characteristics thereof. It is often said that there is a direct relationship between the permeability of a rock and its susceptibility to weather, meaning that the more permeable the sample, the faster it will deteriorate and disintegrate (Venter, 1980). Because the rate of weathering of a rock is more often than not a direct function of its permeability and absorption characteristics, a unique absorption test was conducted at the geotechnical rock laboratory at the University of Stellenbosch following similar tests by Deo (1972) and Venter (1980), only with a few minor changes tailored to the purpose of this project.

As part of trying to find a proper solution towards the defined slope stability problem at the Kimberley "Big Hole" Mine (which includes the vast susceptibility of the Kimberley shales to weather and deteriorate under natural conditions, especially during times of heavy rainfall), five different *"dust and erosion control liquids (DECL)"* were identified with the aim of: (1) decreasing rock permeability; (2) increasing rock slake index / resistance; and (3) strenghtening internal rock parameters, with the ultimate goal to slow down the weathering rate of the Kimberley shales and in turn enchance the stability thereof. All five liquids represent water repellent bases, which resists water infiltration through the surface. It is applied to and binds the soil and dust size particles on the surface of the rock together. In short, it forms a water resistant protective coat around the surface of the rock, ultimately acting as a soil modifier that not only enhances the physical properties of the rock, but also increases its resistance to deformation. In theory, all five DECL products should therefore decrease a rock's permeability and the rate at which it absorps water.To test this theory, all five DECL products were integrated into the following absorption tests. The exact description as well as the unique chemical composition and characterisitcs of each individual liquid is attached in Appendix A and the following will only serve as a brief description of each:

- **NanoSil** is a water-soluble, UV and heat stable, reactive soil modifier with the ability to retain strength of soil (or rock) particles and resist deformation. It is most commonly used in the industry as a breathable soil waterproofing product for road bases and slopes.
- **NanoBond** is an acrylic co-polymer emulsion with the ability to bond to soil particles and resist soil erosion. It is most commonly used in the industry as a dust suppressant especially in side shoulders and slopes.
- **NANO** is an even mixture bewteen NanoSil and NanoBond. It is usually mixed together in the industry for one step waterproofing and bonding of compacted soils. It combines the effects of both NanoSil and NanoBond products to get the most effective results.
- **Sasbind** is a uniquely formulated water-based emulsion of modified acrylic polymers. It is suitable for the binding and stabilisation of various soil layers and types in the construction of roads and is also commonly used for application to the surfaces of already constructed roads that require dust palliation.
- **Sasbind (+Bit)** constitues the exact same product as "Sasbind", only with an added component of bitument to the mixture.

Before absorption tests commenced, the samples were prepared and included the following steps:

1. Five equidimensional rock lumps, weighing between 50 and 60g each, were collected for each test set as illustrated in Figure 38. In other words, five rock lumps made up a single

test batch. Six individual absorption tests were undetaken, that is, one for each DECL product and one for an untreated reference batch as illustrated in Table 7.

Figure 38 - Average sample size and shape for a single absorption tests.

2. Treated samples were all sprayed with two layers (or coats) of the respective DECL product on a 1:2 water to product ratio (i.e. 200ml of water mixed with 400ml of product to give a 600ml mixture) (see Table 7).

Table 7 - Sample preparation for each absorption test

Test:	DECL Product:	Dosage:
1	Untreated	None
2	Product 1: Nanosil	1:2 water to product ratio (200ml:400ml)
3	Product 2: NanoBond	1:2 water to product ratio (200ml:400ml)
4	Product 3: NANO	1:1:2 water to product ratio (200ml:200ml:800ml)
5	Product 4: SasBind	1:2 water to product ratio (200ml:400ml)
6	Product 5: SasBind (+Bit)	1:2 water to product ratio (200ml:400ml)

*Note: The DECL product "NANO" is a combination between DECL products NanoSil and NanoBond, which is why the dosage of the applied liquid to the rock surface in Test 4, differs from the rest of the indicated dosages (in other words 200ml of NanoSil was mixed with 200ml of NanoBond to give 400ml of product, but because the water to product ratio remains 1:2, 800ml of water was needed to complete the mixture).

3. Between treatments (or coatings), samples were left to dry for 24 hours in order to make sure the surface was completely dry before submurging in water as seen in Figure 39.

Figure 39 - Sample preparation (or treatment) with DECL liquids prior to commencement of the individual absorption tests.

After the necessary sample preparation had taken place, absorption tests commenced and included the following steps (tests were conducted in the Geotechnical Laboratory at the University of Stellenbosch):

1. Samples were dried in the sun for 12 hours to get rid of any moisture still left in the rock.
2. Subsequently, rock lumps were weighed together as a batch for each individual absorption test and the combined weight was documented in Table 8.
3. Each batch was then completely immersed in water for 15 minutes after which it was taken out, surface-dried and weighed again (see Figure 40).

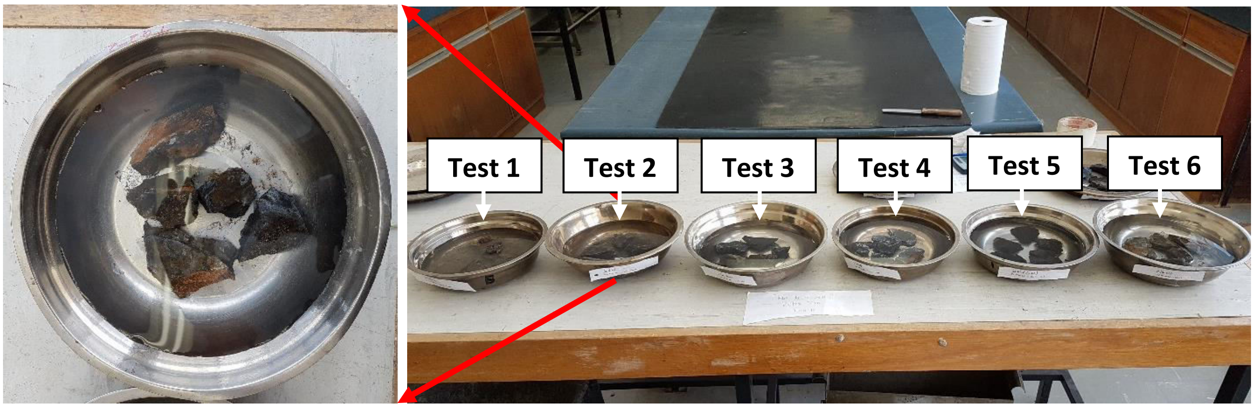


Figure 40 - Absorption tests 1 - 6, completely immersed in water for 7 days and weighed at regularly timed intervals. Each batch represents a different DECL product, whilst one contains an untreated reference sample.

4. After the first weighing-session, rocks were placed back in the water for another 15 minutes (submerged for a total of 30 minutes), taken out, surface dried and weighed.
5. The submergence period was then increased systematically with periods 30 minutes, 1 hour, 2 hours, 4 hours, 8 hours and 1 day with the process of surface drying and weighing consecutively being repeated.
6. For the latter mass determinations the exact weighing times were not adhered to as strictly, as the readings were by then out of the high rate of absorption part of the curve.

These tests were run for a total of 168 hours (or 7 days), to ensure that the maximium moisture content was recorded for each individual batch and that each sample reached its maximum saturation weight in order to represent the most accurate results. The following table represents the weighed mass of each sample at regularly timed intervals in grams and gives a good idea of the raw data that was used to calculate the overall absorption rate / moisture intake for each individual absorption test as a function of time (see Table 8).

Table 8 - Raw data representing the weighed mass of each sample (or absorption test) at regularly timed intervals for a total of 7 days.

Sample:	Original batch weight (g):	Total absorbed weight as a function of time:													
		After 15min (g):	After 30min (g):	After 1h (g):	After 2h (g):	After 4h (g):	After 8h (g):	After 16h (g):	After 1 day (g):	After 2 days (g):	After 3 days (g):	After 4 days (g):	After 5 days (g):	After 6 days (g):	After 7 days (g):
Untreated	240	272	277	281	285	289	292	294	295	296	296	296	296	296	296
NanoSil	275	279	282	286	286	287	287	287	287	287	287	287	287	287	287
NanoBond	261	263	263	265	265	268	270	273	275	275	276	276	276	276	276
NANO	257	259	260	264	264	265	265	266	266	267	267	267	267	267	267
Sasbind	280	282	283	287	288	289	290	292	293	293	294	294	294	294	294
Sasbind (+Bit)	260	263	267	272	273	274	274	275	276	276	277	278	278	279	279

The moisture content for each batch was further calculated for each time interval as a percentage of the total dry mass during regularly timed intervals. This was done by means of the following equation:

$$\%\ moisture\ absorbed\ after\ x\ time = \left(\frac{mass\ after\ x\ minutes\ (g) - original\ mass (g)}{\text{original mass (g)}}\right)\ x\ 100\%$$

As a result, the calculated percentages of the total moisture intake (or absorption rate) for each individual sample as a function of time was tabulated and will be displayed graphically during the discussion of the results in Chapter 6.

The reason for conducting these absoprtion tests were to:

- Determine the general absoprtion characteristics of the Kimberley shales by means of assessing the absorption rate of untreated samples when immersed in water over a long period of time.
- Determine whether any of the DECL products would have an effect on the absorption rate of the Kimberley shales and if so, to what extent.
- To determine which one of the DECL products proved most effective in decreasing a rock's permeability characteristics and showed the slowest absorption rate when immersed in water for a long period of time.

5.3.4 Cyclic wetting and drying tests

In general, clay-bearing rocks (such as the Kimberley shales) are highly sensitive to changes in their moisture / water content and the strength and deformability properties of such rocks seem to deteriorate rapidly when exposed to a continues process of wetting and drying (Erguler & Ulusay, 2009). This nondurable behaviour of clay-bearing rocks is exactly the reason for numerous slope stability, engineering and underground excavation problems which seems to be no exception in the specific case of the Kimberley "Big Hole" Mine (Erguler & Ulusay, 2009).

In order to specifically test the extent of this nondurable behaviour on the Kimberley shales, as well as to evaluate the effects of a continuesly changing water / moisture content on the stability and durability of these rocks, a long term weathering cycle was simulated in the form of weekly "cyclic wetting and drying" tests in combination with the application of the same DECL products as had previously been mentioned in Section 5.2.3. These tests were conducted at the University of Stellenbosch following a similar test by Venter (1980) and aided in determining the strength and deformability of the Kimberley shales (both treated and untreated) when exposed to a simmulation of extreme weather conditions. However, before the cyclic wetting and drying tests commenced, certain sample preparations were first required:

1. Ten rocks ranging in size from 20 to 30cm in length and weight from 1 to 5 kg were chosen to represent the strongest and most durable shale samples.
2. Five of these were left untreated, whilst the other five were respectively treated with the same DECL products as mentioned in Section 5.2.3 (see Figures 41 A & B).

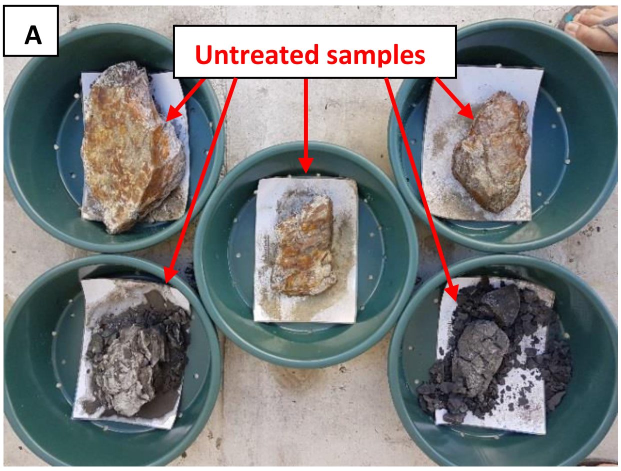


Figure 41 A - Cyclic wetting and drying tests - five untreated samples.

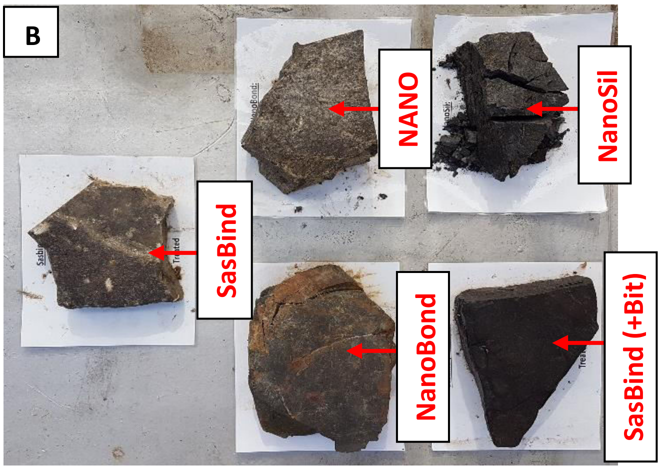


Figure 41 B - Cyclic wetting and drying tests - five DECL treated samples.

3. Each of the five treated shale samples were sprayed and coated in the same way and by using the same dosages as described in Section 5.2.3.

After leaving samples to dry for 24 hours following the second protective coat, the cyclic wetting and drying tests commenced on the 21st of February 2017 for a total of 6 months and included the following procedure:

1. First, all ten samples (both treated and untreated) were photographed and weighed with the purpose of assessing their structural characterisitcs throughout the course of the cyclic wetting and drying tests.
2. All samples were then subsequently left outside in the sun (on a platform at the Civil Engineering faculty at Stellenbosch University) in order to test their response to natural weathering conditions such as heat, rain, wind and low temperatures.
3. To help simulate the heavy rainfall periods between the summer months of November and February over the town of Kimberley, samples were also wetted on a weekly basis with 5 litres of water per sample and left to dry.
4. Changes in their physical appearance / structure (especially in terms of slaking and disintegration) were narrowly documented each week along with weekly weight measurements in order to assess and evaluate the extent of material loss during the accelerated weathering test.
5. After six months and 24 cycles of weekly wetting and drying, samples were photogrpahed and weighed for the last time in order to compare their physical characteristics, as well as their overall mass difference as a percentage of their original weight since conduction of the first wetting and drying cycle to the last wetting and drying cycle.

The overall results of the cyclic wetting and drying tests includes the overall mass (or material) loss as a percentage of the original mass for each rock and is summarized and tabulated in the results section of this thesis. In addition, the table also contains a brief description of each of the samples pre- and post- cyclic wetting and drying, to highlight any mentionable observations during the course of the test which might indicate a favourable DECL product for the defined slope stability problem. The results however, will only be discussed in Chapter 6, although it is worth mentioning that the *DECL* treated samples performed much better than their untreated counter parts, which already indicates a successful result in terms of preserving the shale's strength, deformability and durability characteristics when exposed to natural weathering conditions.

The reason for conducting these extended cyclic wetting and drying tests over a long period of time were to:

- Test the strength and durability properties of the Kimberley shales (both treated and untreated) against a simmulation of natural weathering conditions and in turn determine their average deterioration rate against the sidewalls of the Kimberley "Big Hole" Mine when exposed to the atmosphere.

- Determine whether any of the DECL products would have an effect on the disintegration and slaking rate of the Kimberley shales and if so, to what extent.
- Determine which one of the DECL products proved to be most affective in preserving the rocks strength and deformability characteristics and showed the best protection against its exposure to natural weathering agents.

5.3.5 Comparative accelerated weathering tests (AWT)

Understanding the rock mechanics and properties of a specific terrain from a geotechnical perspective is the first step towards developing successful solutions for specific engineering problems. Therefore, with specific reference to the Kimberley "Big Hole' Mine, understanding the mechanical properties of the Kimberley shales from a geotechnical point of view would be the first step towards developing a valuable solution to help combat its vast suceptibility to slake or disintegrate when exposed to natural weathering conditions. One way of testing the durability of these rocks, was to conduct a full scale accelerated weathering test (AWT), where the effects of five different DECL products on the stability and durability of these rocks could be tested directly against each other.

The following AWT was therefore conducted at the University of Stellenbosch according to several South African National Standards (SANS) and it involved the durability determination of the Kimberley shales, which typically seem to **slake** or **disintegrate** into long angular fragments, when treated with five different DECL products. The general test procedure is very similar to the slake-durability index (SDI) test as described in the following section (see Section 5.2.6), although differences occured during result interpretation and DECL products selection / testing. The AWT actually served as a prerequisite for the SDI test, where the AWT test was used to decide which one of the five DECL products showed the most potential in terms of strengthening the mechanical properties of the Kimberley shales and was subsequently also used as the comparative DECL product for the following SDI test. In other words, the DECL product with the best results after completion of the AWT tests was used as the representative DECL product to compare against an untreated shale sample from the Kimberley "Big Hole" Mine during the ISRM-standardized SDI test.

Before commencement of the AWT however, the sample preperations included the following procedures:

1. Six shale samples were each cut into seven smaller equidimensional rock lumps, so that each individual DECL product, along with one untreated reference batch contained a sample batch as illustrated in Figure 42 (in other words, seven rock lumps made up a single test batch).

Figure 42 - Average sample size and shape for accelerated weathering tests (AWT). This specific batch represents the untreated reference sample.

2. Five test batches / samples were treated with five different DECL products in the same manner as mentioned in Section 5.2.3 and by means of using the same method and dosages as illustrated in Table 7. In other words, each rock set was treated with a different DECL product and one set left untreated (i.e. all seven pieces treated in the same manner and with the same product).
3. Between treatments (or coatings), samples were left to dry for 24 hours in order to make sure the surface was completely dry before commencement of the AWT procedures.

Following the sample preperation, the AWT aparatus needed to be set up. The test aparatus for the AWT consisted of the following components as seen in Figure 43:

- Four bins, each with a width of 100 mm and a diameter of 250 mm.
- The circumference of each bin consisted of Polyvinyl Chloride (PVC) pipes, with a matrix of 20 mm diameter holes.
- The pipes were closed on either sides with 13 mm diameter mesh.
- Each bin was positioned on an axle and rotated at five rotations per minute (5 rpm) via a small motor.

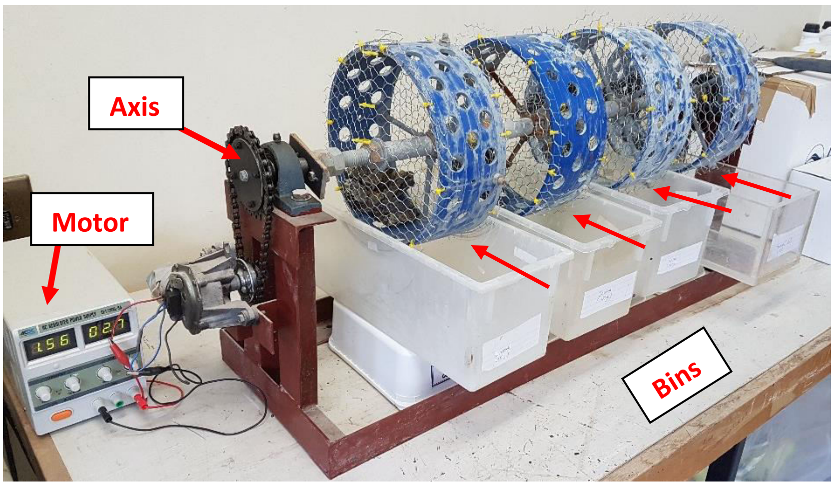


Figure 43 - Apparatus used for the accelerated weathering tests (AWT) of the Kimberley shales at the University of Stellenbosch.

After the necessary sample preparation and apparatus set up as described above, the AWT was conducted via the following procedure:

1. Six individual AWT were run (i.e. one for each DECL product (x5) and one for an untreated reference batch (x1)).
2. For each of the five DECL products and an untreated reference batch, seven rock lumps were placed in different bins.
3. The assembly was rotated on an axle for three wet-and-dry cycles, where one cycle is wet for 6 hours during the day and dry for 6 hours during the night).
4. During the wet period of a cycle, the bins were partially submerged in water so that when stationary, all lumps of rock were submerged.
5. During the dry period of a cycle, the water was completely drained.

This wet-and-dry process was repeated for a total of 36 hours per sample (18 hours wet / 18 hours dry) and the raw data documented as seen in Table 9.

Table 9 - Accelerated weathering test (AWT) raw data results for each individual sample and associated DECL product after every wet-and-dry cycle.

Sample:	Rocks (g):	Container (g):	Rocks + Container (g):	Waste after first cycle (g):	Residual after first cycle (g):	Waste after second cycle (g):	Residual after second cycle (g):	Waste after third cycle (g):	Residual after third cycle (g):	Total amount of material lost in suspension (i.e. unmeasurable) (g)	Remarks
Untreated	244	143	387	237	0	237	0	237	0	7	Completely disintegrated & dissolved into silt sized particles (i.e. lost in suspension)
NanoSil	199	334	533	157	37	180	11	183	10	6	Waste - intact (i.e. little suspension)
NanoBond	244	311	555	107	132	179	53	212	22	10	Waste - failry intact (i.e. little suspension)
NANO	273	95	368	146	117	217	46	234	27	12	Waste - failry intact (i.e. little suspension)
Sasbind	249	90	339	125	114	156	98	163	70	16	Waste - mostly suspension
Sasbind (+Bit)	220	97	317	149	63	159	54	170	45	5	Waste - failry intact (i.e. little suspension)

After completion of the abovementioned procedure and three wet-and-dry cycles on all 6 shale sample batches, the mass of the rock left in each respective bin was compared to that of their original mass and the data was then subsequently used to calculate the percentage of deterioration that each batch had undergone during testing by means of the following equation:

$$\%\ degraded\ or\ residual\ material\ after\ the\ third\ cycle$$

$$=$$

$$\left[\frac{(degraded\ or\ residual\ material\ after\ the\ third\ cycle) - (original\ sample\ mass)}{original\ sample\ mass}\right] x\ 100$$

A visual evaluation was also undertaken by means of comparing before-and-after photos to estimate which materials, or more accurately which DECL product, had undergone the least weathering and deteriotration during the AWT.

Unfortunately, because this is a home-based apparatus and test methods were developed by Mr. Leon Croukamp and Mr. Peter van Wyk at the University of Stellenbosch (US), there are certain assumptions and limitations associated with the results of this type of test namely:

- The accelerated weathering apparatus, as built by Mr. Leon Croukamp and Mr. Peter van Wyk at the US, conforms to the American Society for Testing and Materials (ASTM D4644, 1998) standard used to test the slake-durability of rocks via a rotating drum mechanism, which means that the apparatus can only be used to test the disintegration and slaking of rocks (especially mudrocks) into smaller particles (≤ 20 mm) and nothing else.
- Because shale often breaks down into particles (or fragments) of many shapes and sizes, the AWT test and apparatus might sometimes cause these rocks to seem more durable when compared to other typically stronger rock types such as sandstone for example, which is why a test mentioned in Brink (1983) was adapted and an apparatus was built that would typically release ≤ 20 mm particle / lump sizes (Brink, 1983);
- AWT tests by Brink (1983) only included a visual evaluation, which was done by comparing before-and-after photos to estimate which materials had undergone the most weathering and deterioration. No physical mass comparisons between before-and-after the apparatus were run, which means that actual tabular results which would have enabled comparison to a test similar to the one conducted (i.e. breakdown percentages of the slaking or disintegrating of rocks into different shapes and sizes) was not possible.
- Brink's (1983) AWT was also done by substituting water with saturated sodium sulphate and sodium hexamet – aphosphate known as Calgon (a dispersive agent), which could not be done for this specific AWT due to the lack of available mixtures (±30 L of each mixture) and cost implications.

5.3.6 Slake-durability index (SDI) tests

An abundant group of rock materials, especially those with a high clay content, are often prone to weakening either by **slaking** or **disintegration** when exposed to short term weathering processes of a wetting and drying nature. Special types of tests are therefore required to predict the exact extent of their mechanical performance and these tests are often referred to as *"index tests"*. It is worth mentioning that index tests are best used in classifying and comparing one rock sample with another, which is why for this particular test an untreated shale sample was tested against a DECL treated shale sample, in order to determine the effectiveness of the DECL product on the stability and durability of the Kimberley shales. The following slake-durability tests were conducted at Rocklab in Pretoria according to the ISRM's specifications and was used to simulate a short term natural wetting and drying process for the Kimberley shales.

Two samples were sent in for analyses, one treated with the **Sasbind** DECL product (chosen as the best result of the above mentioned AWT test) and the other left untreated. The durability of both samples were classified according to their slake-durability index after the second (2nd) wetting and drying cycle using the classification table as recommended by ISRM and proposed by Gamble (1971) (see Table 10 below).

Table 10 - Slake-durability index (SDI) classification system according to Gamble (1971).

SDI	30 - 60	60 - 85	85 - 95	95 - 98	> 98
Classification	Low	Medium	Medium -High	High	Very high

Since the fabric of a rock has a very important effect on the properties being measured during the given SDI test, both samples were ensured to represent two undisturbed rock specimen as far as possible, having being treated or handeld as little as possible prior to commencement of these tests. The apparatus used to test the durability of these rocks essentially consisted of:

- A test drum comprising a 2 mm standard mesh cylinder of unobstructed length (100 mm) and diameter (140 mm).
- A horizontal trough axis to contain the test drum and allow free rotation.
- A motor drive capable of rotating the drum at a speed of 20 rotations per minute (rpm).
- An oven capable of maintaining a temperature of 105° to within 3°C for a period of at least 12 hours.
- A scale capable of weighing the drum plus sample to an accuracy of 0.5 grams.

These components of the SDI test equipment are shown below in Figure 44:

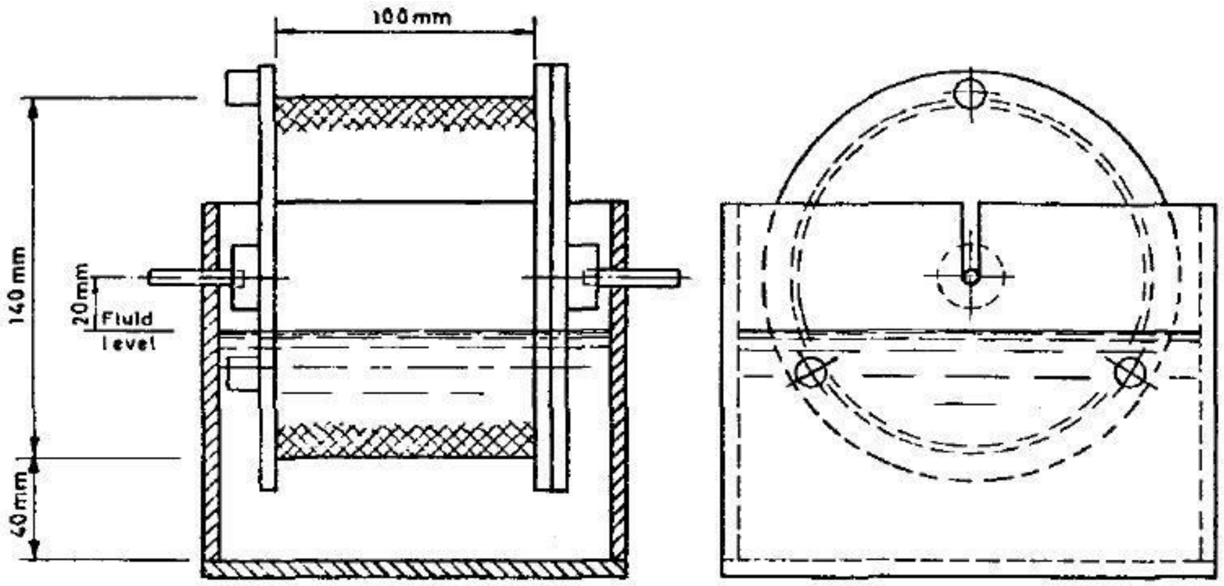


Figure 44 - Critical dimensions of the slake-durability test equipment (Franklin & Chandra, 1972).

The exact procedure as followed by the laboratory personnel at Rocklab, to run the SDI test for the purpose of this project, is summarized below:

1. Two representative shale samples were selected and cut into ten equidimensional rock lumps, each with a mass of 40 – 60 grams, to give a total sample mass of 450 – 550 grams each.
2. The first sample was left untreated whilst the second sample was treated in the exact same manner as discussed in Section 5.2.3 – Table 7 with the DECL product, Sasbind.
3. After coating the treated rock sample with two protective layers of the Sasbind DECL product, both samples (treated and untreated) were dried to a constant mass at a temperature of 105°C.
4. The mass (A) of the drum plus each individual sample was then recorded.
5. The trough was filled with slaking fluid (in this case, tap water) and the drum was rotated for 200 revolutions during a period of 10 minutes.
6. Thereafter the drum plus the retained portion of the sample was dried again to a constant mass of 105°C.
7. The mass (B) of the drum plus the retained portion of the sample was recorded for a second time.
8. Steps (5) – (6) were repeated again and the mass (C) of the drum plus the retained portion of the sample was recorded for a third time.
9. Finally the drum was brushed clean and its empty mass (D) was also recorded.

To accurately calculate the slake-durability index for both the treated and untreated shale samples, the second cycle of the SDI test was calculated as a percentage ratio of the final to initial dry sample mass as shown below:

[SDI (I_{dz}) = $\frac{C-D}{A-D}$ x 100%]

In order to fully understand the results and accurately interpret the state of the samples after completion of the test, which is directly related to a samples resistance towards weathering and a good visual indication of its durability, the following symbols were used to denote the end state and structure of both rock specimen (treated and untreated) after completion of the fourth cycle of the SDI test (see Tabel 11):

1 - Specimens were still intact after 4 cycles of slake durability tests.

2 - Some specimens were broken into a few big pieces after 4 cycles of tests.

3 - Some specimens were broken into small pieces after 4 cycles of tests.

4 - Specimens were broken into a lot of small pieces after 4 cycles of tests.

Table 11 - Calculated results of the slake-durability index (SDI) tests as carried out by Rocklab in Pretoria on both an untreated shale sample as well as a DECL treated (Sasbind) sample.

SPECIMAN PARTICULARS			SLAKE-DURABILITY INDEX TEST RESULTS										
Specimen	Sampling location	Rock type	Zero Mass	Mass after ... cycles (including tray mass)				Slake Durability	Slake Durability	Slake Durability	Slake Durability	Durability	Notes
			A	Cd1	Cd2	Cd3	Cd4	Index (1st Cycle) Id1	Index (2nd Cycle) Id2	Index (3rd Cycle) Id3	Index (4th Cycle) Id4	Class	
			(g)	(g)	(g)	(g)	(g)						
Untreated	Bultfontein Mine	Kimberley shale	855.93	808.37	674.79	585.31	506.69	94.4	78.8	68.4	59.2	Medium	4
Treated (Sasbind)	Bultfontein Mine	Kimberley shale	802.83	797.71	796.29	795.76	794.58	99.4	99.2	99.1	99.0	Very high	1

The results will be presented and discussed in Chapter 6. The reason for conducting a short term SDI test on both a untreated and DECL - treated shale sample was to:

- Predict the exact extent of the mechanical performance of the Kimberley shales, both treated and untreated, under exposure to a short term weathering process of a wetting and drying nature.
- Classify and compare one rock sample with another (treated vs. untreated) as to determine the effectiveness of the DECL product on the stability and durability of the Kimberley shales and to document the differences in behviour during commencement of the test.
- Determine the slake-durability index of the Kimberley shales in their natural state (untreated) by using international ISRM standards. This allowed the Kimberley shales to be classified and categorized against other shale samples from around the world that underwent the same test under the same standards.
- Evaluate whether the DECL product (Sasbind) would have a strengthening effect on the disintegration and slaking rate of the Kimberley shales and if so, to what extent.

5.3.7 Summary

The methodological procedure as followed and described above produced very valuable and accurate results in terms of proposing a viable solution towards the defined slope stability problem at the Kimberley "Big Hole" Mine. The desktop study (i.e. aerial photography, drone modelling and pixel tracking) produced very informative maps and illustrations of sidewall boundary migration at the Big Hole Mine over the past few years and a lot of valuable conclusions could be drawn from this work, including the entire extent of slope stability problems and the rate at which they ensue. Furthermore, the petrographic analysis in combination with a full geochemical analysis proved extremely useful in identifying the different types of clay minerals present within the internal structure of the rock and provided enough mineral phase diagrams for identifying the different mineral phases in each rock sample. From this, the swelling and shrinkage potential of the Kimberley shales could be deduced, which gave a lot of insight into the suggested weathering rate of the rocks as a function of time and water content.

In terms of the laboratory tests as conducted and described above, all four tests provided valuable results in terms of assessing the effectiveness of the different DECL products on the durability and weathering resistance of the Kimberley shales. A strong correlation between the results of the cyclic wetting and drying test, the comparative accelerated weathering test and the slake-durability index test could be drawn. As for the conducted absorption test, the results showed a slight deviation when compared to the rest of the test results, which could possibly be attributed to human and mechanical errors during measurement of each sample.

Chapter 6: Results and interpretations

6.1 Visual inspections

The following figures illustrate numerous examples of slope instability indicators in and around the sidewalls of the Kimberley "Big Hole" Mine including small- and large-scale tension cracks, landslides, toppling structures and toppling slope failure events. Each figure is introduced by a brief description of the occurring event (see Figures 45 - 52):

Visual evidence of **multiple smaller-scale tension cracks** (± 2.5 meters in length) propagating through nearby railway tracks on Bultfontein Road is shown in Figure 45. The propagation direction of these cracks run parallel to the sidewalls of the Kimberley "Big Hole" Mine, which seems to suggest some sort of mass movement event towards the center of the pit (i.e. soil creep for example).

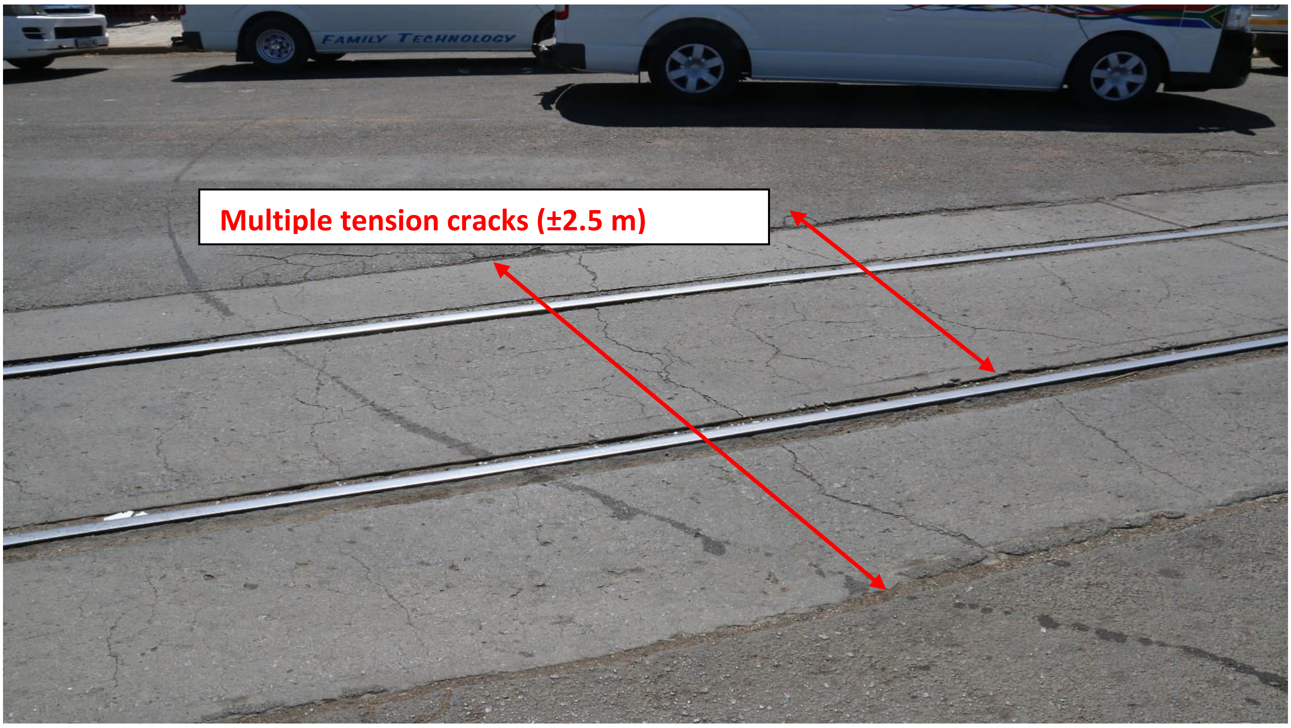


Figure 45 - Multiple small-scale tension cracks on Bultfontein Road.

A recent occurrence of **a fresh landslide** on the northeastern slope of the Kimberley "Big Hole" Mine is shown in Figure 46.This landslide was most likely caused by a single block toppling failure event of the overlying dolerite caps due to regression of the underlying Kimberley shales resulting in a loss of support. Evidence for the occurrence of a landslide is supported by loose dolerite boulders scattered across the slope of the sidewall as well as the difference in color and lack of vegetation within the loose soil material that have formed in the shape of an overturned funnel.

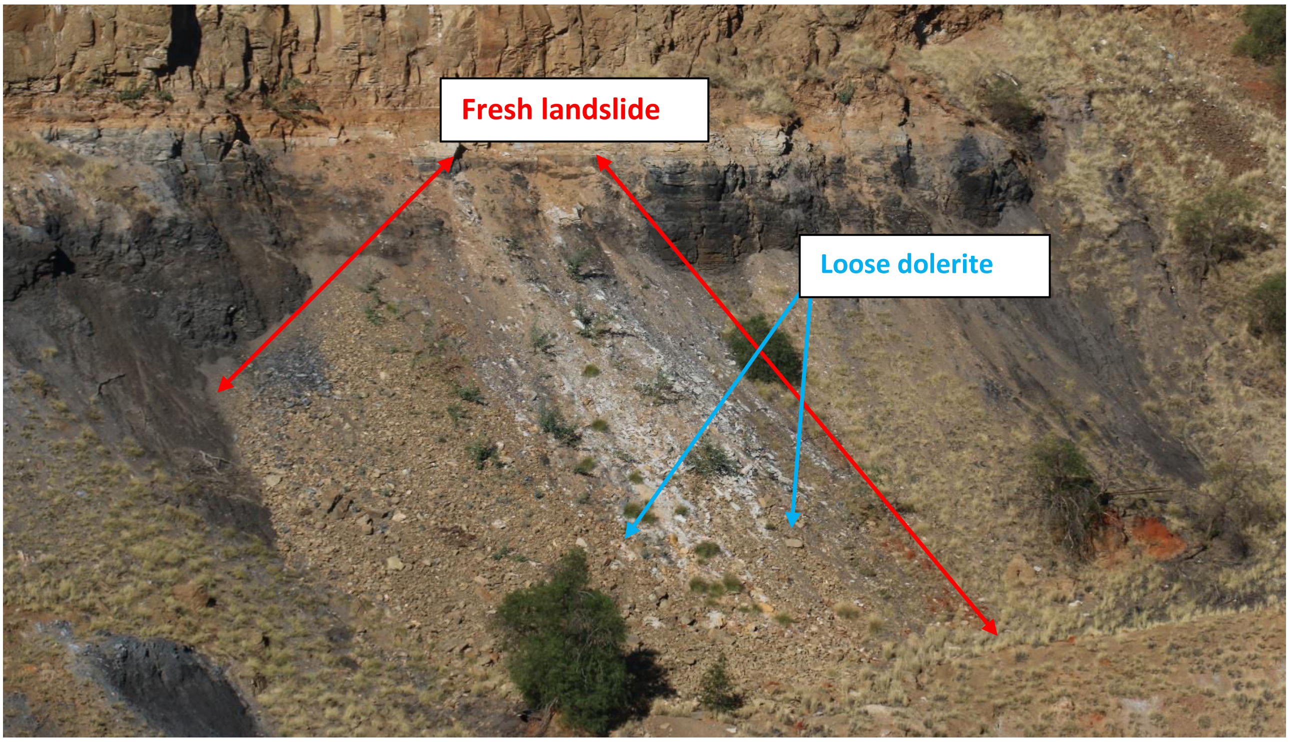


Figure 46 - Recent landslide on the northeastern slope of the Kimberley "Big Hole" Mine.

Figure 47 shows **multiple small-scale erosional landslides** on the eastern slope of the Kimberley "Big Hole" Mine caused by rapid weathering and deterioration of the underlying Kimberley shales. Weathering of the shale unit creates plenty loose and unstable soil material that is eventually transported away by small-scale erosional landslides such as the ones illustrated in the figure below.

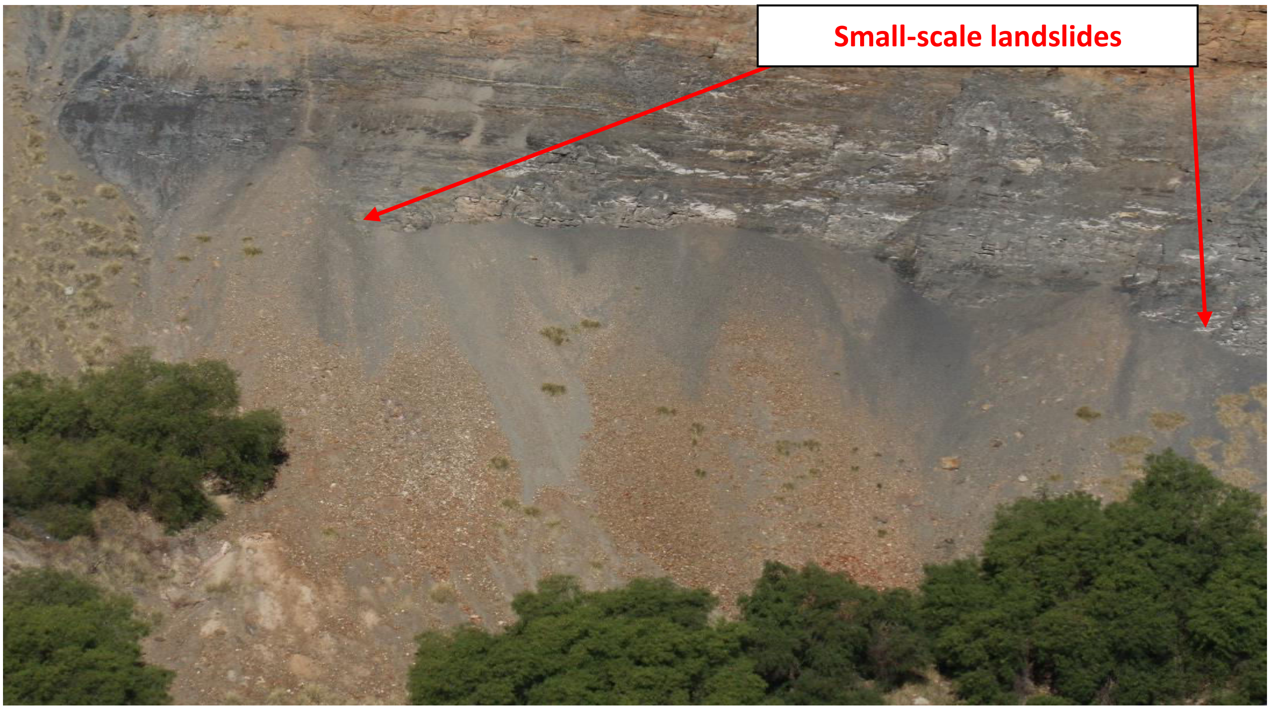


Figure 47 - Small-scale erosional landslides on the eastern slope of the Kimberley "Big Hole" Mine.

Loose dolerite blocks that have toppled over and into the open mine pit as a result of support loss (or regression) from the underlying Kimberley shales can be seen in Figure 48. The image depicts a typical end result of a single block toppling slope failure event at the Kimberley “Big Hole” Mine.

Figure 48 - Block toppling (slope) failure of the overlying dolerite caps.

Drone footage depicting both the relative proximity of Bultfontein Road to the nearest edge of the Kimberley “Big Hole” Mine, which is only approximately 22 meters, as well as the development of **large-scale tension cracks** on the northeastern side of the pit, which results in the formation of **large-scale toppling structures** can be seen in Figure 49. These large-scale block toppling structures eventually break off and topple over and into the open mine pit in the form of massive dolerite blocks or boulders as soon as regression of the underlying shale unit reaches a critical state and cannot support the weight of the overlying dolerite caps anymore (i.e. support loss). Block toppling slope failure events, such as the one depicted in the image below, cause multiple large- and small-scale landslides along the slopes of the sidewalls of the Kimberley “Big Hole” Mine, which only further widens and increases the mine pit parameters.

Figure 49 - Proximity of Bultfontein Road to the nearest edge of the Kimberley "Big Hole" Mine as well as large-scale toppling structures on the northeastern side of the pit.

Along with sufficient evidence of slope instability indicators such as tension cracks and landslides on the eastern edge / slope of the Kimberley “Big Hole” Mine for example, Figure 50 also indicates evidence of **soil creep** (or mass movement) along the same pit boundary (see Figure 50). This very slow but continuous process of mass movement towards the center of the Big Hole Mine creates a slumping effect along the eastern edge of the pit, which will subsequently lead to the formation of tension cracks and the further development of large toppling structures before a block toppling slope failure event is inevitable.

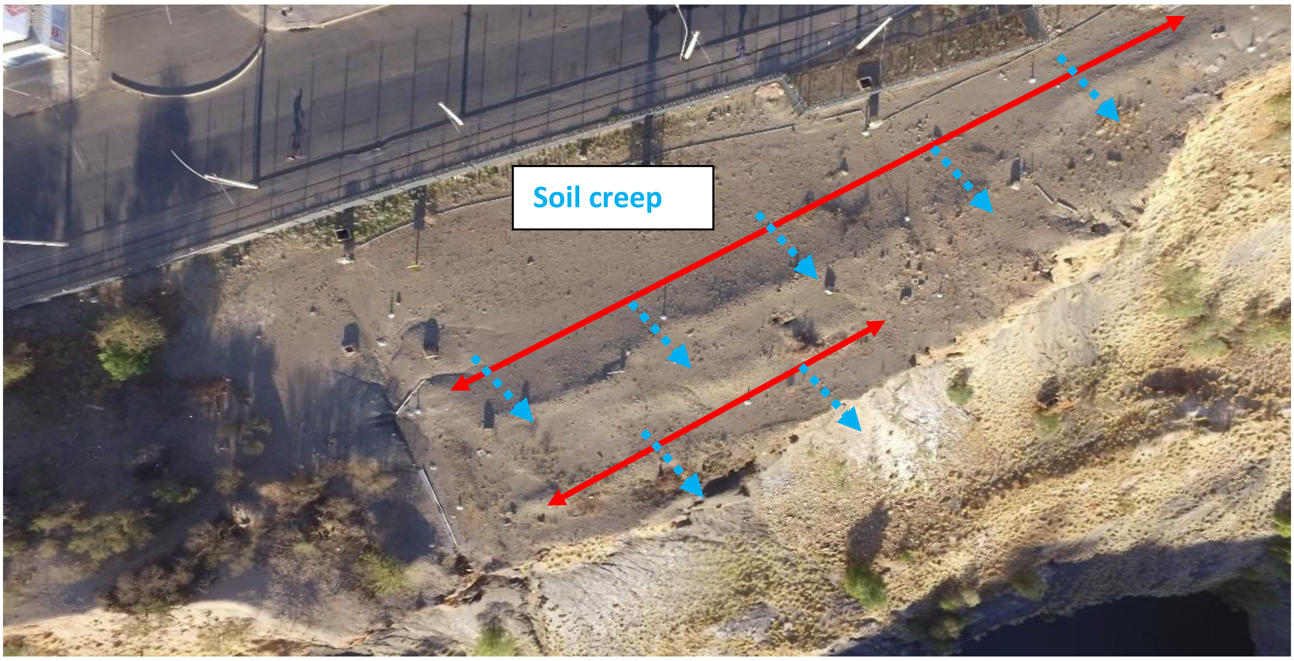


Figure 50 - Soil creep along the eastern boundary of the Kimberley "Big Hole" Mine.

Large-scale toppling structures / blocks around the northern and northeastern side of the pit (closest to Bultfontein Road) depicting sizeable areas of possible slope failures or slips as seen in Figure 51. The indicated blocks also represent areas with the highest associated risk in terms of large-scale block toppling (slope) failure events as large-scale tension cracks have started to develop on the surface of the ground directly behind these unstable blocks.

Figure 51 - Large-scale toppling blocks around the northern and northeastern side of the Kimberley Mine (closest to Bultfontein Road).

A typical example of **a block toppling (slope) failure event** at the Kimberley “Big Hole” Mine **prior to failure** is shown in Figure 52. Exposed dolerite blocks, such as the ones depicted in the image below, are usually the first indication or warning of a coming block toppling slope failure event.

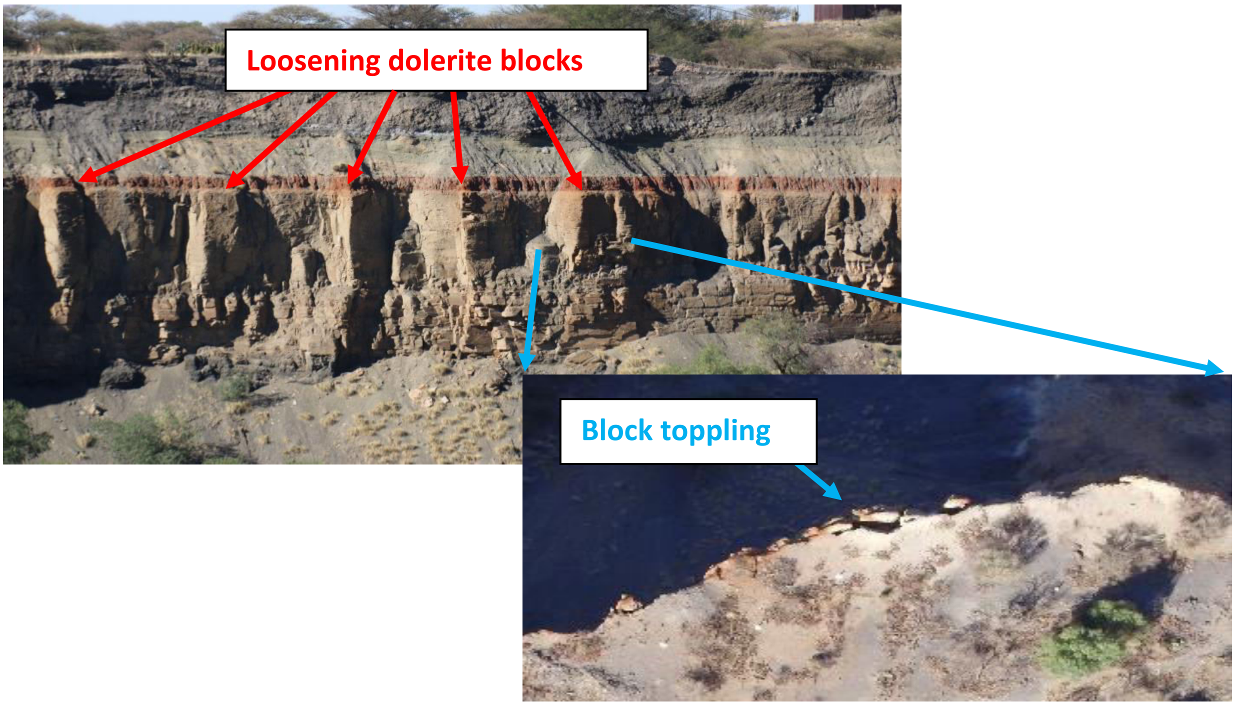


Figure 52 - Block toppling at the Kimberley “Big Hole” Mine prior to failure.

The existence of tension cracks at the head of a slope is often a strong indication that instability is imminent. Tension cracks only tend to form when ground (or soil) is being deformed (or moved) in a specific direction over time, causing cracks to open up at the surface of the soil and propagate perpendicular to the direction of the mass movement event. Therefore, the mere presence of tension cracks running parallel to the slopes of the Kimberley “Big Hole” Mine, as seen in Figures 45 and 49, is enough evidence to suggest that mass movement is still taking place in and around the sidewalls of the Big Hole Mine and that the pit is still progressing towards its natural angle of repose. In other words, the sidewalls of the pit are still actively migrating in an unstable manner towards natural equilibrium and toppling of the overlaying dolerite cap is inevitable. Block toppling at the Kimberley “Big Hole’ Mine is a slow but continuously occurring process that leads to the existence of large-scale block toppling structures as seen in Figures 48 and 51.

Fresh landslides and soil creep occurrences are evident all around the slopes of the sidewalls at the Kimberley “Big Hole” Mine as seen in Figures 46, 47 and 48 and the relative freshness of these landslides can be deducted from the absence of any vegetation on the surface of the slope as well as a triangulated trail (in the form of an upside-down funnel) of fresh soil, which is usually not the same colour as the surrounding material. These landslides are thought to be the end result of multiple block toppling events in and around the sidewalls of the Kimberley “Big Hole” Mine where the underlying shale bench could not support the weight of the overlying dolerite caps anymore, causing the orthogonally jointed dolerite blocks to break off and topple over and into the open mine pit.

To conclude this section, there is enough visual evidence in and around the mine pit slopes to suggest that regression of the underlying shale unit is still taking place and that toppling of the overlying dolerite cap is imminent as best seen in Figure 53. Unfortunately, due to site restrictions and limited access to the pit, no clear photographic evidence of shale regression showing the exact extent and severity of undermining of the Kimberley shales underneath the overlying dolerite cap could be documented and Figure 53 therefore represents the best obtainable example. Most of the evidence suggesting and supporting this regressive theory comes from other slope stability indicators, such as the existence of multiple tension cracks and large scale toppling structures in and around the sidewalls of the Kimberley “Big Hole” Mine, as well as conformation from previously written geological and geotechnical reports by Preece et al., (2008) and Croukamp (2008).

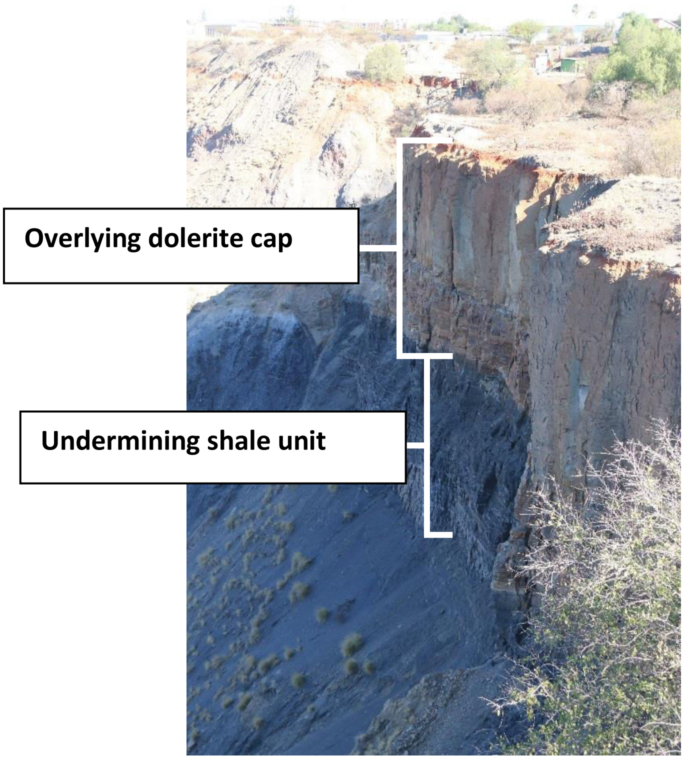


Figure 53 - Photographic evidence of shale regression at the Kimberley "Big Hole" Mine.

Furthermore, looking at the sheer scale and size of the toppling structures along the eastern and northeastern boundaries of the Kimberley "Big Hole" Mine, as well as the extent of propagating tension cracks along the paved surfaces of Bultfontein Road, the general consensus is that slope stability problems at the Big Hole Mine is still a very imminent threat and worth further investigation. Comparing the recent size, frequency and extent of slope instability indicators as presented above to those discussed during the last written geotechnical report from 2008, a fair conclusion would be that slope stability problems at the Kimberley "Big Hole" Mine have slightly worsened over the past few years and that a big slope failure, especially within the vicinity of Bultfontein Road, is inevitable.

As part of the findings of this project and in conclusion to the preceding visual assessment of the slopes of the Kimberley "Big Hole" Mine, a conceptual image was brought forward as to illustrate the process of sidewall regression at the open pit mine. Figure 54 was developed to represents a cross sectional drawing of a typical regressive profile on the sidewalls of the Kimberley "Big Hole" Mine as a function of time and includes a basic illustration of the various processes that contribute to the undermining of the Kimberley shales and the subsequent toppling of the overlying dolerite caps. The conceptual illustration aims to show that slope failures at the Kimberley "Big Hole" Mine, as a result of the vast susceptibility of the Kimberley shales to weather and deteriorate under natural weathering conditions and as a function of time (i.e. undergo regression), is inevitable. As the underlying support of shale weathers away, no support is given to the overlying dolerite cap.

This causes a tension force to develop at the top of the slope, subsequently leading to the formation of tension cracks after which toppling occurs.

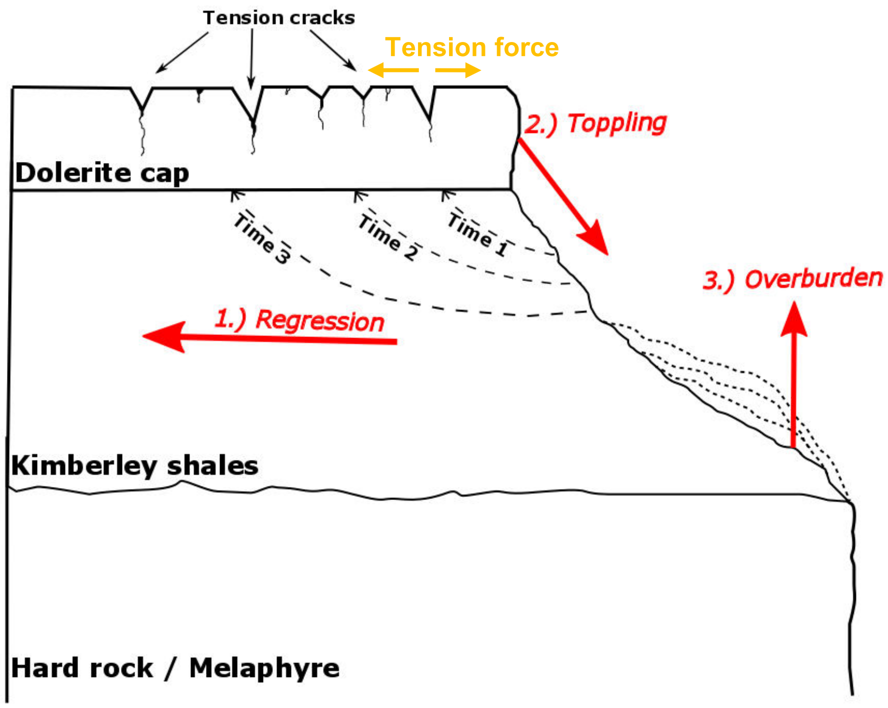


Figure 54 - Conceptual cross sectional drawing of the sidewalls of the Kimberley "Big Hole" Mine.

6.2 Aerial photography

The following figure represents a sequence of spatially georeferenced aerial photographs from the years 1975 to 2014 over the Kimberley "Big Hole" Mine that was used to visually track and trace the outward migration and systematic evolution of the sidewalls of the Big Hole Mine over the past 39 years. Figure 55 represents a non-conventional way of monitoring slope movement or mass movement events around an open pit mine, such as the Kimberley "Big Hole" Mine, by means of aerial photography as a measuring technique.

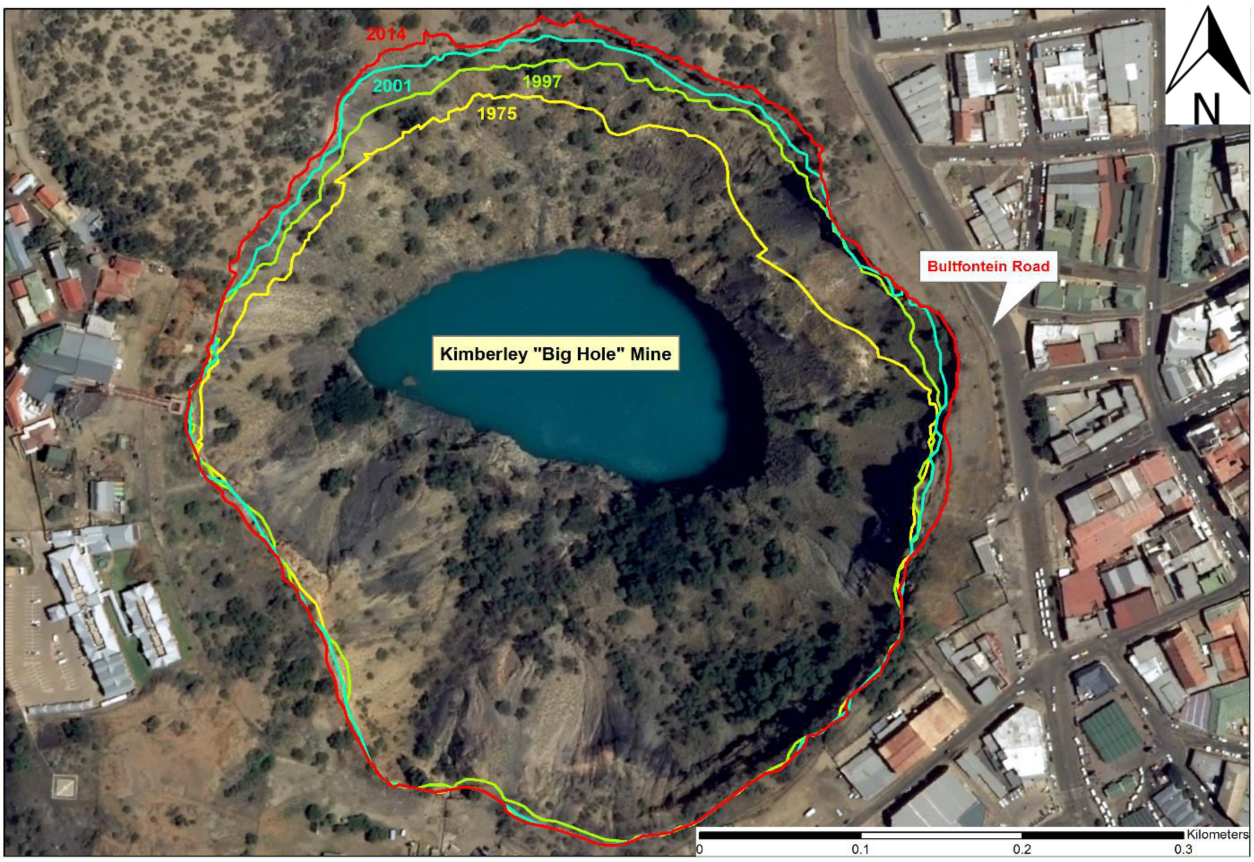


Figure 55 - Digitized boundaries for the sidewalls of the Kimberley "Big Hole" Mine as per years, 1975, 1997, 2001, and 2014.

As illustrated in Figure 55, most of the ground movement events (including landslides and toppling slope failures) seemed to have occurred on the northern and northeastern side of the pit during the past 39 years, with most of the sidewall deformation occurring between 1975 and 1997. Thereafter, ground deformation and sidewall migration have been less pronounced and occurred less frequently, although still evident. Due to the relative proximity of Bultfontein Road to the eastern edge of the mine, it provokes most attention and concern for the town of Kimberley. The relative proximity of Bultfontein Road to the eastern edge of the pit is only approximately 22 meters and poses an immediate threat to surrounding infrastructure and businesses. The map also seems to suggest that even though landslides and ground movement events decreased in volume and frequency over the past 17 years, movement was still recorded up until 2014. The corresponding table gives both the area and perimeter calculations for the outer boundary of the Big Hole Mine for the years 1975, 1997, 2001 and 2014, as well as the increase of each as a percentage for each successive year as shown (see Table 12). Both area and perimeter calculations exhibit an increase in overall shape and size from the year 1975 to 2014, acting as sufficient evidence for still-active migration of the outer perimeter / boundary of the sidewalls of the Big Hole Mine outward.

Table 12 - Area and perimeter calculations for the Kimberley “Big Hole” Mine, including the overall increase of each as a function of time.

Year:	Area (m²):	Increase (%)	Perimeter (m):	Increase (%)
1975	150319		1538	
1997	164707	9.57	1584	2.99
2001	172025	4.44	1597	0.82
2014	178486	3.76	1651	3.38

Two bar charts were put forward to illustrate the above-tabulated results, visually. The figures therefore represents the total area and mine pit perimeter increases of the Kimberley “Big Hole” Mine over the past few years and is illustrated below by Figure 56 and Figure 57 respectively. When considering only Figure 56, the visual representation seem to suggest that mine pit failures and slope migrations around the sidewalls of the Kimberley “Big Hole” Mine have started to decrease over the past few years, especially with regards to the last 13 years. In other words, when looking only at the area increase as a measurement criterion, it might suggest that the stability issue surrounding the slopes of the Kimberley “Big Hole” Mine have started to regress. This however, is not the case when measuring it against the perimeter increase calculations. Figure 57 shows a clear increase in the perimeter values of the Kimberley “Big Hole” Mine, especially within the last 13 years, suggesting that these values should always be considered as a whole and not viewed separately. This conclusion agrees with the findings of Section 6.3 (discussed below), which seem to suggest that slope failures and sidewall migration at the Kimberley “Big Hole” Mine occurred very frequently at first, whilst now still drastic but in more localized areas around the pit.

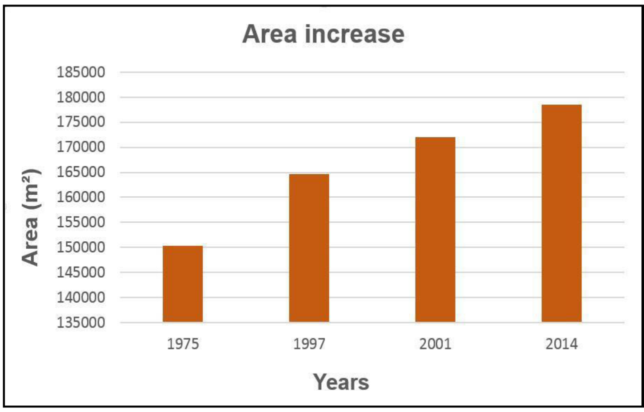


Figure 56 - Graph illustrating the total area increase of the Kimberley “Big Hole” Mine over the past few years.

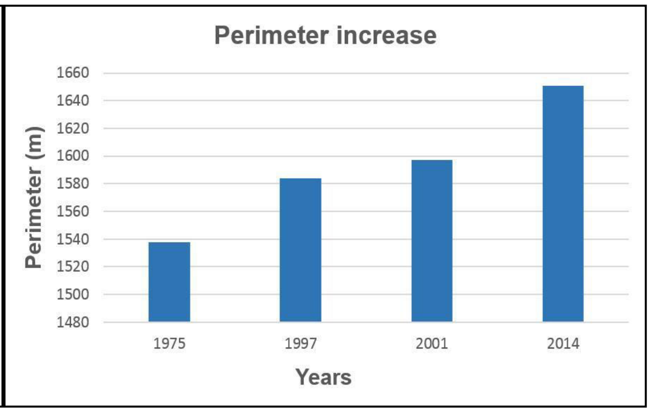


Figure 57 - Graph illustrating the total perimeter increase of the Kimberley “Big Hole” Mine over the past few years.

6.3 Pixel tracking

Figure 58 represents a final deformation vector map between the oldest (1968) and the youngest (2014) aerial photographs of the Kimberley “Big Hole” Mine, which gave the best representation of ground movement patterns / deformation around the Big Hole Mine as a function of time.

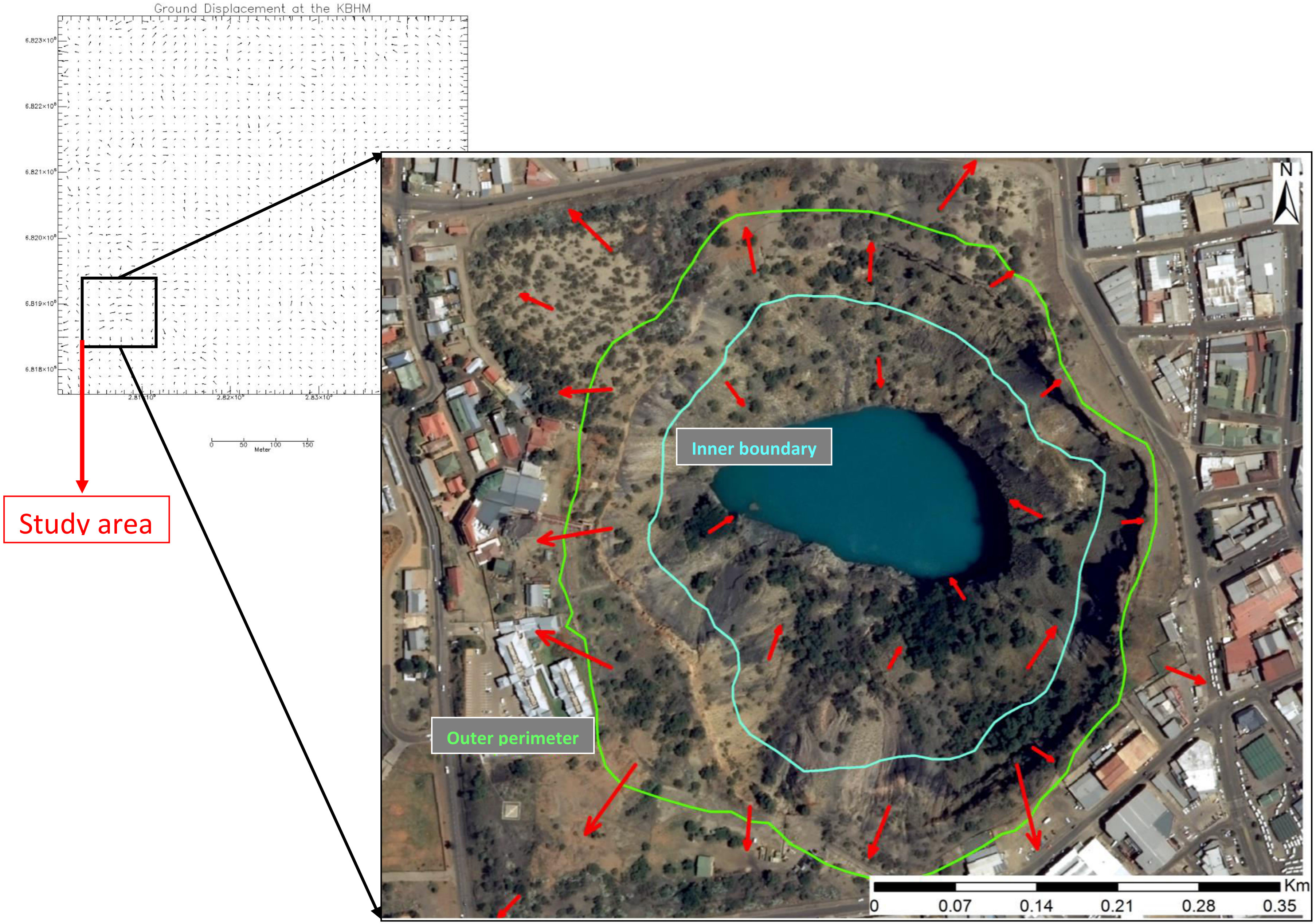


Figure 58 - Final output image of a deformation vector map for the Kimberley "Big Hole" Mine between 1968 and 2014. The map was created at CSIR (Stellenbosch) with COSI-Corr software.

The first and probably most significant conclusion that could be drawn from the pixel tracking results and the final (raw) deformation vector map, as illustrated by the black and white insert map in Figure 58, is that ground movement activity was most significant and pronounced around the general area of the Kimberley “Big Hole” Mine (i.e. depicted by a square as the defined study area) and to a lesser extent everywhere else. In other words, when looking at the entirety of the final deformation vector map (i.e. the black and white insert), vector arrows seem to be fluctuating (or moving) in different directions and to different extents mostly around the immediate vicinity of the Kimberley “Big Hole” Mine, which falls squarely within the boundaries of the defined study area as shown in Figure 58. Vector arrows throughout the rest of the deformation vector map however (i.e. excluding the defined study area), seem to indicate less or no movement and appear as small lines or dots, which seem to suggest fewer ground movement activity and overall deformation over the years. The fact that pixel tracking produced a final deformation vector map that showed very little to no ground movement activity / deformation outside the perimeter of the study area (i.e. the Kimberley “Big Hole” Mine), is seen as sufficient evidence to suggest that ground movement / displacement around the pit is still taking place and that the sidewalls of the mine are still actively migrating outward in an unstable manner towards their natural angle of repose, hence vector arrows showing an increase in movement and activity around the general area of the pit.

It is worth mentioning however that, because this is a very unique and modern day method of measuring ground movement / displacement around large open pits (such as the Kimberley “Big Hole” Mine for example) and the fact that results are arbitrarily defined by COSI-Corr software, there is much room left for interpretation and improvement as is also the case with the final deformation vector map that was created and presented within this project (i.e. Figure 58). For example, even though it is probably still safe to say that ground movement / displacement is taking place around the immediate vicinity of the Kimberley “Big Hole’ Mine (as a result and interpretation of the movement / activity of the vector arrows in the final deformation vector map as discussed above), it is less accurate to say why these movements occurred and what the exact reason for these ground displacements are. Pixel tracking only quantifies movement and not a reason therefore (unless it is completely obvious). As a result, the most likely reasons (or methods) for ground movement around the sidewalls of the Kimberley “Big Hole” Mine (i.e. soil creep, slumping or landslides for example) can only be assumed and suggested based on other slope stability indicators and supporting evidence, which is exactly what was done below.

The main concept behind the final output of COSI-Corr software is that the longer the vector arrow in resulting vector maps, the bigger the actual ground displacement in real life. It should also be mentioned that the vector arrows do not quantify or define an exact scaled measurement, meaning that they are only measured relative towards one another and not towards real life movement, hence the results being arbitrarily defined. Furthermore, COSI-Corr software also generally defines the direction of the arrow as the true direction of ground movement around the pit and horizontal ground movement / displacement in and around the sidewalls of the Kimberley "Big Hole" Mine from 1968 to 2014. From Figure 58 it can therefore be seen as quite significant.

Within all of the successive displacement vector maps that were created for the purpose of this project, and especially within Figure 58, there seem to be two sets of vector arrows pointing both inward and outward from the inner drawn boundary and the outer mine pit perimeter respectively. The first set of vector arrows situated within the inner boundary of the Kimberley "Big Hole" Mine, as illustrated in Figure 58, point inward towards the center of the pit, suggesting some sort of ground / mass movement from the sidewalls inward. Considering the direction and overall extent of these vector arrows, along with other slope stability indicators found in and around the sidewalls of the Kimberley "Big Hole" Mine, these inward pointing vector arrows most likely represent some sort of landslide or slumping effect of the soil from the outer boundary of the pit, inward, as slope failure events occurred over time. In other words, pixel tracking was used to track a pixel from the outer boundary of the pit, inward, between the years 1968 and 2014. This means that within the same time frame, soil must have moved in the same direction in response to some sort of soil / mass movement event, which can only be assumed to suggest the occurrence of a landslide or slumping effect that occurred in response to a preceding toppling slope failure event.

The second set of vector arrows on the other hand, extend outward from the inner drawn boundary towards the outer mine pit perimeter and in some cases even beyond the boundaries of the sidewalls (see Figure 58). These longer vector arrows are thought to represent the moving mine pit perimeter and is seen as very indicative of the occurring weathering processes associated with the Kimberley shales and the resultant toppling slope failures of the overlying dolerite caps. It supports the evidence for regression and undermining at the Kimberley "Big Hole" Mine and stands as additional evidence for slope movement / migration of the sidewalls of the pit outward (i.e. regression of the perimeter). The unique outward radiating flow pattern of the second set of vector arrows around the outer perimeter of the Kimberley "Big Hole" Mine, also implies that movement of the mine pit perimeter (i.e. the sidewalls) around the Kimberley "Big Hole" Mine is taking place from the inside, outward, which agrees with previously mentioned evidence of the Big Hole increasing in size and shape. The second set of vector arrows therefore represent net movement, meaning that even though mass movement of soil inward towards the center of the pit is also occurring, as evident by the presence of multiple tension cracks in and around the sidewalls of the Kimberley "Big Hole" Mine, the mine pit boundary is still largely moving outward and increasing in size.

Although not indicated on Figure 58, but evident in all other successive vector maps created for the purpose of this project, the longest vector arrows are encountered within the boundaries of the Big Hole Mine's perimeter, whilst the further away you move, the smaller the arrows tend to get. The reason for this is that ground movement activities linearly decrease as a function of distance. In other words, the further you move from the center of the pit, the less ground movement / deformation will affect the slope and the smaller the vector arrows will be as it meets balance. It is also worth mentioning that vector arrows falling just outside the immediate vicinity of the Kimberley "Big Hole" Mine's perimeter (i.e. overlaying infrastructure such as buildings and roads for example), were automatically discarded based on their tendency to take land cover changes as a sign of ground movement / displacement and was therefore seen as being ambiguous and inaccurate. In other words, it was not able to judge whether vector arrows outside of the Kimberley "Big Hole" Mine's perimeter indicated true signs of ground movement / displacement, or whether they merely tracked the development of infrastructure, such as the resurrection of a new building or the appearance of a new road for example. For this very reason, they were automatically discarded from the results as being ambiguous and inaccurate. Vector arrows falling within the mine pit perimeter however, had no external interference with regards to movement measurements in COSI-Corr software, especially considering that the only changes that could have occurred within and around the sidewalls of the Kimberley "Big Hole" Mine over the past few years, could have been as a result of some type of ground movement or displacement in response to some sort of slope stability problem or slope failure event. Therefore, these results were considered accurate and viable for interpretation.

All of the abovementioned evidence seems to address the same theme that keeps reoccurring throughout this project: that regression of the underlying shale unit, due to its vast susceptibility to weathering and deteriorate, causes it to undercut the overlying dolerite caps and initiate an even bigger block toppling slope failure event. This, in effect, is what causes the sidewalls of the Kimberley "Big Hole" Mine to radially migrate outward (as proven by the outward radiating flow pattern of the obtained deformation vector maps) and what causes the surrounding land cover to experience a general subsidizing effect due to support loss from underlying soil horizons and the overbearing load from surrounding infrastructure (as proven by the abundance of surrounding tension cracks).

6.4 Drone footage

What follows is a comprehensive discussion and illustration of the respective drone footage maps as created and displayed in *DroneDeploy* software. The aim of this section was to assess and subsequently better understand the state and stability of the Kimberley "Big Hole" Mine as it stands today by means of utilizing a remote controlled drone.

6.4.1 High-resolution two-dimensional (2D) image

As previously indicated, the eastern and northeastern margins of the pit represents the areas of highest associated risk for an immediate toppling slope failure, seeing as it contains strong visual evidence for the development of tension cracks and toppling structures in the surrounding slope surfaces. Subsequently, the eastern margin is also the closest edge of the pit to Bultfontein Road, which only increases its potential for a high-risk slope failure. In fact, the relative proximity of Bultfontein Road to the nearest edge of the Kimberley “Big Hole” Mine (as it stands today) was determined from the high-resolution 2D image as being only approximately 22 meters, raising major concerns in terms of surrounding infrastructure damages and public safety. However, when zoomed in to the high-resolution 2D image, tension cracks, toppling structures, soil creep and fresh landslides could be seen all around the mine pit slopes and was not exclusive to only the eastern and northeastern margins of the pit. Tension cracks in particular, seem to form radially parallel to the sidewalls of the Big Hole Mine, whereas toppling structures are most pronounced / developed along areas where the underlying shale unit has been weathered and eroded away largely (see Figure 59).

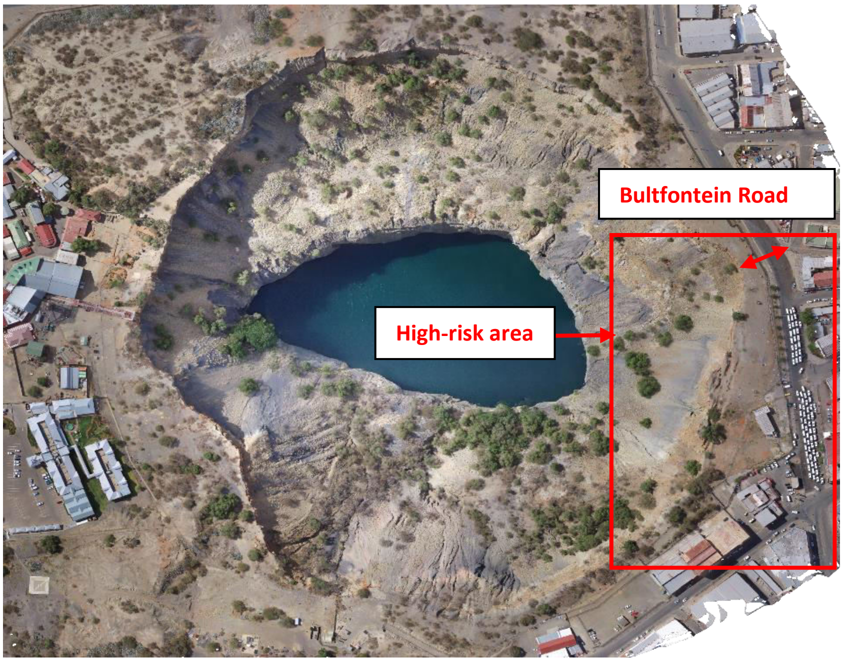


Figure 59 - High-resolution two-dimensional (2D) image of the Kimberley "Big Hole" Mine as it stands today.

6.4.2 Elevation maps

As indicated on Figure 60 A, an abundance of tension cracks are seen on the eastern and northeastern boundaries of the Kimberley “Big Hole” Mine by means of visual elevation values that highlight the differences in elevation. In other words, tension cracks are mostly highlighted by green, orange and yellow lines depending on their elevation value, that run radially parallel to the outer boundary of the pit. They follow the same structural trend as the slope of the sidewalls, indicating a certain extent of instability and ground movement in the direction of the hole. Visual evidence of soil creep is also evident on the associated elevation map, although not as abundant or as prominent as the existing tension cracks. This could be because soil creep typically involves the movement of a large mass / area of soil (mass movement) to such an extent that the elevation of the area will not show an abrupt change in elevation values, rather it will follow a gradual decreasing or increasing trend. Tension cracks on the other hand, exist much more clearly on the associated elevation map due to the abrupt changes in elevation as a crack starts to form and open up.

Figure 60 B showed higher elevation values on the eastern and southeastern margin of the pit compared to the western and northwestern side. The conclusion is that landslides and toppling slope failure events tend to occur more frequently on the eastern and southeastern edge of the pit, due to it being more unstable in terms of existing tension cracks and developing toppling structures and closer to Bultfontein Road, which is still frequently being used on a daily basis by local taxi drivers (i.e. vibrations and extra load). Subsequently, the frequent occurrence of landslides and toppling slope failure events on the eastern side of the pit causes rock lumps and soils to heap on these slopes, which not only adds to the overall overburden, but also creates higher elevation values compared to the western and northwestern side of the slopes as seen in Figure 60 B. Public interference in the form of mechanical vibrations, load-bearing infrastructure and transportation only seem to contribute to the overall stresses on the sidewalls of the Kimberley "Big Hole" Mine, which is why Figure 60 B suggests an increase in the occurrence and frequency of landslides and toppling slope failure events on the eastern and southeastern side of the Kimberley "Big Hole" Mine, hence showing higher elevation values on the associated elevation map.

Figure 60 C was created to exemplify the features as illustrated and discussed for elevation maps 60 A and B, with the only mentionable point of interest being the visual evidence of ground subsidence immediately outside the mine pit perimeter. Around the pit there are numerous areas where the elevation is not the same as the surrounding cover, being slightly lower in elevation values than the mine pit slope itself. This is considered areas of ground subsidence, where regression of the underlying shale unit has caused the overlaying dolerite cap to move inward towards the hole and set in place a process of soil creep. Soil creep at the Kimberley "Big Hole" Mine is a slow and continuously occurring process that causes the surrounding groundmass to vertically subside, which correlates well with the obtained pixel-tracking results as described and discussed in above. Subsidence of the surrounding area / groundmass, as indicated in Figure 60 C, means that a radius of ground instability exists around the Kimberley "Big Hole" Mine and should be considered as part of the natural angle of repose. In other words, areas were ground subsidence are taking place is considered to be still actively migrating and deforming towards the slope's natural angle of repose and will eventually, with time, undergo some sort of slope failure or collapse.

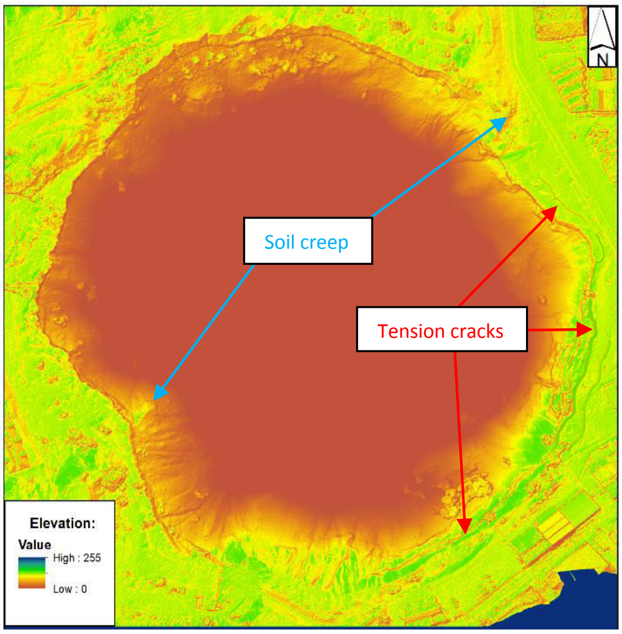


Figure 60 A - Outer perimeter elevation map of the Kimberley "Big Hole" Mine indicating the presence of soil creep and tension cracks around the pit.

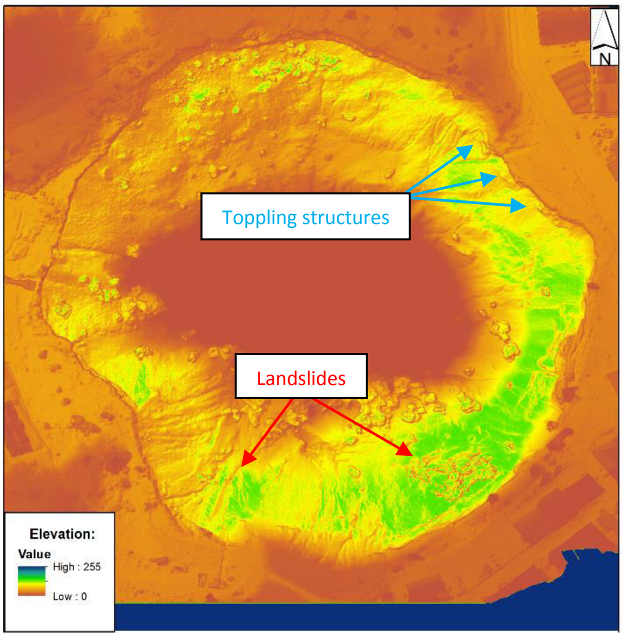


Figure 60 B - Inner perimeter elevation map of the Kimberley "Big Hole" Mine indicating areas of fresh landslides and toppling failures around the slope of the sidewalls.

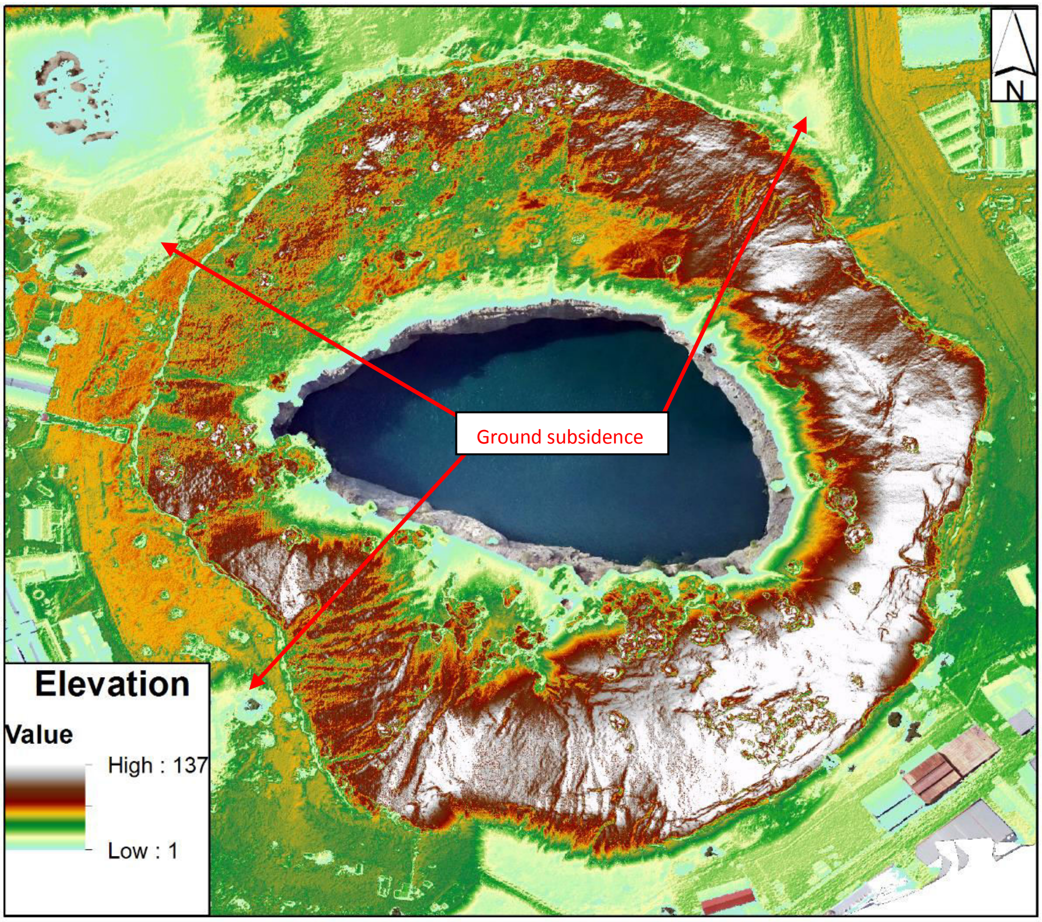


Figure 60 C - Combined elevation map of the Kimberley "Big Hole" Mine showing the entire extent of elevations in and around the open pit. This three dimensional (3D) elevation map also overlays a two-dimensional (2D) vector map as to better represent its relative position and elevation with regards to the sidewalls of the Kimberly “Big Hole” Mine.

6.4.3 Contour map

The ensuing contour map did not show any significant indications of slope stability problems or evidence of any slope stability indicators in and around the sidewalls of the Kimberley “Big Hole” Mine, especially when compared to the results obtained from the respective elevation maps and the 2D image. The reason for this being that *DroneDeploy* software only allows for 1.5 meter contour lines to be created, which means that they form a very tight and closely knit profile when viewed over the entire extent of the Kimberley “Big Hole’’ Mine. This causes difficulty in visualizing and interpreting the results, as many of the contour lines become ambiguous. Even though the resultant contour map as produced and viewed for the purpose of this project did not disclaim any significant results in terms of the defined slope stability problem at the Kimberley “Big Hole” Mine, it is still considered to be a very accurate manner of tracking and monitoring slope and ground movement patterns around big open pit mines, such as the Kimberley “Big Hole” Mine for example. Unfortunately, it is also worth mentioning that no previous such maps (i.e. elevation maps of the Kimberley area, especially around the Kimberley “Big Hole” Mine) could be found for comparison and thus, this was the only map left for interpretation and discussion (see Figure 61).

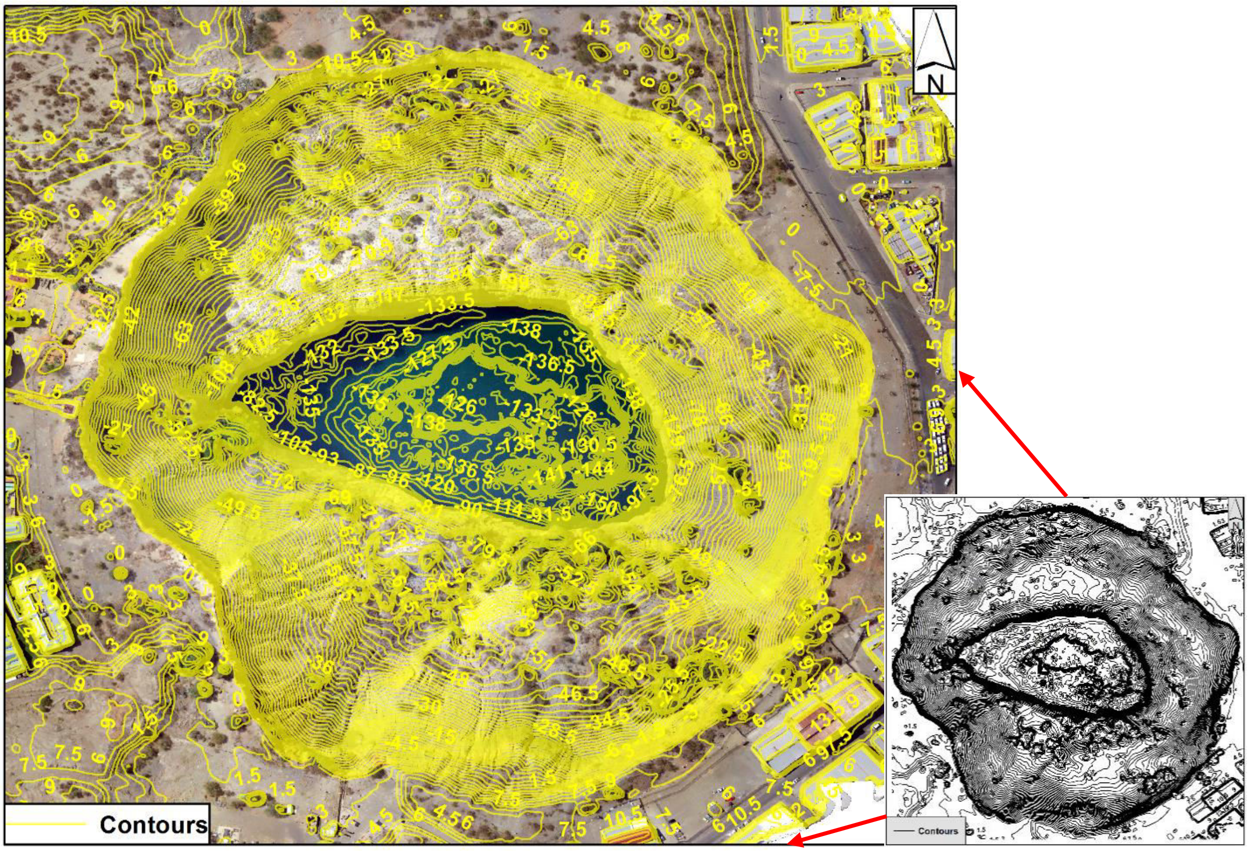


Figure 61 - 1.5 meter contour map of the Kimberley "Big Hole" Mine.

6.4.4 Three-dimensional (3D) model

The acquired 3D model, as created for the purpose of this project, aided in visualizing the entire extent of slope stability problems at the Kimberley “Big Hole” Mine and created an easy way of showcasing the exact parameters of the pit, without being on site. From the obtained 3D model, the following parameters concerning the sidewalls of the Kimberley “Big Hole” Mine could be determined and used as a future reference from here on out to evaluate whether the sidewalls of the pit is increasing in size and shape over the next few years.

The Kimberley “Big Hole” Mine parameters, as it stands today (2017), include:

Area of pit: 17.91 Ha

Perimeter of pit: 1.697 Km

Area increase from 2014 to current: 0.34%

Perimeter increase from 2014 to current: 2.79%

The total area and mine pit perimeter increase from the last obtainable measurement (which was recorded in 2014 as mentioned and discussed in Section 6.2) to its current state, is calculated as 0.34% and 2.79% respectively. This means that ground movement and sidewall migration at the Kimberley “Big Hole” Mine is still actively taking place to this day and would explain the overall increase in both area in mine pit perimeter calculations for the year 2017.

In conclusion, both the elevation and contour maps proved to be very insightful and aided in identifying and visualizing specific areas of slope stability problems within and around the sidewalls of the Kimberley “Big Hole” Mine as it stands today. It proved that slope stability indicators such as tension cracks and landslides are still very prominent and frequent around the slopes of the pit and that slope stability problems still pose an immediate as well as a long time threat, not only to the people of Kimberley, but also with regards to the surrounding infrastructure.

Both the 2D image and 3D model on the other hand, helped visualize and describe the entire extent of slope stability problems at the Kimberley “Big Hole” Mine and made it easier to relate theoretical work done during the first phase of this project, to the real-world problem and finding a hands-on solution. Being able to visualize the exact perimeters of the Kimberley “Big Hole” Mine from a perspective that is not always accessible, made it easier to assess and provide a better and more suitable solution (see Figures 62 A - D).

Figure 62 A - 3D model of the north facing sidewall of the Kimberley "Big Hole" Mine.

Figure 62 B - 3D model of the east facing sidewall of the Kimberley "Big Hole" Mine.

Figure 62 C - 3D model of the south facing sidewall of the Kimberley "Big Hole" Mine.

Figure 62 - 3D model of the west facing sidewall of the Kimberley "Big Hole" Mine.

6.5 Petrographic analysis

The two samples of Kimberley shales studied under the microscope showed very little variations and can both be described as very fine-grained rhythmites, comprising alternating layers of fine-grained quartz to interstitial finer grained clay material / organic matter (see Figure 63). The petrographic study revealed that the degree of sorting is generally very good, with grains that are typically similar in size and shape. Individual grains tend to be elongated parallel to the bedding plane of the rocks, with a preferred orientation in the same direction as the layering. The fact that grains are sub-rounded to rounded and very well sorted, probably suggests a long transportation distance of sediments from the source location to where it was deposited. Mineral composition in sediments varies considerably as a function of particle size.

The quartz content of the studied rocks varies according to grain size distribution from 10% to 60% approximately and seems to form the most dominant detrital grain constituent. Quartz grains typically present uniform to undulose extinction under stage rotation and commonly exhibit quartz overgrowths at the margins and in the fractures of the rock, as shown in Figure 63. Undulose extinction is usually a result of strain or grain fracturing, which can be either inherited from the sediment source or resulting from mechanical compaction.

Other major detrital grain components are biotite and feldspar, although feldspathic alterations are very difficult to examine under the petrographic microscope due to the fine-grained nature of the rocks. Also, due to the very fine-grained nature of the rocks, it was not possible to distinguish any known heavy minerals such as zircon and rutile.

The matrix generally ranges from 60 to 90% in some layers and is completely dominated by detrital clay / organic matter. Mica (predominantly biotite) is a typical constituent and in some cases exhibit alteration to clay-rich mica or clay minerals such as illite and chlorite. Micas are aligned and exhibit a preferred orientation in the same direction as the cleavage planes of the rocks. These minerals occur as both sub-angular grains as well as aggregates. Opaque minerals (such as iron oxides) also form a significant portion of the matrix material. The description of each sample, as well as photos can be seen in Appendix B.

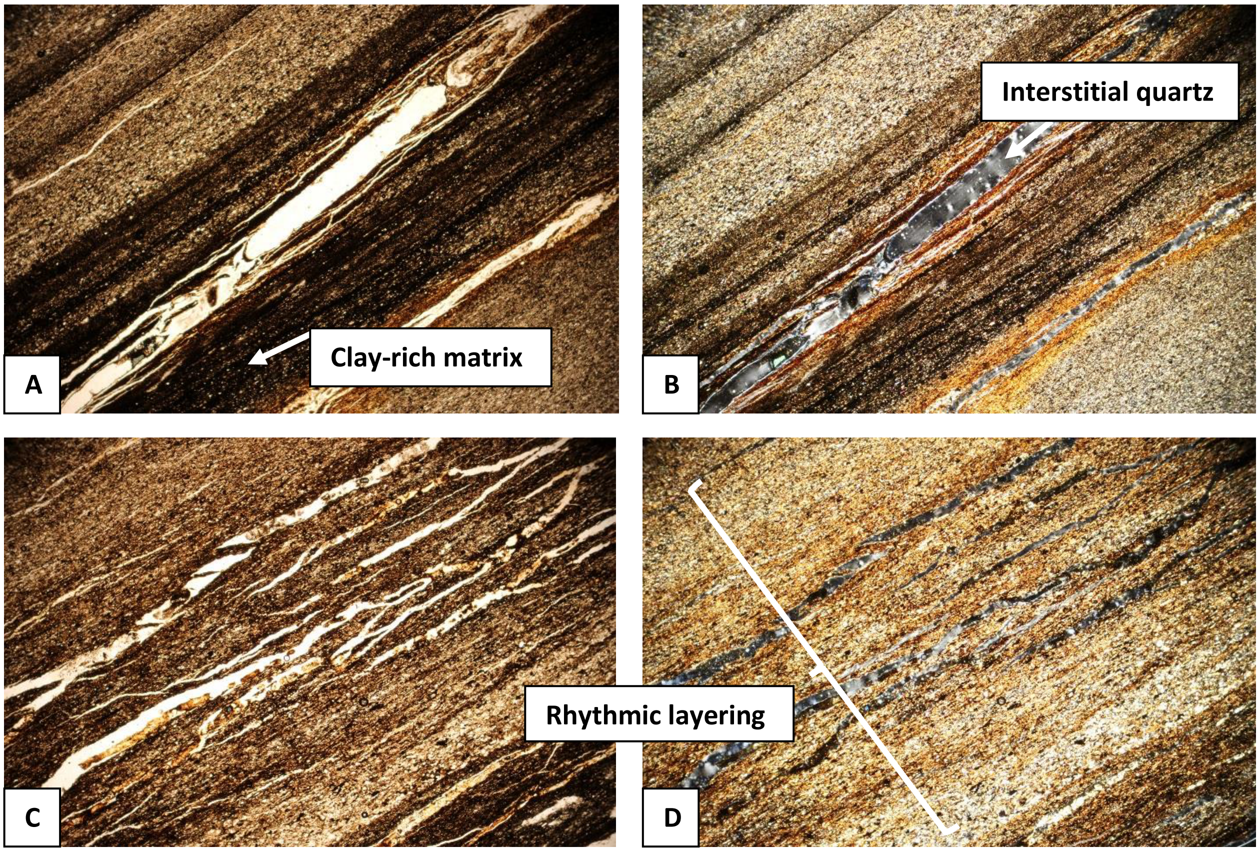


Figure 63 - A & C represent Kimberley shales in plain polarized light (PPL), whilst B & D represents the same samples only in cross polarized light (XPL). All four images highlight the fine-grained nature of these rocks, as well as the characteristic rhythmic layering. Both thin sections generally represent well-sorted layering of detrital quarts in a fine-grained clay (mica) matrix.

To conclude the above made petrographic analysis of the Kimberley shales, Stead's (2016) classification table of the different types of shales, as shown in Table 13, was used to identify and classify these rocks as: **"clayey shales or clay-bonded shales"** containing more than 50% of clay-sized particles (<0.002mm) and being welded by the recrystallization of clay minerals in the matrix. The very fine-grained nature of these rocks, along with their exceptionally high clay (organic matter) content within the matrix material, supports this classification and leads to it being the most logic and common characterization of the Kimberley shales.

Table 13 - Shale classification table according to Stead (2016) and modified after Yagiz (2001).

Group	Name	Main Components
Compacted Shale	Clayey shale	Contain 50% or more clay-sized particles (< 0.002mm)
	Silty shale	Contain 25 - 45 % silt-sized particles
	Sandy shale	Contain 25 - 45 % sand-sized particles
	Black shale	Contain an abundance of organic-rich materials
Cemented Shale	Calcereous shale	Contain 25 - 35% $CaCO_3$
	Siliceous shale	Contain 70 - 85% silica
	Ferruginous shale	Contain 25 - 35% Fe_2O_3
	Carbonaceous shale	Contain 3 - 15% carbonaceous material (imparts toughness)
	Clay bonded shale	Welded by recrystallization of clay minerals

6.6 Geochemical analysis

After completion of a full geochemical investigation on the chemical composition of the Kimberley shales, which constitutes the reason for slope stability problems at the Kimberley "Big Hole" Mine, certain conclusions surrounding the exact chemical construct of these rocks as well as the most dominant clay mineral within their crystal lattice could finally be drawn. This was done by undertaking two basic geochemical tests on the Kimberley shales, which included a complete X-ray fluorescence (XRF) major element analysis as well as a complimentary X-ray diffraction (XRD) mineral phase analysis.

6.6.1 X-Ray Fluorescence (XRF) analysis

The bulk rock composition obtained from the XRF analysis for the two shale samples is shown in Table 14.

Table 14 - Whole rock (bulk) chemistry of two Kimberley shales by means of an XRF analysis.

Sample name	Al2O3 (%)	CaO (%)	Cr2O3 (%)	Fe2O3 (%)	K2O (%)	MgO (%)	MnO (%)	Na2O (%)	P2O5 (%)	SiO2 (%)	TiO2 (%)	L.O.I. (%)	Sum Of Conc. (%)
KBU1	16.91	0.58	0.01	6.54	2.43	1.55	0.05	0.64	0.08	52.01	0.79	16.43	98.01
KB2	17.59	0.57	0.02	6.54	2.63	1.62	0.05	0.62	0.08	52.13	0.81	15.45	98.11

Looking at the obtained XRF results from Table 14, it is clear that there are very little variations between the chemical structures of the samples and that both represent the same bulk rock chemistry. Both contain an average amount of silica (SiO_2) close to 52%, whilst being fairly enriched in aluminium (Al_2O_3), which can generally be ascribed to the high clay content of these rocks (seeing as clay minerals tend to have a lot more almunimium within their molecular structure than most other minerals). In terms of the most dominant clay mineral constituent within the chemical construct of the Kimberley shales, illite seems to fit the above mentioned compositional profile the best and would therefore be considered the most abundant (or most likely) clay mineral within the chemical structure of the Kimberley shales. In other words, when comparing the abovementioned XRF results, as an average of both shale samples, to the compositional profiles of the most common types of clay minerals as suggested by Pettersen (2014) and recreated by Botha (2015) (see Table 2), it shows that illite generally contains an average aluminium content of 17.02 % and an average silica content of 54.01%, which seems to fit the average compositional profile of both samples very well. The rest of the most common types of clay minerals, including montmorillonite, vermiculite and kaolinite could be eliminated based on their chemical compositions. The process of elemental and compositional elimination entails the process of eliminating the possibility of a mineral being present within the chemical structure of a rock by the mere fact that one of the most important (or critical) chemical compositions / elements needed to create such a mineral, is missing or lacking in presence and is therefore impossible to be the most dominant. The full XRF analysis as run by the Central Analytical Facility (CAF) of Stellenbosch University, along with the various standardizations is attached as Appendix C.

The reason for the sum total of each analysis being slightly less than a hundred percent (<100%), is because of the presence of Sulfur (S) in both samples. Unfortunately, sulfur does not form part of the major element analysis at CAF (Stellenbosch), which means that it was not accounted for during the calibration and calculation of the sum total for each sample. It is worth mentioning however, that even though sulfur did not form part of the major element components for this analysis, the sum total for each rock is still sufficiently close to a 100%, which means that the sulfur content for each rock must have been very small and therefore acceptable to exclude. It has no negative effect on the end result of the analyses in any way.

6.6.2 X-Ray Diffraction (XRD) analysis

In terms of the undertaken XRD analysis, both Figures 64 and 65 represent a count profile of the most dominant mineral phases within each individual sample. Various national (SARM, 2017) and international (NIST, 2017) standards were used to find a profile that best fits the original test profile of each sample and for each individual mineral constituent. It is evident, without further analysing the results, that there are two mineral constituents which seem to dominate within the crystal lattice of both samples. Both rocks seem to contain a considerable amount of quartz (as illustrated by the large red spikes) and to a lesser extent, although still in considerable amounts, potassium feldspar in the form of muscovite (as illustrated by the large blue spikes). In other words, the XRD analysis of both rock samples definitely seem to suggest that quartz and muscovite form the two most dominant mineral phases within the Kimberley shales, being much more abundant than any other mineral. This agrees with the high traces of silica (52%) and pottasium (2.5%) detected during the major element analysis of the associated XRF analysis. This is because if a rock contains a lot of quartz and pottasium felspar (such as muscovite for example), it will inevitably also contain a lot of potassium and silica within its chemical construct.

However, from both graphs (see Figures 64 and 65) many, not so fimiliar, mineral phases also make a contribution to the unique chemical composition of the Kimberley shales including minerals such as jarosite, hematitie and clinochlore (although it is worth mentioning that they were not represented in large quantities and mostly formed part of the matrix mineral phases). A specific reason for running an XRD analysis on two shale samples (in correspondence with the preceding XRF analysis), was to more accurately identify the phase of the most dominant clay mineral within the crystal lattice of the Kimberley shales, which would subsequently reveal a lot about its weathering properties and characterisitcs.

As a result, sample KBU1 showed a significant phase spike for the clay mineral illite, which seemed to fit the associated phase diagram best, whereas sample KB2 showed a phase spike that fit both the compositional profile of illite and kaolinite. However, seeing as only one sample (KB2) contained a profile spike for kaolinite, but both samples showed a match for the clay mineral illite, it was automatically assumed that illite probably forms the most dominant clay mineral within the chemical structure of the Kimberley shales as had already been determined and concluded by the abovementioned XRF results.

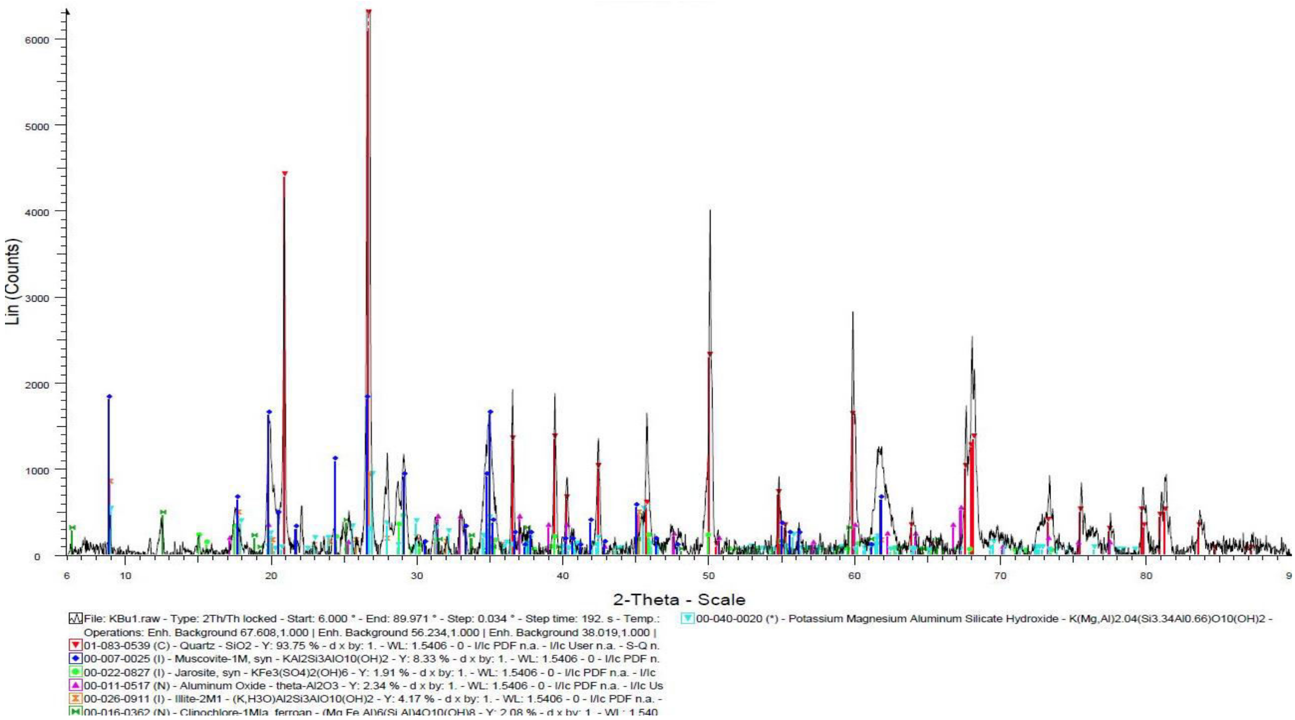


Figure 64 - XRD phase analysis for Kimberley shale sample - KBU1.

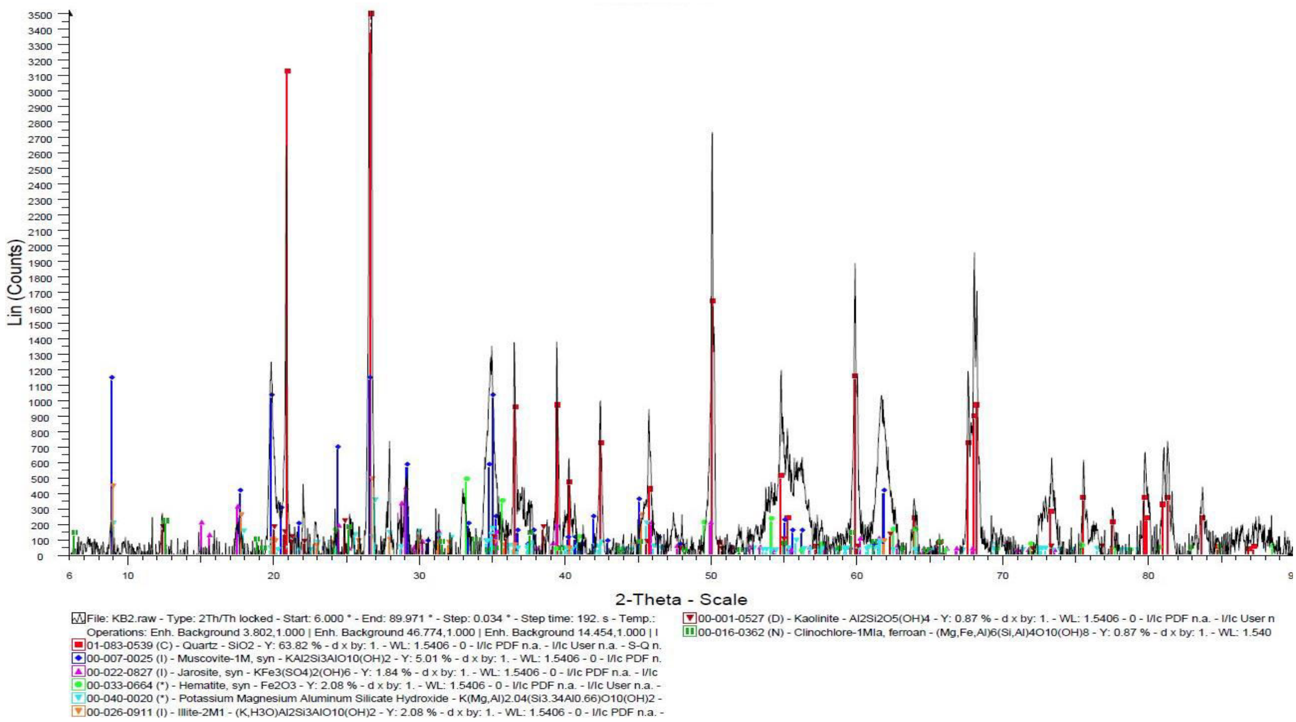


Figure 65 - XRD phase analysis for Kimberley shale sample KB2.

Both quantitative tests revealed an expected elemental shale composition and mineral phase diagram with average silica (SiO_2) contents of approximately 52% and slightly elevated aluminum (Al_2O_3) contents ranging between 16 – 17 % for the two tested shale samples respectively. This is slightly higher than what is normally expected for other types of rocks, such as sandstones or granites for example, which supports the evidence of the Kimberley shales being dominantly clay-bearing rocks and agrees with the associated petrographic analysis, which concluded the Kimberley shales to be identified and classified as "**clayey shales or clay-bonded** shales". Both geochemical analyses further suggests that the most dominant clay mineral within the crystal lattice of the Kimberley shales, which would account for the slightly enriched aluminum contents of these rocks, is best represented by the clay mineral Illite.

Illite, in nature, is generally known as a non-expansive clay mineral that undergoes the least (if any) amount of swelling and shrinkage when in contact with water / moisture. This is because of its basic 2:1 structural unit comprising of silicon-oxygen tetrahedra and an aluminum-hydroxyl octahedron, which causes the spaces between individual clay crystal sheets to be occupied by poorly hydrated and tightly held potassium cations (K+), which in turn is generally responsible for the overall absence of swelling when in contact with a fluid or moisture.

Compositionally, the presence of Illite within the chemical structure of the Kimberley shales accounts for the slight potassium enrichment as seen from the XRF analysis of both tested shale samples, more so than any of the other common types of clay minerals (such as montmorillonite or vermiculite for example) would have shown. Mineralogically, Illite is often compared to the potassium feldspar mineral known as *muscovite*, being only slightly more enriched in silica (Si), magnesium (Mg), iron (Fe) and water (H_2O) and they are therefore more often than not found to form together in the same rock. Focusing specifically on the associated XRD results, this accounts for the large muscovite peak within the mineralogical phase diagram of both shale samples, which suggests that muscovite forms a prominent constituent within the chemical construct of the Kimberley shales, fostering a close relationship with the clay mineral, Illite, as they seem to grow from the same chemical elements. In other words, the strong presence of muscovite within the phase diagrams of both rock samples (as indicated by the phase analysis of the associated XRD analysis) is usually a good indication for the presence of Illite within the same rock mass, which further supports the concluded results from the preceding petrographic analysis and XRF results about the most dominant clay mineral of the Kimberley shales.

In conclusion, other smaller and less significant elemental compositions as determined by the preceding XRF analysis, such as magnesium (Mg), calcium (Ca), iron (Fe), sodium (Na) and titanium (Ti) is thought to be divided and taken up unevenly between the other not-so-familiar mineral phases, such as jarosite [$KFe_3(SO_4)_2(OH)_6$], hematite [Fe_2O_3] and clinochlore [$(Mg, Fe, Al)_6(Si, Al)_4O_{10}(OH)_8$]. These minerals and chemical composition occur within the Kimberley shales to such a small extent that it does not have an immense effect on the stability and weathering properties of these rocks at all.

As to visually showcase the results of both XRD analyses for samples KBU1 and KB2 respectively, the following graph was created as an illustration of the results together with the presence of the most dominant mineral phases (see Figure 66):

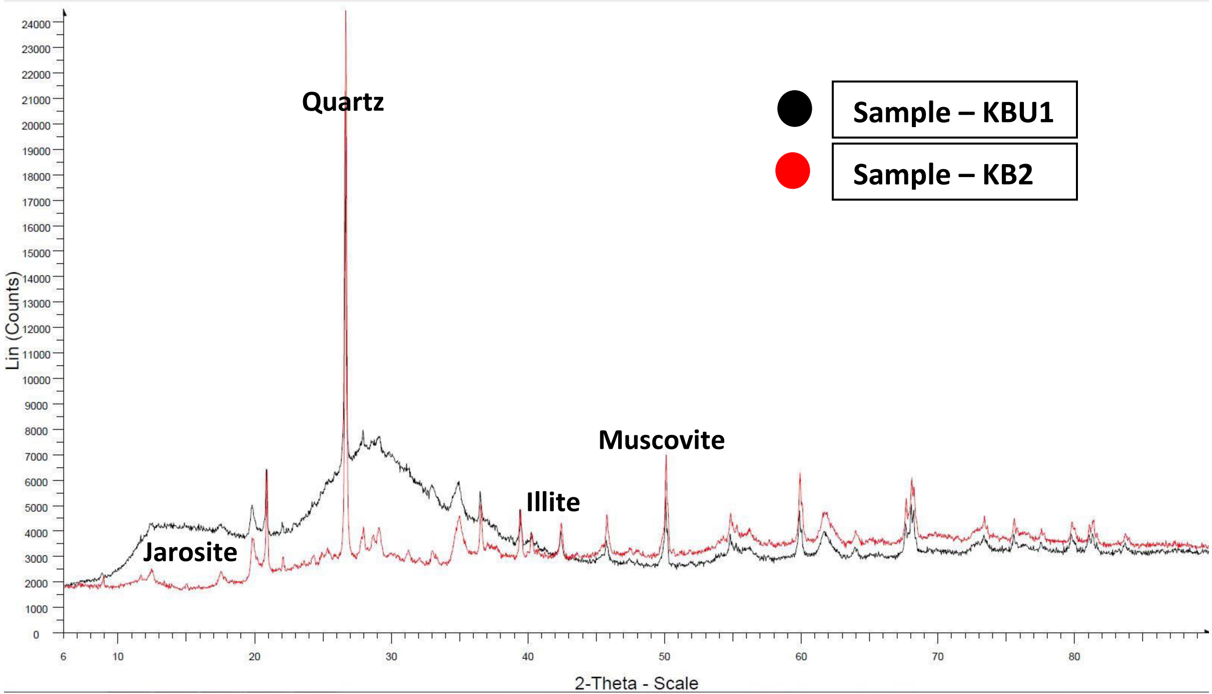


Figure 66 - Final XRD results for both analyzed Kimberley shale samples together with the presence of the most dominant mineral phases.

6.7 Absorption tests

As a dual function to accurately test the permeability characteristics of the Kimberley shales, as well as to identify which dust and erosion control liquid (DECL) product proved most successful in preserving the physical (both internal and external) characterisitcs of the rocks, the conducted absoprtion tests proved very insightfull and revealed promising results. The respective absorption tests, in which the samples were submerged for a period of fifteen mintues and thereafter for longer time intervals, not only revealed the Kimberley shale's water to body mass absorption ratio over a certain period of time if untreated, but it also identified a potential DECL product that can be used as a water repellent base to largely decrease the rock's permeability. Table 15 represents the obtained results for each individual absorption test corresponding to each individual DECL product used:

Table 15 - Total moisture intake (or absorption rate) for each sample batch during regularly timed intervals.

Sample:	Original batch weight (g):	Total absorbed weight as a function of time:														Average moisture intake per interval (g):	Total moisture intake after one week (%)	Remarks:
		After 15min (g):	After 30min (g):	After 1h (g):	After 2h (g):	After 4h (g):	After 8h (g):	After 16h (g):	After 1 day (g):	After 2 days (g):	After 3 days (g):	After 4 days (g):	After 5 days (g):	After 6 days (g):	After 7 days (g):			
Untreated	240	272	277	281	285	289	292	294	295	296	296	296	296	296	296	4	23.33	Samples completely disintegrated
NanoSil	275	279	282	286	286	287	287	287	287	287	287	287	287	287	287	0.86	4.36	No cracks - some dust
NanoBond	261	263	263	265	265	268	270	273	275	275	276	276	276	276	276	1.07	5.75	No cracks - clayey on the outside
NANO	257	259	260	264	264	265	265	266	266	267	267	267	267	267	267	0.71	3.89	No cracks
Sasbind	280	282	283	287	288	289	290	292	293	293	294	294	294	294	294	1	5.00	No cracks - some dust
Sasbind (+Bit)	260	263	267	272	273	274	274	275	276	276	277	278	278	279	279	1.36	7.31	No cracks

From the results obtained as tabulated above, the first significant conclusion that can be made with regards to the absorption properties and permeability characteristics of the Kimberley shales, if left untreated, is that they possess a great potential to absorb water / fluid over a very short period of time. In fact, they proved to be so permeable that the absorption test conducted for the untreated reference batch of the Kimberley shales, showed an increase in almost a quarter of its own body mass (56 grams equaling 23.33%) in only seven days, which suggest that these rocks are fairly permeable compared to other rock types and on average, absorp water at relatively high rates. This will subsequently have an effect on the internal strength parameters of the Kimberley shales and can be used to explain their high susceptibility to natural weathering processes including both physical and chemical weathering.

Their relatively permeable rock structure (as proven by the absorption test of an untreated reference batch) and their propensity to absorb water if left undrained or immersed, is undoubtedly the reason why the Kimberley shales will continue to weather and regress at an alarming rate by means of slaking and deterioration processes. Slaking and deterioration as both physical and chemical weathering agents, tend to exponentially increase / activate in the presence of a fluid and in humid climatic conditions, which is the conditions experienced during the summer months of November to February in the town of Kimberley. It was therefore of critical importance to examine and test the effects of different DECL products on the absorption characteristics of the Kimberley shales and to test whether they assisted in decreasing the rock's permeability and in turn delay the physical and chemical weathering process.

On average, the untreated reference batch absorbed 4 grams of moisture per interval, which is 1.67% of its original dry mass. This is 1.15% more than the highest average absorption rate per interval from any of the five DECL treated sample batches. The DECL products performed exceptionally well under the relevant absorption tests and showed very promising results in terms of decreasing the permeability properties of the Kimberley shales and in preserving the physical characteristics thereof, especially when comparing the results to the untreated reference batch.

Four of the five DECL products, that is, **NanoSil**, **NanoBond**, **NANO** and **Sasbind**, showed very similar results in terms of their overall moisture intake, ranging on average between only 3.89% and 5.75%, whereas one DECL product, namely **Sasbind (Bit)**, did not perform quite as well with an average moisture intake of 7.31%. This is slightly more than the rest, but still a great improvement compared to the untreated reference batch. The fact that all of the DECL treated sample batches showed a tremendous decrease in the average moisture intake when immersed in water for a certain period of time, is considered to be a successful outcome to this specific test and towards finding a proper solution for the defined slope stability problem at the Kimberley “Big Hole” Mine. It means that the DECL products were successful in their role to decrease the rock permeability characterisitcs of the Kimberley shales and to lower the absorption rate of these rocks. They are therefore also considered to be valuable products in delaying the weathering rate of the Kimberley shales when exposed to natural weathering conditions and in reducing the susceptibility of the shales to slake or disintegrate when immersed in water.

However, in order to identify which of the five DECL products proved most sucessful in their role as a water repellent base for the Kimberley shales, the results as calculated in Table 15 was graphically illustrated below in Figure 67 and shows the performance of each individual DECL product as a function of time and against an untreated reference batch.

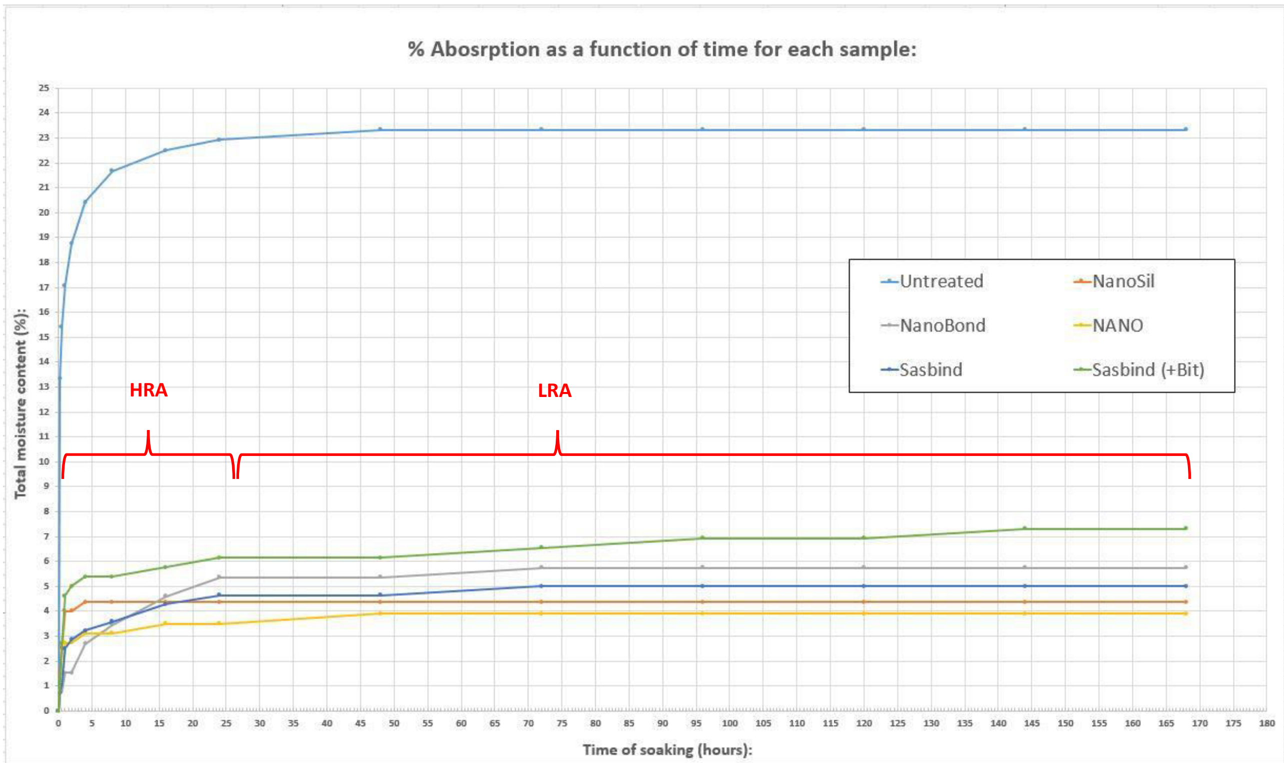


Figure 67 - Absorption rate as a percentage of the original dry mass for each DECL product and an untreated reference batch as a function of time. HRA – High Rate of Absorption; LRA – Low Rate of Absorption.

From the graph it is clear that for each individual absorption test as conducted for the purpose of this project, there was a period between approximately 0 and 25 hours (or 1 day) where rock lumps from each sample batch experienced most of their moisture intake (or absoprtion) compared to their original dry body mass, increasing between approximately 1% - 6% for the different DECL treated shale samples and 13% - 23% for the untreated reference batch. In other words, for the first ± 24 hours most of the rock samples managed to fill their pores with fluid (or water) to gain maximum permeability and this is considered the "*high rate of absorption (HRA)*" part of the curve. After filling their voids with water to become fully saturated, samples reached a plateau where their moisture intake / absorption rate remained fairly constant (i.e. weight measurements remained the same) as seen by the "*low rate of absorption (LRA)*" part of the curve.

The HRA part of the curve is therefore the section of interest for the purpose of this test, as it reveals most about the initial absoprtion resistance for each individual DECL product. According to the graph, all DECL products performed relatively well and managed to keep their initial rate of absoprtion to less than approximately 6% for the first 25 hours. However, the DECL product that proved to have the lowest initial absorption rate / moisture intake as well as kept the most constant profile (or weight) as time went on, was the DECL product named **NANO**.

NANO constitutes a combined mixture of the DECL products named **NanoBond** and **NanoSil**, which might explain its success in the resultant absorption tests. For the **NANO** product, an average moisture intake of 3.89% for the whole immersion period was documented and it managed to keep a constant weight throughout, which concluded the best performance of all five DECL products. Based solely on the trail of this absorption test, the order in which the respective DECL products performed in terms of decreasing the Kimberley shale's permeability and delaying water absoprtion through the surface of the rocks can be seen in Table 16.

Table 16 - Overall performance of the DECL products after completion of the absorption tests.

Rank:	DECL product:
1	NANO
2	Sasbind
3	NanoSil
4	NanoBond
5	Sasbind (+ Bit)
6	Untreated

These ranks were determined based on the average moisture intake (or absorption rate) for each indivudual DECL treated shale sample batch, as well as considering the results of the HRA part of each individual curve that indicated the respective DECL product's resistance to absorption and moisture intake. For instance, even though the **NanoSil** product graphically shows better results than the **Sasbind** product in terms of the *low rate of absorption* part of the curve, the initial HRA is slightly higher, resulting in a larger average moisture intake compared to its original body mass than expected. Based on the average moisture intakes as calculated above as well as looking at the HRA part of the curves, **NANO** still represent the most effective water repellent base and seems to decrease water absorption through the surface of the rock the best, hence also decreasing rock permeability most.

The visual evaluation of the individual rock lumps as described in Table 15, supports the concluded results exceptionally well seeing as rock lumps sprayed with **NANO** liquid were the only ones that did not exhibit any cracks on the surface of the rocks, nor any material lost in suspenion by means of slaking or disintegration.

6.8 Cyclic wetting and drying tests

As part of the shale durability and weathering resistance tests that were conducted for the purpose of finding a viable solution (i.e. a viable DECL product) for the defined slope stability problem at the Kimberley “Big Hole” Mine, a full scale cyclic wetting and drying test was also completed with the hope of better idintifying a suitable DECL product that could assisit in increasing the rock strength parameters of the Kimberley shales. The conducted cyclic wetting and drying tests proved to be an accurate method of measuring slaking and disintegration in the Kimberley shales when exposed to natural weathering conditions and when exposed to frequent wetting and drying cycles. The test was purely based on the rock’s behaviour when exposed to natural elements (such as heat, water and low temperatures) and introduced no other external factors such as mechanical aggitation (that was factored in to the following AWT and SDI tests) for example.

In other words, the respective cyclic wetting and drying tests for each DECL treated shale sample and an untreated reference sample, simulated the closest weathering conditions to that expereinced by surface rocks at the Kimberley “Big Hole” Mine and involved the longest test period out of all durability tests conducted for the purpose of this project, therefore also seen as probably the most accurate. The full scale weathering test, in the form of weekly wetting and drying cycles, was evaluated both quantitatively through weekly weight measurements in order to track mass / material loss and qualitatively through weekly visual inspections.

Before evaluating the results of the cyclic wetting and drying tests however (as done below), it is improtant to first note the practical importance of these tests on the rocks at the Kimberley “Big Hole” Mine, with specific reference to the Kimberley shales and the rate at which they weather / deteriorate. Only when a comparison between the test conditions of the cyclic wetting and drying tests and the actual weathering conditions at the Kimberley “Big Hole” Mine is drawn, can a direct correlation and conclusion be made towards the weathering (or deterioration) rate of the Kimberley shales and the impact it has on the defined slope stability problem. When comparing test conditions to actual weathering conditions experienced by rocks at the Kimberley “Big Hole” Mine, it is first and foremost important to note that test conditions were much more intense in terms of: 1.) Exposure to natural weathering elements / agents (such as wind, water, heat and low temperatures for example), being completely exposed to the atmosphere on a 24 hour basis and for a total of six months without any coverage. 2.) Exposure to a continuous cycle of wetting and drying, being wet once a week with 2 litres of water for a period of 6 months, equating to a total of 48 litres per sample. 3.) Smaller sample sizes of individual rock lumps, meaning that more of the surface area of each rock was exposed to the abovementioned conditions / elements, as oppose to an in-situ rock at the Kimberley “Big Hole” Mine that only has one surface exposed to the atmosphere and is protected from the sides and from below by a confining pressure.

Besides the fact that individual cyclic wetting and drying tests were more intens and focussed in terms of the direct conditions under which they were tested, each individual test was also accelerated by weekly cycles of wetting and drying, representing a simmulation of accelerated weathering conditions. In fact, to put this into perspective and to better understand the accelerated rate at which these tests were conducted compared to actual weathering conditions experienced by rocks at the Kimberley “Big Hole” Mine (under normal circumstances), the following calculations and conlusions were made:

Taking the average size and shape of all five DECL treated shale samples along with an untreated reference sample into account (which equates to an average surface area of apporxiamtely 572.98 cm^2 for each sample) and working back from the amount of water they were exposed to during the duration of the cyclic wetting and drying tests (i.e. 48 litres per sample), the average rainfall in milimeters (mm) experienced by the shale samples of the cyclic wetting and drying tests equates to an average of approximately 910 mm over a six month period. When considering the average precipitation values for the town of Kimberley, the average rainfall amount for the passing year (2016) adds up to approximately 602 mm per year or 301 mm for half a year (i.e. six months). Comparing this to the calculated amount of 909.92 mm for the test conditions of the cyclic wetting and drying tests, it becomes clear that the test was conducted at almost three times (x3) the average rainfall rate that would have been expected over the town of Kimberley for the same period of time. The cyclic wetting and drying test conditions can therefore be seen as highly accelerated when compared to the actual weathering conditions experienced around the general area of Kimberley and with specific focus on the Kimberley “Big Hole” mine, as it would require an enormous amount of rainfall over a very short period of time to get the same results in real life. The test was accelrated to this extent due to time constraints and for the purpose of testing each DECL product to its maximum potential and within the shortest period of time. The end goal was not to precisely simmulate actual weathering conditions over the town of Kimberley, but to determine which of the five DECL products would perform best under an accelerated and long term process of continuous wetting and drying. In terms of temperature conditions however, the average minimum and maximum temperatures recorded over the six month period of the cyclic wetting and drying tests were 13°C and 27°C respectively, whereas average minimum and maximum temperatures over the town of Kimberley during the first six months (from January to June) of this year was between 18°C and 33°C respectively. This means that the only factor that might have been slightly more intense in terms of the actual weathering condtions experienced by rocks at the Kimberley "Big Hole" Mine and test conditions experienced by rocks of the cyclic wetting and drying tests, would be the average temperature conditions that is slightly higher / warmer and more humid over the town of Kimberley, which would defintely spead up the process of slaking and disintegration and reciprocate weathering.

It is also worth mentioning that all cyclic wetting and drying tests were conducted over a full period of six months, except where complete slaking or disintegration of a sample occured before this time, then the test was stopped. The following table illustrates weekly weight (or material) loss of each DECL treated shale sample and an untreated reference sample, together with a visual indication of each pre-and post cyclic wetting and drying test (see Table 17).

Table 17 - Cyclic wetting and drying test evaluation.

	
Untreated shale sample	
Original weight: 4084g	**End weight: Unmeasurable**
First visual assessment (Week 0): No visual evidence of cracks or fractures on the surface of the rock (i.e. completely intact), although some evidence of flaking around the edges. Laminations run parallel to the surface of the rock and red / orange colour due to iron staining.	**Last visual assessment (Week 4):** Went through various stages of slaking and disintegration. First, during week 1, small cracks and fractures started to develop along the surface of the rock due to mobilization of its swelling and shrinkage potential, which initiated as a result of the wetting and drying cycle. During week 2, larger cracks and fractures started to form along the foliation planes of the rock. This initiated an even

	larger swelling and shrinkage potential, because as the sample started to break along its planes of weakness, it allowed more water ingress through the surface of the rock and subsequently, more weathering. Finally, during week 3, the whole rock started to slake and disintegrate into smaller rock fragments. Slaking seemed to precede the disintegration process and the rock first started to slake into smaller rock fragments of approximately 20mm. Thereafter, disintegration of the rock proceeded and chemically started breaking down the smaller rock fragments into even smaller fine particles of less than 20mm. The slaking and disintegration process however, seemed to occur hand-in-hand and left the rock completely broken down and deteriorated after only four weeks. In other words, in 4 weeks' time, the untreated shale sample had been entirely broken down (i.e. not intact anymore) and completely weathered into many smaller rock fragments of less than 20mm in size. It retained nothing of its physical characteristics and lost all of its original strength parameters, which is why the test was stopped before the full duration of the cyclic wetting and drying test procedure (i.e. six months). In other words, the test for an untreated reference batch only lasted up to four weeks before being terminated.

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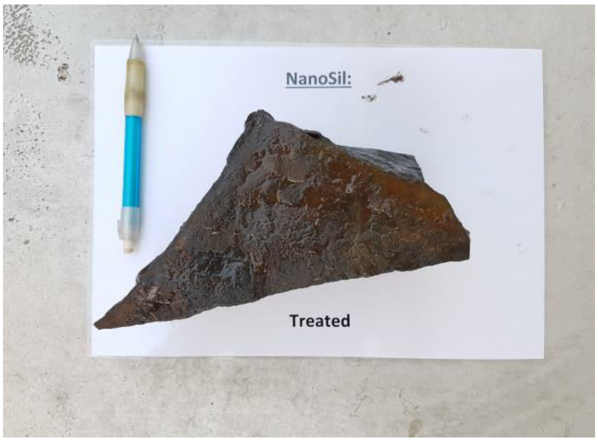
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Nanosil</td></tr>
<tr><td>Original weight: 1608 g</td><td>End weight: 1549 g</td></tr>
<tr><td>First visual assessment (Month 0):

No visual evidence of any crakcs or fractures on the surface of the rock. Laminations run parallel to the surface of the rock and the brown colour indicated in the image above is only due to application of the Nanosil product, causing the rock to darken in appearance.</td><td>Last visual assessment (Month 6):

During the first three months, no visual changes in the physical structure of the rock was observed (i.e. no cracks or fractures), which is a good indication that the Nansil product worked well against the wetting and drying cycle and offered enough weathering resistance for the rock to withstand natural weathering conditions. In other words, the Nanosil DECL product seemed to preserve the rock structure quite well for the first three months, before signs of weathering and deterioration started to show. During month 4, small cracks and fractures started to develop on the surface of the rock and only worsened over time until the rock was completely cracked through by the end of month six. Slaking and disintegration did play a part in the weathering and deterioration process of the Nanosil treated shale sample, although not as intens as was observed with the untreated shale sample. During month five, (after reasonable size cracks had already started to form on the surface of the</td></tr>
</table>

	rock and alongside the planes of weakness) the rock started to slake into smaller rocks fragments of approximately 20mm in size, which eventually broke off and weathered away. Disintegration was not really observed and if so, it was only noticed on a very small scale and to a lesser extent. After six months however, the Nanosil treated shale sample still largely remained intact and only exhibited large cracks and fractures through the body of the rock, cutting perpendicular to the lamination planes and leaving large size clasts of approximately 3 to 5cm behind. Total percentage material loss for the Nanosil treated shale sample, mostly due to slaking and to a lesser extent disintegration processes, equated to approximately 3.67%. This is not a lot compared to the untreated reference shale sample (above), but quite substanital when compared to the rest of the treated shale samples (below).

	
NanoBond	
Original weight: 3613g	**End weight: 3501g**
First visual inspection (Month 0):	**Last visual inspection (Month 6):**

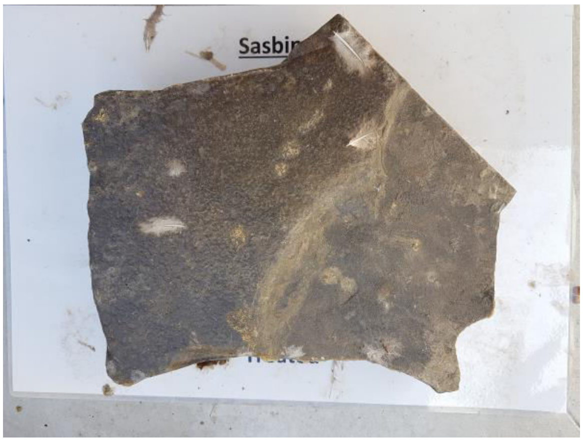
No visual evidence of cracks or fractures on the surface of the rock. Laminations run parallel to the surface of the rock. The applied NanoBond product is transparent in colour and caused the rock to attain a slight glow. No signs of weakness or flaking along the surface of the rock was observed.	During the first 5 months, no visual changes in the physical structure of the rock was observed. In other words, the rock remained completely intact and showed no signs of weathering or deterioration (i.e. no signs of cracks or fractures on the surface of the rock). Only during the last month of visual inspections (month 6), did the rock sample start to crack and fracture along one of its edges. Small cracks started to develop along the lamination planes of the rock, slowly growing into one large fracture as seen in the above illustrated image. The fracture developed and further propagated along the laminations of the rock, but did not propagate all the way through and at the end of month six, the rock was still intact. This is a very good representation of NanoBond's abillity to provide weathering resistance against a continuous cycle of wetting and drying and proved to be very effective in preserving the physical structure of the rock, as well as in enhancing general rock durability. No signs of slaking or disintegration were observed throughout the six month monitoring period and it could therefore be concluded that the NanBond DECL product was successful in slowing down the weathering processes of slaking and disintegration. Total percentage material loss for the NanoBond treated shale sample after six months of wetting and drying equated to approximately 3.01%. This is slightly better in terms of what was calculated for the material loss of the abovementioned NanoSil treated shale sample, although still not as good / effective as the rest of the treated shale samples

	(discussed below). The reason for material loss in this specific case and which seems to contrast the reasons for material loss of the previously discussed NanoSil treated shale sample (i.e. slaking and disintegration), is that eventhough the NanoBond treated shale sample showed very little to no evidence of slaking or disintegration, the rock still fractured along one of its planes of weakness as a result of temperature fluctuations. It is thought that constant temperature changes (i.e. maximum and minimum temperatures) were responsible for the NanoBond treated shale sample to swell (or expand) and shrink on a regular basis, causing an already formed plane of weakness in the rock, such as a bedding plane for example, to slowly open up (or crack) and expand. This, in turn, allowed for more water ingress through the surface of the rock as time went on and eventually allowed to rock to successively fracture into smaller rock fragments. In other words, the reason for material loss in the NanoBond treated shale sample is not directly related to the ineffectiveness of the NanoBond DECL product to prevent water ingress / absorption through the surface of the rock, but more with the shale sample itself and its reaction towards constant climatic (or temperature) changes. The opinion is still that the NanoBond DECL product served its purpose in providing a waterproof coat around the treated shale sample and that fracturing, as a result of swelling and shrinkage in response to constant temperature changes, is what eventually caused the rock to

	weather and deteriorate.

 	
NANO	
Original weight: 5363g	**End weight: 5321g**
First visual inspection (Month 0): No visual evidence of cracks or fractures on the surface of the rock with laminations running parallel to the surface. The white speckled appearance, as seen in the above illustrated image, is only as a result of the applied NANO DECL product. No signs of weakness (i.e. cracks or fractures) nor flaking were observed along the surface or the edges of the rock and the sample remained completely intact prior to commencement of the test.	**Last visual inspection (Month 6):** After 6 months of continuous wetting and drying and exposure to natural weathering conditions (such as heat, wind and low temperatures), no visual changes in the physical structure of the rock was observed. In other words, the physical rock structure remained completely unchanged and no signs of weakness (i.e. cracks or fractures) were observed on the surface of the rock. This lead to the conclusion that the NANO DECL product worked exceptionally well towards providing enough weathering resistance for the Kimberley shale sample to withstand the effects of cyclic wetting and drying and as a result, no physical evidence of slaking or disintegration were observed at all. The NANO DECL product enhanced rock durability to such an extent that the respective (shale) rock sample remained completely intact and showed no clear signs

	of material loss or deterioration. It can therefore be concluded that the NANO DECL product effectively opposed the effects of slaking and disintegration of the Kimberley shales when exposed to natural weathering conditions and a continuous cycle of wetting and drying. According to this specific cyclic wetting and drying test, the NANO DECL product can be seen as representing a (possibly) viable DECL product to be used for the defined slope stability problem at the Kimberley "Big Hole" Mine and is worth further investigation. Eventhough no changes or signs of weakness were observed in the physical structure of the rock during the duration of the test, material loss still occurred and even if only to a small extent, it is still worth mentioning. Material loss for the NANO treated shale sample equated to approximately 0.78%, which is very small especially when compared to the material loss of the first three samples. This small amount of material loss can most likely be asribed to other weathering agents / elements such as erosion of the surface of the rock due to wind or the interaction of water with the surface of the rock causing small sand sized particles to break off and wash away. However, material loss for the NANO treated shale sample was so insignificantly small that the reasons therefore will not be discussed any further.

	
Sasbind	
Original weight: 2531g	**End weight: 2510g**
First visual inspection (Month 0): No visual evidence of cracks or fractures on the surface of the rock with laminations running parallell to the surface. The white translucent appearance, as seen in the above illustrated image, is only as a result of the applied Sasbind DECL product. No signs of weakness (i.e. cracks or fractures) nor flaking were observed along the surface or the edges of the rock and the sample remained completely intact prior to commencement of the test.	**Last visual inspection (Month 6):** After 6 months of continuous wetting and drying and exposure to natural weathering conditions (such as heat, wind and low temperatures), no visual changes in the physical structure of the rock was observed. In other words, the physical rock structure remained completely unchanged and no signs of weakness (i.e. cracks or fractures) were observed on the surface of the rock. This lead to the conclusion that the Sasbind DECL product worked exceptionally well towards providing enough weathering resistance for the Kimberley shale sample to withstand the effects of cyclic wetting and drying and as a result, no physical evidence of slaking or disintegration were observed at all. The Sasbind DECL product enhanced rock durability to such an extent that the respective (shale) rock sample remained completely intact and showed no clear signs of material loss or deterioration. It can therefore be concluded that the Sasbind DECL product effectively opposed the effects

	of slaking and disintegration of the Kimberley shales when exposed to natural weathering conditions and a continuous cycle of wetting and drying. According to this specific cyclic wetting and drying test, the Sasbind DECL product can be seen as representing a (possibly) viable DECL product to be used for the defined slope stability problem at the Kimberley "Big Hole" Mine and is worth further investigation. Total percentage of material loss for the Sasbind treated shale sample equated to 0.83% and is considered to have occurred due to the same processes as explained for the previous sample. Material loss for both the NANO treated shale sample, as well as the Sasbind treated shale sample was so insignificantly small that the reasons therefore will not be discussed any further.

<table>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Sasbind (+Bit)</td></tr>
<tr><td>Original weight: 3753g</td><td>End weight: 3727g</td></tr>
<tr><td>First visual inspection (Month 0):
No visual evidence of cracks or fractures on the surface of the rock with laminations</td><td>Last visual inspection (Month 6):
After 6 months of continuous wetting and drying and exposure to natural weathering</td></tr>
</table>

running parallell to the surface. The dark brown colour of the rock, as seen in the above illustrated image, is only as a result of the applied Sasbind (+Bit) DECL product. No signs of weakness (i.e. cracks or fractures) nor flaking were observed along the surface or the edges of the rock and the sample remained completely intact prior to commencement of the test.	conditions (such as heat, wind and low temperatures), no visual changes in the physical structure of the rock was observed. In other words, the physical rock structure remained completely unchanged and no signs of weakness (i.e. cracks or fractures) were observed on the surface of the rock. This lead to the conclusion that the Sasbind (+Bit) DECL product worked exceptionally well towards providing enough weathering resistance for the Kimberley shale sample to withstand the effects of cyclic wetting and drying and as a result, no physical evidence of slaking or disintegration were observed at all. The Sasbind (+Bit) DECL product enhanced rock durability to such an extent that the respective (shale) rock sample remained completely intact and showed no clear signs of material loss or deterioration. It can therefore be concluded that the Sasbind (+Bit) DECL product effectively opposed the effects of slaking and disintegration of the Kimberley shales when exposed to natural weathering conditions and a continuous cycle of wetting and drying. According to this specific cyclic wetting and drying test, the Sasbind (+Bit) DECL product can be seen as representing a (possibly) viable DECL product to be used for the defined slope stability problem at the Kimberley "Big Hole" Mine and is worth further investigation. Total percentage of material loss for the Sasbind (+Bit) treated shale sample equated to a mere 0.69%, which is the smallest amount of material loss calculated for all five DECL treated shale samples, uncluding the untreated reference sample. The fact that

	material loss for this specific sample was so small and the fact that reasons therefore can only be suggested, means that it will not be discussed any further as it is insignificant.

After completion of the respective cyclic wetting and drying tests as conducted for each DECL product and an untreated reference sample of the Kimberley shales, the visual inspections and mass determinations (as desribed and discussed above for each shale sample) rendered some interesting and worthwhile results. According to the cyclic wetting and drying test of an untreated shale sample , the rock will not withstand the effects of natural weathering conditions, especially if confronted with a continuous cycle of wetting and drying. The untreated shale sample only managed to retain its physical (rock) structure for approximately 4 weeks before completely weathering and deteriorating to an unstable state. In other words, after only four weeks, it had completely lost its durability and weathering resistance to the processes of slaking and disintegration, to such an extent that it became unmeasurable. First, slaking and then disintegration completely dominated the rock sample until the rock was completely broken down and weathered into smaller rock fragments (~20mm) and even smaller finer-sized particles (≤ 20mm). The rock lost all support characteristics and proved completely invaluable after commencement of the test.

Of the five DECL treated shale samples, two DECL products proved less effective than the rest namely NanoSil and NanoBond. Both NanoSil and NanoBond DECL products showed an improvement towards rock durability and weathering resistance for the Kimberley shales, but only to a certain extent. After a short period of time, cracks started to form and both rock samples started to weather and deteriorate through the processes of slaking and (to a lesser extent) disintegration. After six months of subjecting the rock samples to a simulation of long term weathering conditions, by continuously wetting and drying them, the NanoSil treated shale sample lost 3.7% of its original dry mass through slaking and disintegration processes and the NanBond treated shale sample 3.1%. Although this does not seem like a lot of material / mass loss, especially when compared to the untreated reference sample, it is still significantly more than that experience by the other three DECL treated shale samples and can be seen as “unsatisfactory” or “unsuccessfull” results in terms of the undertaken cyclic wetting and drying tests.

The other three DECL products, namely NANO, Sasbind and Sasbind +(Bit), proved to be much more effective in combatting the effects of natural weathering conditions and a continuous cycle of wetting and drying as no traces (or evidence) of slaking and disintegration were observed at either of the repsectively treated shale samples. In other words, all three samples remained completely intact and showed very little to no signs of material loss or disintegration. In fact, after six months of testing, NANO, Sasbind and Sasbind (+Bit) treated shale samples only indicated mass loss of 0.8%, 0.8% and 0.7% respectively. This, combined with the visual assessments, proved that the NANO, Sasbind and Sasbind (+Bit) DECL products were exceptionally effective towards increasing rock durability and weathering resistance of the Kimberley shales, to such an extent that all three rock samples remained completely intact. Thus, either one (i.e. NANO, Sasbind, Sasbind (+Bit)) might possibly be used as a viable solution towards the defined slope stability problem at the Kimberley "Big Hole" Mine and would be advised for further testing and investigation.

The reasons for the difference in performance / effectiveness between the "Nano" DECL products (i.e. NanoSil & NanoBond) and the "Sasbind" DECL products (i.e. Sasbind & Sasbind + Bit) as discussed above, might involve the fact that these products are made of slightly different chemical constructs. According to the safety and hazard reports of both the "Nano" and "Sasbind" products, the only noticeable difference between the two is that the "Sasbind" DECL products are made up of a string of acrylic **polymers**, whilst the "Nano" DECL products are made up of a combination of acrylic **coplymers**. To explain the difference between an acrylic polymer and an acrylic coploymer, a brief description / definition of the words "polymer", "monomer" and "acrylic" will first be provided:

- A "polymer" is a large molecule (or macromolecule) that is composed of many repeating sub-units (or micromolecules).
- A "monomer" represents one of these sub-units that are used to create a ploymer. In other words, it is a smaller molecule (or micromolecule) that, if bonded together with other identical molecules, forms a polymer.
- "Acrylic" refers to a group of polymers which can generally be referred to as plastics. They are noted for their transparency, resistance to breakage and elasticity.

Thus, the difference between an acrylic polymer and an acrylic copolymer is that an acrylic polymer is made by linking only one type of identical molecule (or monomer) together, whilst an acrylic copolymer is made by joining two different types of molecules (or monomers) to the same polymer chain. In other words, polymers generally represent a much more pure type of monomer chain, containing only one type of monomer (A) that is identic in every way. This is graphically illustrated below by showcasing mutiple molecular bondings between only one type of monomer, named (A) for this example:

A-**A**-A-**A**-A-**A**-A-**A**-A-**A**-A

Acrylic polymer

Copolymers on the other hand, usually represent much large polymer chains with alternating sub-units of monomers (A & B). This might cause them to be slightly weaker than their polymer counterparts, in the sense that they have weaker bondings between alternating molecules. However, this is not always the case as it is very dependant on the type of molecules within the chain. A basic example of an alternating acrylic copolymer is illsusrated below with two different types of monomers namely A and B for this example:

A-**B**-A-**B**-A-**B**-A-**B**-A-**B**-A

Alternaring acrylic copolymer

This might be a possible reason why the "Nano" DECL products performed less effective in the conducted cyclic wetting and drying tests than their "Sasbind" DECL counters, as their chemical construct is made up of acrylic copolymers instead of acrylic polymers. It is generally assumed that acrylic copolymers would lose their inner molecular bondings much quicker when exposed to an external aggitation, such as water or heat for example, due to their alternating monomer structure. Acrylic polymers on the other hand, will presumably have closer inner molecular bondings with identical monomers that are held more tightly, hence resisting weathering and deterioration much easier. Although this is only a speculation towards the reason for a difference in performance / effectiveness between the "Nano" DECL products and the "Sasbind" DECL products after the conducted cyclic wetting and drying tests, further research on this matter is recommended and beyond the scope of this project, which is why it will not be discussed any further.

Another possible reason for the "Nano" DECL products performing slighty worse in the conducted cyclic wetting and drying tests than their "Sasbind" DECL counterparts, especially in terms of exhibiting weathering resistance and increased durability against frequent wetting, might be ascribed to the disintegration or dissolution of the "Nano" DECL liquids themselve, which would have required a re-application procedure. The fact that the "Nano" treated shale samples, changed surface colour from dark (after application) to pale (a few weeks into testing), might indicate that the "Nano" DECL products started to disintegrate or fade away, causing the rocks the slowly become less waterproof and allow for more water ingress through the surface of the rock. This would have prompted the application of another layer (or coat) of the "NANO" DECL products to the surface of the rocks as to ensure it remains completely waterproof. Eventhough the health and safety reports of both the "Nano" and "Sasbind" DECL products suggested that the various liquids be applied on a 2 to 4 basis, meaning between 2 and 4 coats with the coat thickness not specified, it is logically assumed that the more coats applied to the surface of the rock, the better its weathering resistance and overall durability. As had previously been mentioned in Chapter 5 (i.e. Section 5.2.3), due to cost limits and time constraints associated with this project, only two layers or coats of each DECL product was applied to the surfaces of the shale samples for each respective durability and weathering test. According to the health and safety reports for each DECL product, the application of two layers or coats should be sufficient enough (as a minimum requirement) to last a lifetime after application assuming no mechanical / external agitation to the surface it is applied to. This is why two coats of each DECL product to the surfaces of the test samples was considered sufficient enough to obtain the necessary results, keeping the cost factor of each DECL product in mind. Unfortuantley, within the scope of this project, it was also not possible to measure whether the applied DECL products started to disintergrate / wash off after a certain period of time based on their applied thicknesses and therefore the abovementioned theory could only be sugessted and assumed.

6.9 Comparative accelerated weathering tests

As oppose to the cyclic wetting and drying and the slake-durability index (SDI) test as discussed above and below respectively, the accelerated weathering test (AWT) simulated a relatively long term weathering process in the form of continuous wetting and drying cycles along with some extent of mechanical aggitation. It managed to not only compare the durability and weathering resistance of all five DECL products and an untreated reference batch against the effects of wetting and drying conditions and mechanical aggitation, but it also managed to equate the effectiveness of the five different DECL products against one another as to determine which proved most successful in terms of increasing rock durability and weathering resistance and would subsequently also be used as the "test" DECL product in the following SDI test.

Table 18 showcases the results of the comparative accelerated weathering tests, including the original dry mass of each sample batch, the total mass in grams of the degraded and residual material after completion of the third and final cycle of wetting and drying as well as the calculated percentages of the total degraded and residual material left in the respective bins after completion of the test. The percentage degradation and retained material in the bins were calculated by taking the total of the each respective mass category and comparing it to the original dry mass, for example, the percentage degradation for the Nanosil product was calculated by dividing the total amount of degraded material in grams (183g) by the original dry mass of the same sample batch (199g) and multiplying it by a hundred (x100%) to get the total percentage of degraded material. These calculations were repeated for each sample batch and for each respective category.

Table 18 - Total percentage of degraded and residual material after the third wetting and drying cycle of the accelerated weathering test, also including remarks on the visual state of the rocks post completion.

Sample:	Original dry mass (g)	Degraded after third cycle (g):	Residual after third cycle (g):	Percentage degraded (%):	Percentage retained in bin (%):	Visual inspection of rock lumps after testing
Untreated	244	237	0	**97.13**	**0**	Completely disintegrated & dissolved into silt sized particles (i.e. lost in suspension)
NanoSil	199	183	10	**91.96**	**5.03**	Waste - intact (i.e. little suspension)
NanoBond	244	212	22	**86.89**	**9.02**	Waste - failry intact (i.e. little suspension)
NANO	273	234	27	**85.71**	**9.9**	Waste - failry intact (i.e. little suspension)
Sasbind	249	163	70	**65.46**	**28.12**	Waste - mostly suspension
Sasbind (+Bit)	220	170	45	**77.27**	**20.46**	Waste - failry intact (i.e. little suspension)

From the results, it could once again be concluded that the DECL treated shale samples performed much better in terms of exhibiting weathering resistance and overall durability against mechanical agitation than the equivalent untreated reference batch. In fact, the untreated reference batch did not even surpass the first wetting and drying rotation and failed to deliver any residual material in the bin after the first cycle. In other words, 97.13% of the original rock mass was degraded during the first wetting and drying period, whilst the rest of the sample was unmeasruably lost in suspesion. Thus a second and third wetting and drying cycle could not be performed on the untreated reference batch.

This means that without any prior treatment, individual (shale) rock lumps had no resistance or protection against the effects of mechanical aggitation that was experienced during commencement of the test and that they remained extremely susceptible to the processes of slaking and disintegration (to such an extent that all of the untreated rock lumps degraded to a particle size of less than 20mm). The results of the untreated reference batch therefore suggests that the absence of a water repellent coat / base around the surface of the rock to bind soil and mineral particles together, will only cause clay minerals (such as illite for example) to more easily absorb water and undergo internal shrinkage and swelling, even if only to a small extent. This non-durable behaviour will cause the same rocks to fracture and crack along their planes weakness (i.e. cleavage planes / foliations) and become more permeable, which in turn allows more water to infiltrate the surface of the rock and eventually speed up the process of deterioration and breakdown. In the same sense, mechanical agitation is also much more likely to cause soil and mineral particles on the surface of the rock to become unstable and eventually erode (i.e. suspension) if not protected and bound by an outer synthetic coat or layer such as represented by the DECL products. Particles tend to loose cohesion quickly when saturated or in contact with water (or a fluid), which is why the untreated reference batch lost all of its mass / material within the first wetting and drying period. There was no outer syntheitic coat / layer (which acted as a water repellent base or a particle-binder) to protect the rocks against the combined effects of water infiltration and mechanical aggitation, hence the untreated reference batch losing more than 90% of its original rock mass during the first wetting and drying period.

All of the DECL treated shale samples on the other hand, made it to the end of the third wetting and drying cycle with some (although in some cases not a lot) residual material left in the bins, which in essence itself is considered a very successful outcome to the viability and effectiveness of using DECL products to help combat the vast breakdown and deterioration of the Kimberley shales under natural weathering conditions and mechanical aggitation. Even though all five DECL sample batches still showed evidence of slaking and disintegration of individual rock lumps to a certain extent, some proved less so than others. Of the five DECL products used during the procedure of this test, **NanoSil** seemed to have delivered the worst results in terms of preserving rock mass against mechanical agitation and continuous wetting and drying. It retained only 5.03% of the original rock mass with which the test was started and delivered an extremely high percentage of degraded material at 91.96%, meaning that it still left individually treated rock lumps relatively susceptible to the processes of slaking and disintegration. **Sasbind** on the other hand, proved to be most successful and effective in terms of preserving individually treated rock lumps as it retained 28.12% of the original rock mass after the third long term wetting and drying cycle and contained the least percentage of degraded material at only 65.46%. This means that the DECL product, **Sasbind**, combatted the respective effects of slaking and disintegration most successfully and acted as a suitable product to increase rock durability and weathering resistance against mechanical aggitation and wetting and drying conditions.

Unfortunately, due to the external influence of mechanical agitation that was factored in during the conduction of these tests (i.e. rotation of the bins), it is worth mentioning that there was no way of comparing the test conditions experienced by each sample batch for the accelerated weathering tests to the actual conditions experienced by rocks at the Kimberley “Big Hole” Mine. In other words, the comparative accelererated weathering tests, as conducted for the purpose of this project, was purely aimed at contrasting and comparing the performance and effectiveness of the applied DECL products against one another and an untreated reference batch. It was purely a comparative study as to see which of the five DECL product prevailed after three cycles of wetting and drying with the external influence of mechanical agitation taken into account.

As for the remaining DECL products and as illustrated on the graph in Figure 68, **Sasbind (+ Bit)** managed to preserve 20.46% of the original rock mass after the third weathering cycle of the accelerated weathering test, whereas the **Nano** products in general (including **NanoBond** and **NANO**), prevailed to a lesser extent preserving only approximately 9% of the original rock mass on average.

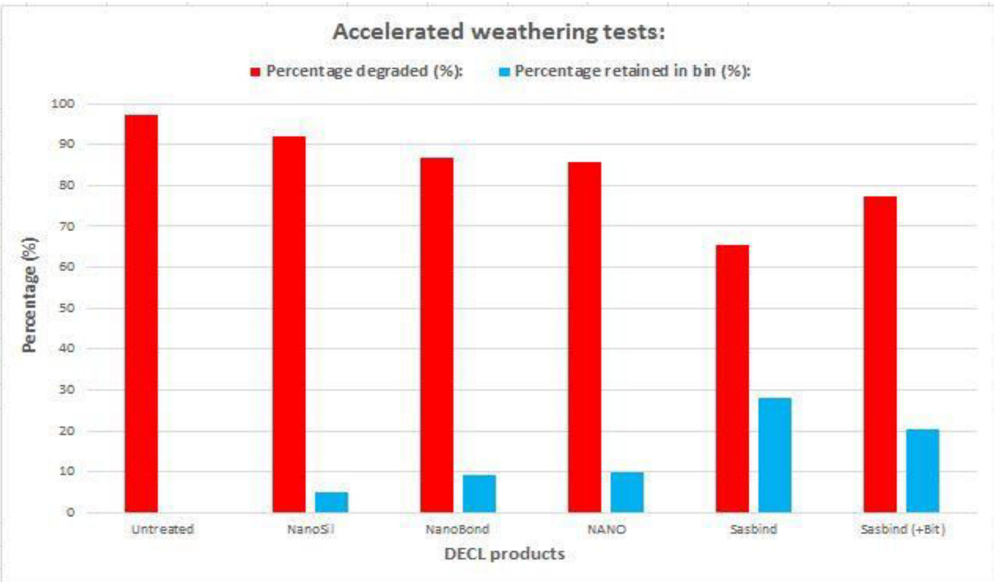


Figure 68 - Graph depicting the total degraded versus retained rock material after the third wetting and drying cycle of each respective accelerated weathering test for the five different DECL products and an untreated reference batch.

The compiled data sheet for each absoprtion test as conducted for the purpose of this project therefore seem to suggest that the **Sasbind** DECL products in general (including **Sasbind** and **Sasbind + Bit**) are much more effective in preserving shale (rock) material against natural weathering conditions and mechanical aggitation than the **Nano** (including **NanSil**, **NanoBond** and **NANO**) DECL counterparts. The **Sasbind** DECL products seem to form much more of a protective, water repellent coat / layer around the surface of the rock, allowing less mechanical aggitation and water infiltration to take place by binding closer and stronger to the the individual soil / mineral particles on the surface of the rocks than did their **Nano** DECL counterparts.

The reason for this might be ascribed to the fact that after the two-coat-application of the DECL products to each respective sample batch, the “Sasbind” DECL products in general seemed to have a thicker protective and waterproof surface coat / layer around them, than what was observed for the “Nano” DECL counterparts (i.e. due to one product being thicker in nature than the other). In fact, the “Nano” DECL products seemed much more water soluble, which means that the thinner surface coat / layer might have been more easily disintegrated by mechanical agitation experienced by the rotation of the bins, than was the thicker protective coat of the “Sasbind” DECL counterparts, which seemed to have lasted longer, hence proving more durable. Logically, the thicker the protective waterproof coat around the surface of the rock, the stronger its weathering and water resistant properties and the more durable the rock. In affect, both the “Sasbind” and “Nano” DECL products should remain unchanged throughout its application lifetime, with both product’s hazard and safety reports claiming a two to four coat application is sufficient enough to last a lifetime. However, these reports did not take mechanical agitation into account, which might be the reason for, especially, “Nano” DECL products to show a fair amount of weathering and deterioration through the duration of these tests. It is therefore recommended that whatever the application procedure, a frequent re-application of the products is necessary, just to be safe. In essence and as previously mentioned, the thicker the protective coat from the DECL product, the more water and weather resistant the rock. In other words, varying thicknesses of the DECL coating will effectively either improve or reduce the water resistance of the surface it is applied to and will also influence the period of time it will remain on the surface of the rock before a fresh coat is needed.

The reason for the successful outcome of this test and for an overall improvement in rock durability and weathering resistance of the Kimberley shales when treated with a DECL, is because of the water repellent and soil-binding properties associated with these products. In general, the application of a DECL product (either one) to the surface of a rock creates a water repellent base (for the most part), which allows very little water / fluid infiltration through the surface of the rock and therefore preserves the chemical structure of the internal clay minerals to a certain degree. By decreasing water infiltration, the effects of swelling and shrinkage on clay minerals such as illite for example is reduced, which leads to less fracturing and cracking of the orginal rock mass. It also binds soil particles closer to the surface of the rock, diminishing the overall effects of mechanical aggitation and leaves soil particles intack, which ultimately decreases rock durability.

In support of these results, a visual inspection of each sample batch was also undertaken pre- and post procedure as to visually evaluate and determine which of the DECL products performed best in preserving the physical structure of the Kimberley shales. The following visual illustration therefore represents the individual rock lumps for each sample batch as seen pre-and post procedure along with a quick evaluation:

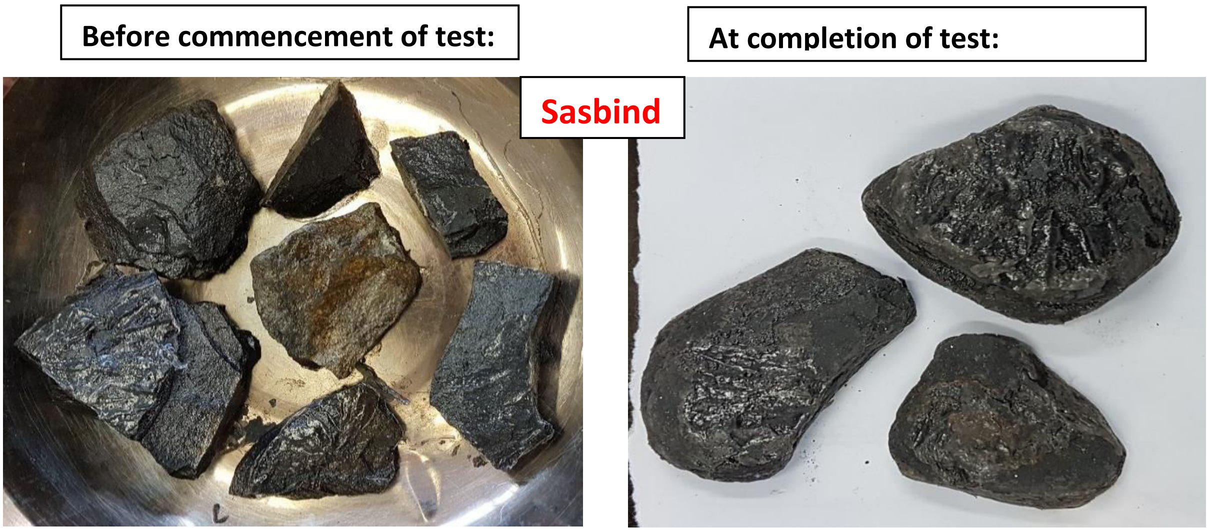


Figure 69 - Visual representation of Sasbind-treated shale rock lumps pre- and post-accelerated weathering test.

Sasbind-treated shale samples showed very little (or the least) physical breakdown and weathering compared to other sample batches and much of the material collected in the container underneath the basket throughout the test was in the form of finer-sized particles (or rock fragments ≤ 20mm) that had degraded through mechanical interaction with the surface of the apparatus and other lumps of rock. In general, the **Sasbind**-treated shale lumps remained in an angular form, but were rounded at the edges.

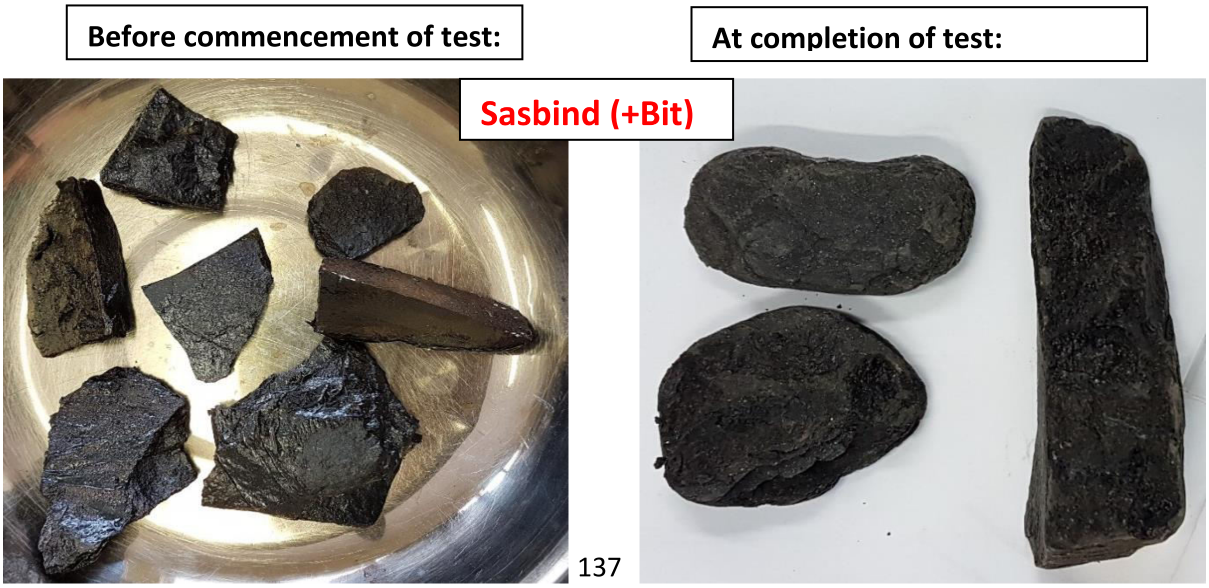


Figure 70 - Visual representation of Sasbind (+Bit)-treated shale rock lumps pre- and post-accelerated weathering test.

Like **Sasbind**-treated shale samples, **Sasbind (+Bit)**-treated shale samples also showed very little breakdown and deterioration and much of the material recovered in the container under the Sasbind (+Bit) bin conisted of angular fragments of rock material with a dusty appearance. The **Sasbind (+Bit)**-treated rock lumps also remained angular and rounded at the lump edges.

Before commencement of test: | **At completion of test:**

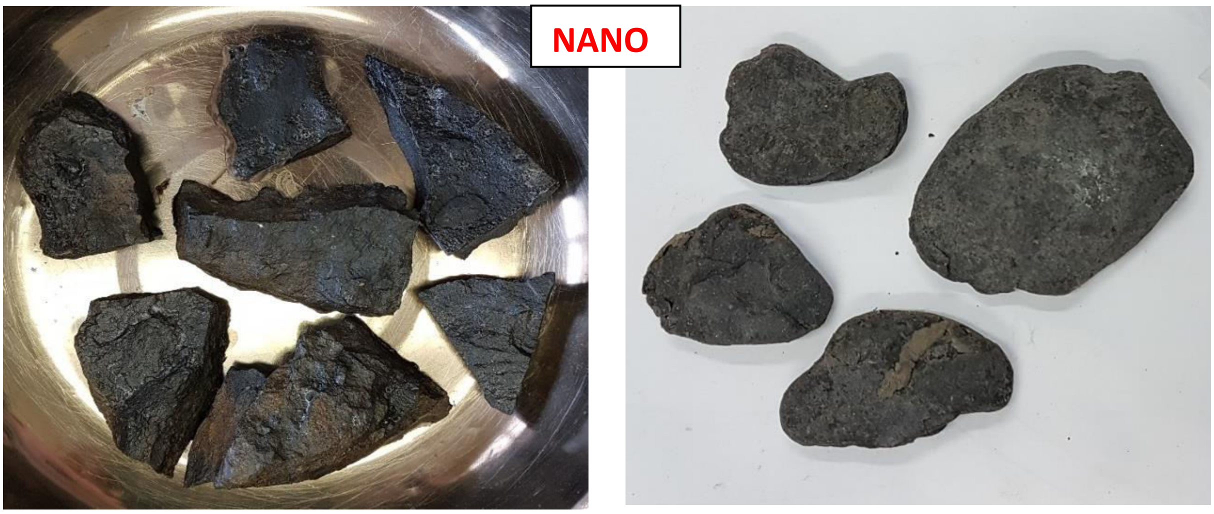


Figure 71 - Visual representation of NANO-treated shale rock lumps pre- and post-accelerated weathering test.

Nano-treated shale samples proved considerably less durable than **Sasbind**- and **Sasbin (+Bit)**-treated shale samples showing an increase in physical breakdown and weathering of individual rock lumps and much of the material collected in the container underneath the basket consisted of larger flaky pieces of rock material along with sand-sized particles in suspension. The **Nano**-treated shale lumps generally lost their angular form and progressed from being angular in appearance to rounded small-to-medium sized pebbles, many of which were small enough to fall out of the bin (< 20mm) and into the container.

Before commencement of | **At completion of test:**

Figure 72 - Visual representation of NanoBond-treated shale rock lumps pre- and post-accelerated weathering test.

Like **Nano**-treated shale samples, **NanoBond**-treated shale samples also showed very similar breakdown and weathering characteristics, following the same progressive trend from angular rock lumps, to small-and-medium sized pebbles that were rounded at the edges.

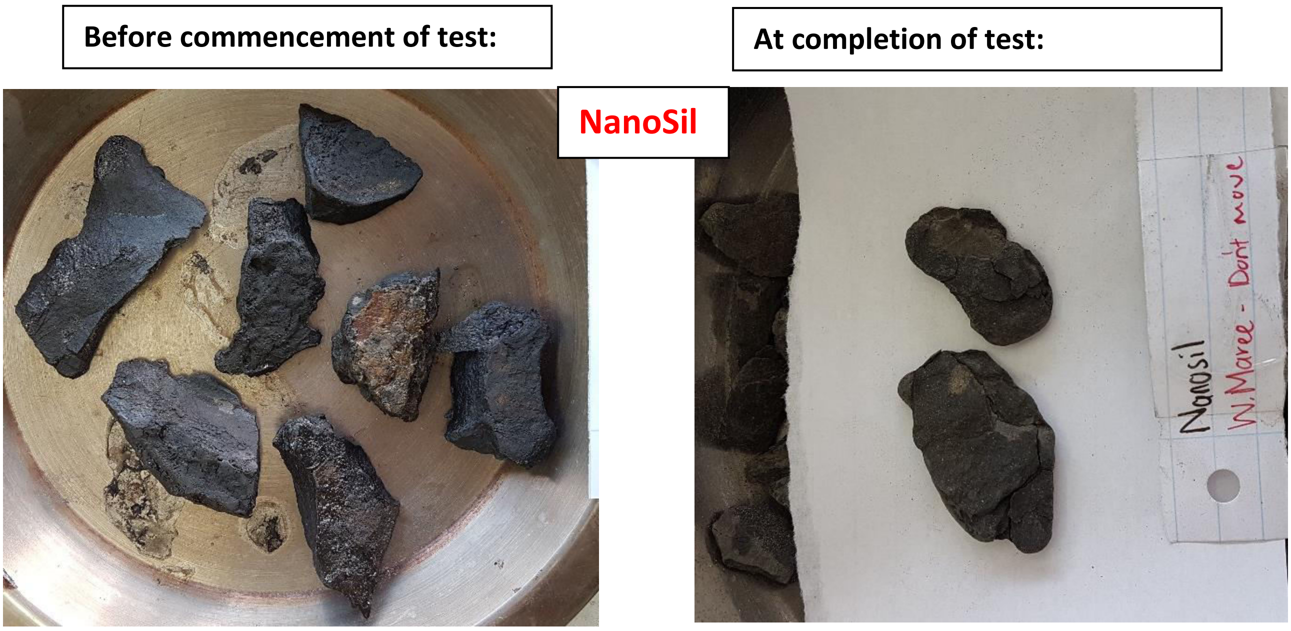


Figure 73 - Visual representation of NanoSil-treated shale rock lumps pre- and post-accelerated weathering test.

NanoSil-treated shale samples showed the most weathering out of all DECL treated sample batches. Of the material collected under the NanoSil bin, most was in the form of sand- and silt-sized particles. The **NanoSil**-treated shale samples completely progressed from being angular in appearance to rounded small-sized lumps, most of which were small enough to fall out of the bin and into the container (< 20mm). Most of the rock degraded through mechanical interaction with the surfaces of the apparatus and other rock lumps.

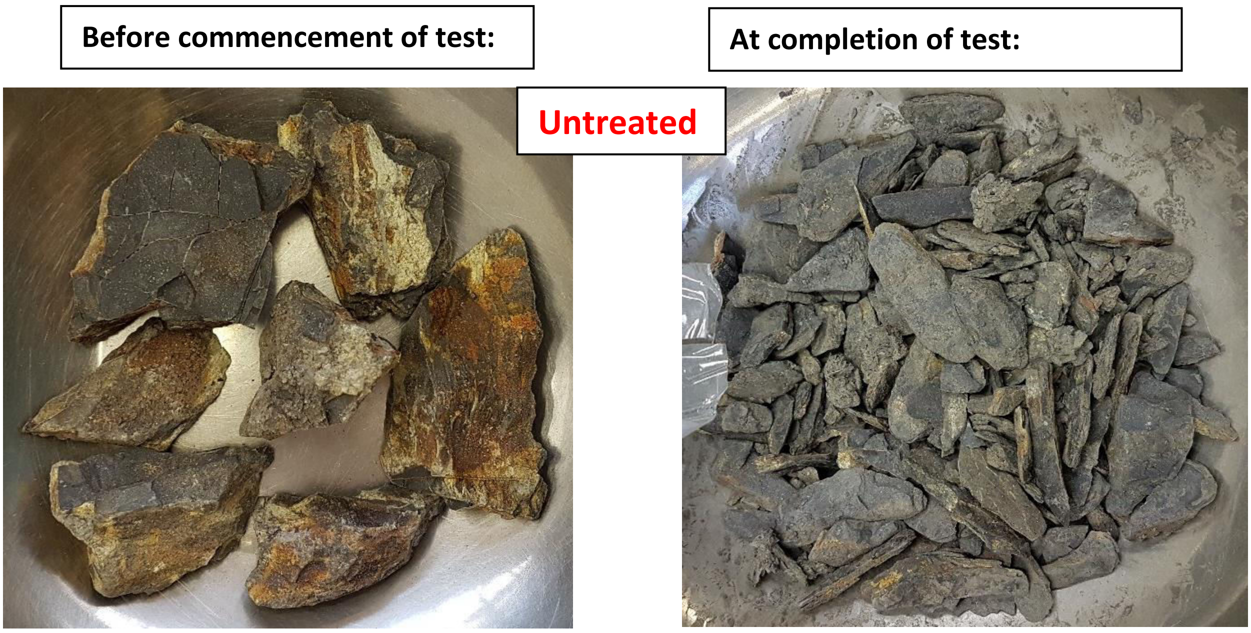


Figure 74 - Visual representation of untreated shale rock lumps pre- and post-accelerated weathering test.

Untreated shale samples showed complete breakdown and weathering. All of the untreated shale lumps progressed from an angular form to small-sized irregular lumps , all of which were small enough to fall out of the bin and into the container (< 20mm). Most of the material collected in the container underneath the basket throughout the test was suspended in the form of silt-sized particles and the recovered material consisted of tiny flaky pieces of rock material with a powderish appearance.

In summary of the abovementioned visual evaluation pre- and post- accelerated weathering test, it is worth mentioning that all rock lumps including both treated and untreated shale samples, broke down into different shapes and sizes (as expected) although to a different degree and extent for each individual test, depending on the DECL product used. The rounded edges of the shale rock lumps after completion of the test, especially for the **Sasbind** and **Sasbind (+Bit)** shale samples, can be ascribed to mechanical aggitation and the tumbling action of the wheel as the test progressed. In nature however, this would not necessarily be the case and most likely the slaked-off fragments would be angular and sharp in size and shape. The individual accelerated weathering tests did however, reveal the extent to which a typical Kimberley shale would degrade if treated with different DECL products and subject to a certain degree of mechanical aggitation and a few wet / dry cycles. In general, **Nano**-treated shale samples proved considerably less durable than **Sasbind**-treated shale samples, losing more than 90% of their initial mass during three wet/dry cycles. Far less silt-sized particles and flaky pieces of rock material were found in the Sasbind and Sasbind (+Bit) containers in all of the **Nano** counterparts. Finally, when comparing the test results of the accelerated weathering test to the test results of the preceding absorption test, there seem to be no direct correlation between the two outcomes. This might only be circumstantial and attributed to human and measurement errors during weighing of each sample in the preceding absorption tests.

6.10 Slake-durability index (SDI) tests

Slake-durability index tests exposed the effects of a short term weathering process on the slaking and disintegration properties of both an untreated and DECL treated shale sample. The results proved useful in classifying and comparing one rock sample to another and in the specific case of this project, it was used to classify and compare an untreated reference sample of the Kimberley shales to an equivalent treated shale sample that was sprayed and coated with the DECL product – Sasbind. The simulation of a short term wetting and drying test (or SDI test) delivered the following results (see Table 19):

Table 19 - Calculated results of the slake-durability index (SDI) tests as carried out by Rocklab in Pretoria on both an untreated shale sample as well as a DECL treated (Sasbind) shale sample.

SPECIMAN PARTICULARS			SLAKE-DURABILITY INDEX TEST RESULTS											
Specimen	Sampling location	Rock type	Initial Mass	Mass after x amount of cycles (including tray mass)				Slake durability				Durability	Notes
			A	Mass (1ste Cycle)	Mass (2nd Cycle)	Mass (3rd Cycle)	Mass (4th Cycle)	Index (1st Cycle)	Index (2nd Cycle)	Index (3rd Cycle)	Index (4th Cycle)	Class	
			(g)	(g)	(g)	(g)	(g)	%	%	%	%		
Untreated	Bultfontein Mine	Kimberley shale	855.93	808.37	674.79	585.31	506.69	94.4	78.8	68.4	59.2	Medium	4
Treated (Sasbind)	Bultfontein Mine	Kimberley shale	802.83	797.71	796.29	795.76	794.58	99.4	99.2	99.1	99.0	Very high	1

The simplicity and effectiveness of this test should not be undermined. Even though the results proved short and concise, the effectiveness of this test to classify and compare the durability of two of the same rock types / samples against one another is very accurate and the interference of an external influence, such as the applied DECL product to one of the samples, was clearly noted. As evident from the obtained results, the DECL treated shale sample performed much better in terms of keeping its physical form and stucture during commencement of the test than did the untreated reference rock. In fact, the shale that was treated / coated with two layers of the **Sasbind** product, almost completely mananged to keep its form by losing no more than 1% of its original dry mass during all four slake-durability cycles. The untreated reference rock on the other hand, lost approximately 40% of its original dry mass, which means that it was much more prone to the slaking and disintegration than was the DECL treated shale sample.

The final durability class for each rock was subsequently classified according to their slake-durability index after the second (2^{nd}) wetting and drying cycle and by using the classification table as recommended by ISRM and proposed by Gamble (1971) (see Table 20). The following results were produced:

- The untreared reference sample was classified as having a “medium durability” towards the simulation of a short term wetting and drying test, with a slake-durability index (SDI) of something between 60% and 85%.
- The DECL (Sasbind) treated sample was classified as having a “very high durability” towards the simulation of a short term wetting and drying cycle, with a slake durability index (SDI) higher than 98%.

Focussing solely on the classification of both samples, there seems to be a major difference in their durability towards the simulation of a short term wetting and drying cycle, with one rock (i.e. untreated) falling towards the lower end of the durability spectrum, whilst the other (i.e. treated) performed within the highest durability class of the proposed classification table (see table 20 below).

Table 20 - Slake-durability index (SDI) classification table, Gamble (1971)

SDI	30 - 60	60 - 85	85 - 95	95 - 98	> 98
Classification	Low	Medium	Medium -High	High	Very high

The only reason for the difference in behaviour between the two rocks, which are equal in every aspect and dimension, can only be ascribed to the external support / influence of the applied DECL product. Seeing as the application of a water repellent base to one rock sample and not the other was the only inconsistnet variable to this test, it can only be assumed that this is the reason for one rock behaving poorly in terms of it's slake durability when exposed to a simulation of short term weathering conditions and the other performing exceptionally well.

As a further evaluation on the abovementioned durability classification of both rock samples, a visual comparison of the rocks were also conducted based on their pre- and post test appearance. Various numbers were used in the obtained results under "*Notes*" as to denote the exact physical appearance of both rocks samples (both treated and untreated) after completion of the 4th cycle of the slake-durability test and according the Rocklab personnel:

- the untreated reference sample, denoted by the symbol (4), was completely broken up into a lot of smaller pieces; and
- the DECL treated (Sasbind) samples, denoted by the symbol (1), was still completely intact.

This suggests that the untreated reference sample was extremely susceptible to the process of slaking and disintegration, to such an extent that it lost its original form and broke / weathered down into smaller fragments (< 20mm). The Sasbind treated shale sample on the other hand, stayed completely intact even through four cycles of continuous wetting and drying, which means that it resisted weathering fairly well and retained rock fragments larger than 20mm. The visual inspection as described above therefore supports the effectiveness of the DECL (Sasbind) product as a rock mechanic stabilizer. It proved extremely successful in protecting the rocks against a continuous process of wetting and drying and enhanced the durability characteristics and the weathering resistance of the Kimberley shales. Even though Sasbind was the only DECL product tested and compared to an untreated reference batch, it is considered that all five products as used within the scope of this project would have shown similar results.

In general, it is worth mentioning that the slake-durability index test as conducted and discussed above for the purpose of this project, was not conducted with the purpose of obtaining a universal standard explaining the durability or weathering resistance of a specific rock type as a whole, but it was rather meant to discriminate between one rock sample and another as to evaluate the performance of the DECL products tested. In other words, slake-durability index tests are generally used to compare one rock sample from the same sample locality or the same time period for example, to another and to use the obtained results / information to draw certain conclusions about the durability or weathering restistance of each sample with regards to the other. Therefore, the slake-durability index tests as conducted for the purpose of this project was only to compare the performance and durability of a DECL treated shale sample to an untreated shale sample from the Kimberley "Big Hole" Mine after four cycles of slaking. The results of this specific test was subsequently used to comment on the effectiveness of the respective DECL product "Sasbind" to increase rock durability and weathering resistance of the Kimberley shales and enhance overall performance with regards to combatting natural weathering conditions. In other words, the abovementioned slake-durability index test was only conducted with the main purpose of assessing whether the Sasbind-treated shale sample would perform better and more effective in terms of durability and weathering resistance than its untreated counterpart and the results did in fact prove very informative and successful. There was a definite correlation between the rate of weathering, the treatment of the sample and the resultant slake-durability index with the correlation being that a DECL treated shale sample (with specific reference to the "Sasbind" DECL product) undergoes a significantly slower rate of weathering compared to an untreated reference sample and hence, also possess over a much higher slake-durability index. The category of highest durability (i.e. "Sasbind" treated shale sample) could be termed "rock" and materials of lower durability (i.e. untreated shale sample) could be termed "soil" as illustrated below in Figure 75.

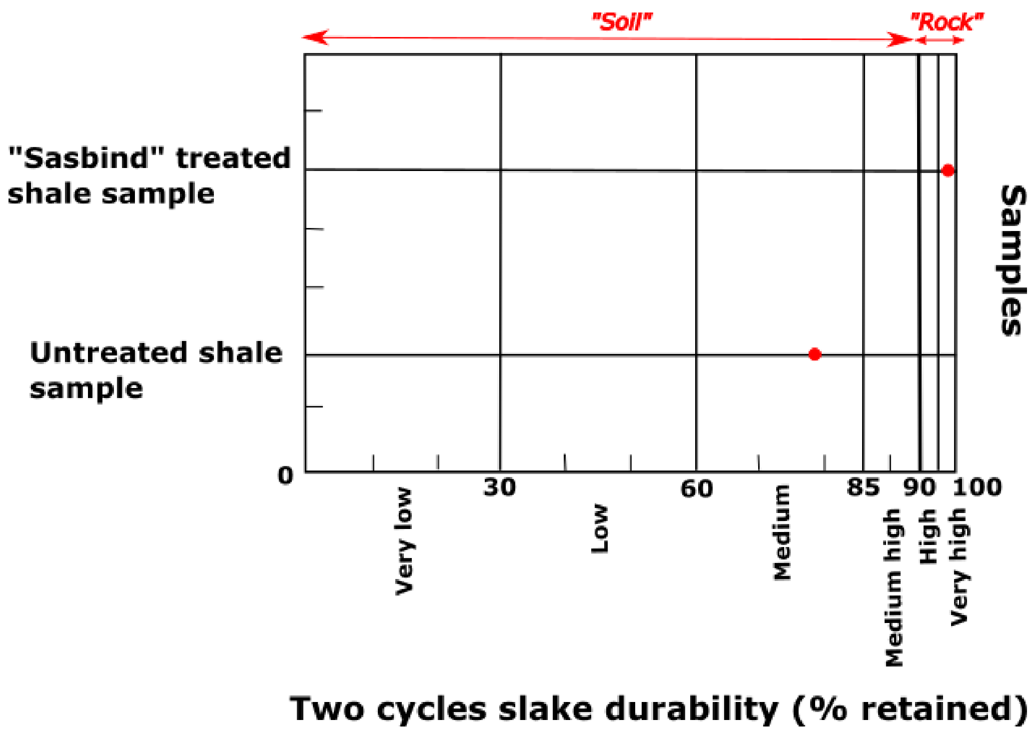


Figure 75 - Gamble's geotechnical classification for the untreated and DECL treated Kimberley shale samples.

A disitinction between rock and soil is often required in engineering practices and the slake-durability index affords a possible quantitative method of discriminating between the two. It is worth mentioning however, that the boundary at 90% slake durability index must be regarded as tentative and should always be re-examined on the basis of experience and specific test conditions. To conclude this section, it is worth mentioning that this test is intended for use with other rock-index tests as an aid to rock classification and in predicting problems of excavation stability and rock support. However, when comparing the test results (as obtained above) to available literature on the predicted safe slope angles and engineering properties of shale slopes after the second cycle slake-durability index test (as discussed in Chapter 2), the Sasbind-treated Kimberley shale sample and the untreated reference shale sample from the Kimberley "Big Hole" Mine can possibly be expected to render the following values (see Table 21).

Table 21 - Predicted safe slope angle and engineering properties of an untreated and Sasbind-treated Kimberley shale sample, according to their respective second slake-durability index values

Sample:	Second slake-durability index value (Id2)	Safe slope angle	Uniaxial compressive strength (Kgf/cm^2)	Tensile strength (Kgf/cm^2)	Shear strength (Kgf/cm^2)
Untreated	78.80%	1.5H:1V or 34°	> 42.20	> 0.605	> 5.084
Sasbind-treated	99.20%	0.5H:1V or 63°	< 51.00	< 0.690	< 6.145

According to literature, an untreated shale slope at the Kimberley "Big Hole" Mine would only start to stabilize at a safe slope angle of something like 34°. This varies slightly from the findings by Preece at al. (2008), whom suggested in his report that a safe slope angle of something between 20° and 30° is expected on the sidewalls of the Kimberley "Big Hole" Mine. In other words, Preece et al. (2008) predicted a natural angle of repose for the slopes of the Kimberley "Big Hole" Mine to be something between those approximate values. The results from the slake-durability index test as conducted for the purpose of this project seem to suggest a more accurate value, with a safe slope angle (or natural angle of respose) of 34°. Compared to the current slope angle of 38° at the Kimberley "Big Hole" Mine, the slake-durability index test of an untreated Kimberley shale sample predicts that the slopes of the Big Hole Mine still need to degrade / regress another 4° before a safe slope angle (or the natural angle of repose) of the sidewalls is reached. This equates to an approximate total of 17.21 metres away (or outward) from the current mine pit perimeter, which means that any and all infrastructure, including businesses and buildings, within the vicinity of this new break-back perimeter needs to be evacuated and cleared for the potential risk of a near future slope slip or failure.

If the sidewalls, with specific reference to the Kimberley shales, had to be treated with the Sasbind DECL product, a safe slope angle (or natural angle of repose) of 63° is expected. This means that the sidewalls of the Kimberley "Big Hole" Mine would have stopped migrating outward a long time ago, having reached stability at a safe slope angle or natural angle of repose of 63° already. One can therefore argue that spaying the surface of the Kimberley shales on the sidewalls of the Kimberley “Big Hole” Mine with the Sasbind DECL product, would effectively stop any and all slope instabilities measured over the past few years as it would effectively address the slope failure mechanism as desribed and discussed in Chapter 2. Using DECL products as a viable solution towards the defined slope stability problem at the Kimberley “Big Hole” Mine, is therefore considered as very plausible and the results as obtained from the completed slake-durability index test, as conducted for the purpose of this project, justifies further research on the matter.

Chapter 7: Discussion of Results

The following chapter will aim to briefly summarize the most important aspects of the findings on the slope stability problem at the Kimberley "Big Hole" Mine, as well as highlight the most significant results as obtained and discussed in the previous chapter (see Chapter 6). This chapter will therefore briefly review the exact mechanism behind slope failures or slope instabilities at the Kimberley "Big Hole" Mine, as well as include an informative section on the advantage and disadvantages of using alternative solutions to help mitigate the slope stability problem at the Big Hole Mine.

7.1 Slope instability at the Kimberley "Big Hole" Mine

The main culprit behind slope stability problems at the Kimberley "Big Hole" Mine could be ascribed to the Kimberley shales and their vast susceptibility to weather and deteriorate when exposed to natural weathering conditions. As the geological shale unit weathers and deteriorates rapidly under humid climatic conditions over the town of Kimberley (especially during the heavy rainfall months of November to February), vast regression of the underlying shales result in support loss for the overlaying dolerite cap causing the orthogonally jointed dolerite blocks to break off and topple over and into the open mine pit as single block toppling slope failure events. This continuously occurring process of undermining and toppling at the sidewalls of the Kimberley "Big Hole" Mine is frequently repeated and consistently exposes fresh pieces of shale to the atmosphere and natural weathering conditions, prompting the whole process of regression and toppling to start all over again. This repeatedly occurring cycle is commonly referred to as mine pit break-back and is considered to be the responsible mechanism behind slope stability problems and failures at the Kimberley "Big Hole" Mine. In other words, mine pit break-back is what causes the sidewalls of the pit to actively migrate outward in an unstable manner towards their natural angle of repose and the process, as a function of time, is illustrated below in Figures 76 A to F.

The defined slope stability problem at the Kimberley "Big Hole" Mine could therefore, after a very comprehensive review of all available literature including geological and geotechnical reports written by Preece et al., (2008) and Croukamp (2008), be defined as a regressive problem where the underlying shale unit undercuts the overlying dolerite caps (due to their vast susceptible to weathering and deterioration under natural weathering conditions), which causes the occurrence of block toppling slope failure events.

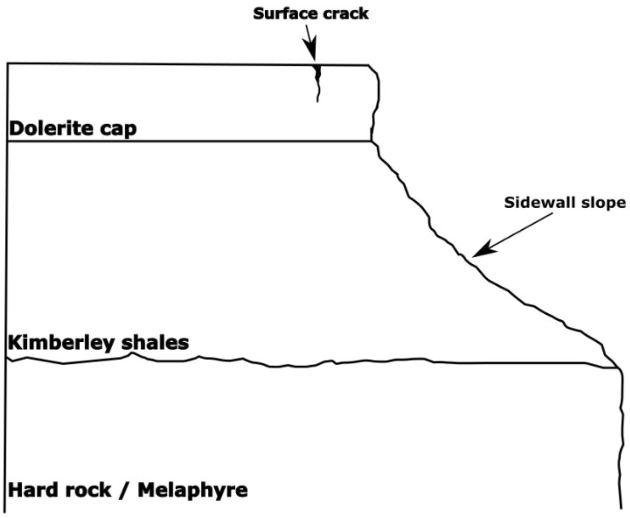


Figure 76 A- Regressive process at the Kimberley "Big Hole" Mine (Time 0).

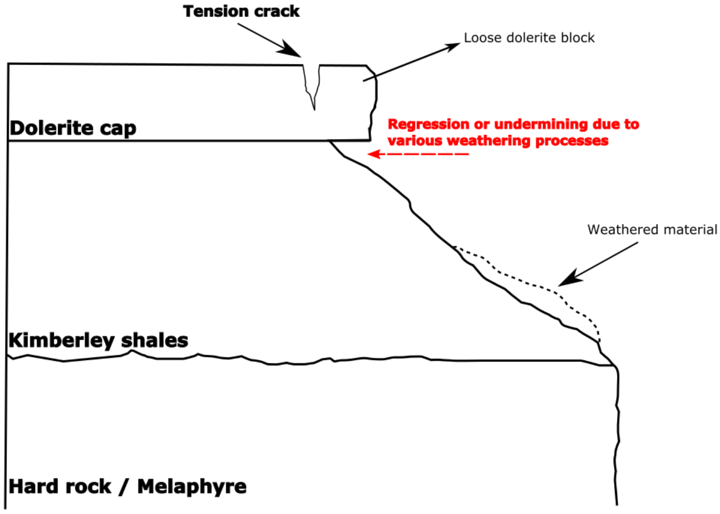


Figure 76 B - Regressive process at the Kimberley "Big Hole" Mine (Time 1).

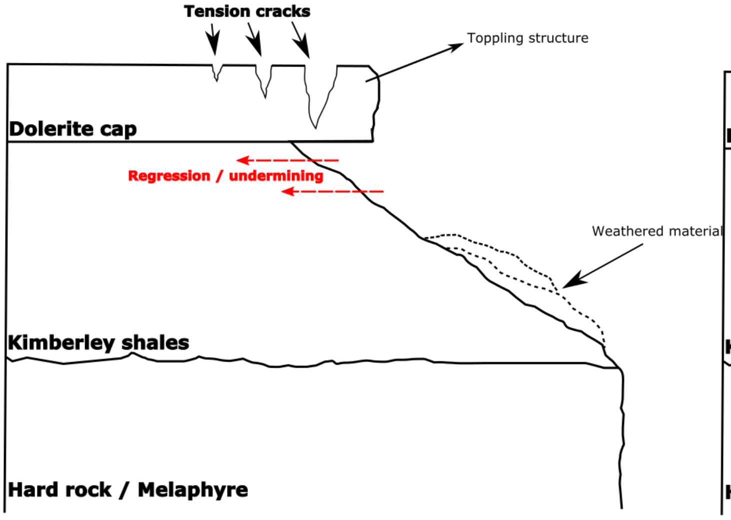


Figure 76 C - Regressive process at the Kimberley "Big Hole" Mine (Time 2).

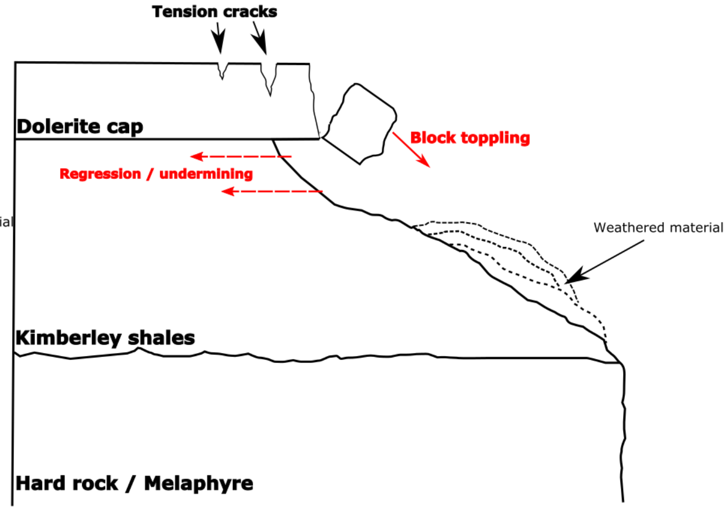


Figure 76 D - Regressive process at the Kimberley "Big Hole" Mine (Time 3).

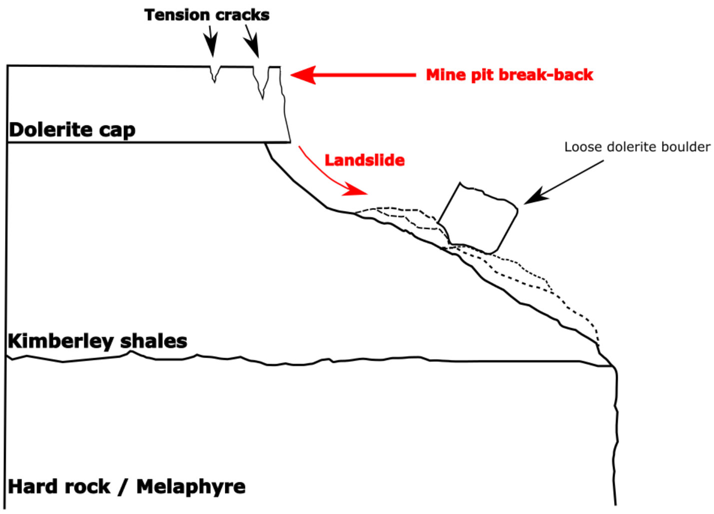


Figure 76 E - Regressive process at the Kimberley "Big Hole" Mine (Time 4).

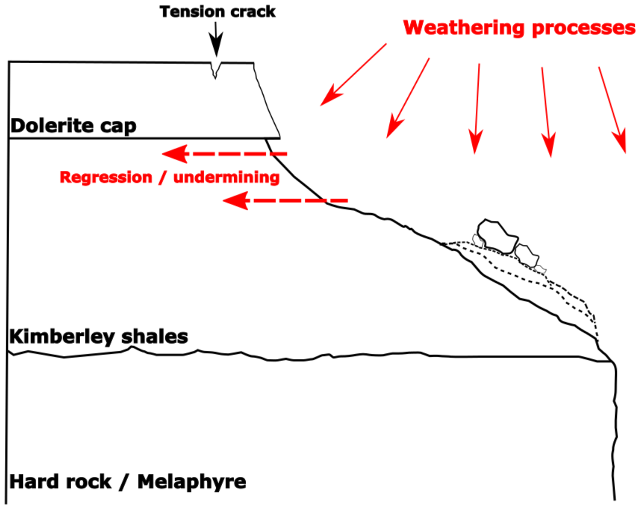


Figure 76 F - Regressive process at the Kimberley "Big Hole" Mine (Time 5).

7.2 Alternative solutions

The solution towards the defined slope stability problem at the Kimberley "Big Hole" Mine was therefore to develop a viable technique / method for decreasing the susceptibility of the Kimberley shales to weather and deteriorate when exposed to natural weathering conditions. In other words, the proposed solution would have to increase the rock durability and weathering resistance of the Kimberley shales without further damaging the sidewalls of the pit, changing the aesthetics of the Big Hole or adding to the overburden of the slopes. If the whole process of sidewall regression and mine pit break-back (with specific reference to the weathering properties of the Kimberley shales) at the Kimberley "Big Hole" Mine could be controlled, then slope slips / failures and subsequent sidewall migration would cease to exist.

Before proposing such a solution however, it was worth briefly looking at previously implemented and other possible slope stabilizing techniques that might be considered as valuable solutions towards the defined slope stability problem at the Kimberley "Big Hole" Mine. Table 22 therefore represents a few mentionable slope stabilizing techniques, together with their respective advantages and disadvantages on the slopes of the Kimberley "Big Hole" Mine.

Table 22 - Advantages and disadvantages of various slope stabilizing techniques.

Solution	Advantages	Disadvantages	Remarks
Installation of water tunnels (or drainage structures)	• Diverts water from slope. • Lowers water table. • Increases shear strength of soil. • Reduces pore water pressure. • Demotes physical and chemical weathering.	• Expensive. • Excavation of slope if constructed directly to the sidewalls of the pit. • Labour intensive.	• *Implementation in the form of a massive dewatering tunnel that circumvents the pit some 60 meters below the surface.* • *Already implemented at the Kimberley "Big Hole" Mine from August, 1995.* • *Does not mitigate the effects of surface exposure of the rocks to natural weather conditions / elements.*
Providing in-situ reinforcement (i.e. anchors or mesh)	• Lateral earth support. • Slope reinforcement. • Buttress effect. • Allows natural vegetation growth.	• Expensive. • Labour intensive. • Aesthetically unpleasing. • Requires drilling. • Adds to slope overburden.	• *Neither horizontal nor vertical emplacement of anchors or mesh to the sidewalls of the pit will successfully stop the effects of regression as the shale will only*

			continue to weather around the reinforcement (i.e. does not address the problem). • *Therefore, not viable at the Kimberley "Big Hole" Mine.*
Chemical treatment (i.e. shotcrete / grouting / gunite)	• Hardens / stabilizes soil. • Seals surface fractures and cracks. • Minimizes erosion. • Reduces raindrop impact.	• Permits water to pond behind slope surface. • Increases surface runoff, which leads to erosion gullies further down slope. • Inhibits surface drainage. • Expensive. • Labour intensive. • Aesthetically unpleasing. • Adds to slope overburden. • Inhibits natural vegetation growth.	• *Implementation against the shale rock face would only cause a buildup of pore water pressure behind the surface of the slope (or rock) and lead to further and far greater slope instabilities.* • *Therefore, not viable at the Kimberley "Big Hole" Mine.*
Vegetation	• Roots hold soil in place. • Natural anchor / slope reinforcement. • Absorbs water. • Aesthetically pleasing. • Cost effective.	• Promotes biological weathering. • Blocks drainage structures. • Loosens rock material.	• *Vegetation growth would fail to fully address the slope stability problem as water will continue to enter the face of the rock or the surface of the slope and therefore, not prevent weathering.* • *Not a viable solution at the Kimberley "Big Hole" Mine.*

For the above tabulated reasons and the fact that other conventional slope stabilizing techniques such as geotextiles for example, could not be used on the slopes of the Kimberley "Big Hole" Mine due to its geometry, geology and aesthetics, five different dust and erosion control liquids (DECL) were introduced and tested within the scope of this project with the aim of identifying one of them as a viable solution towards the defined slope stability problem at the Kimberley "Big Hole" Mine.

7.3 Proposed solution

The main reasons for considering DECL products as the most viable solution towards addressing the defined slope stability problem at the Kimberley "Big Hole" Mine, which refers to the vast susceptibility of the Kimberley shales to weather and deteriorate under natural weathering conditions, and to protect the Kimberley shales from various environmental factors are:

(1) They are easily applied / equipped.

(2) They are relatively cost effective compared to other slope stabilizing techniques.

(3) They will not change the aesthetics of the Kimberley "Big Hole" Mine to any extent.

Therefore, five different DECL products, namely NanoSil, NanoBond, NANO, Sasbind and Sasbind (+Bit) were tried and tested on a small scale during the scope of this project as to identify which proved most effective and successful with regards to increasing rock durability and weathering resistance of the Kimberley shales. The testing program comprised the execution of absorption tests, comparative accelerated weathering tests, cyclic wetting and drying tests and a slake-durability index tests, all referenced to an untreated shale sample of the Kimberley shales.

After completion of all the above mentioned test procedures to test the effectiveness of the DECL products on the durability characteristics of the Kimberley shales, one DECL product in particular stood out from the rest as being the most effective and successful towards combatting the effects of natural weathering conditions. The DECL product that proved most successful in preserving the rock structure and increasing the rock durability and weathering resistance of the Kimberley shales after each weathering and durability test was the DECL product – Sasbind. Sasbind, as a translucent water-repellent base, preserved the physical rock structure and internal rock strength parameters of the Kimberley shales most and prevailed after almost each and every durability test. Sasbind represents an uniquely formulated water based emulsion of modified acrylic polymers that is most suitable and often used for the binding and stabilization of different soil layers, especially with regards to the construction of roads. It is worth mentioning that the Sasbind DECL product is also often applied to various surfaces that require dust palliation, due to its strong binding and cohesive properties. Specific benefits of the Sasbind DECL product are extensive and include:

- It is water-based and dilutes easily with water to increase quantity.
- It is suitable for the application to a wide variety of different soil types.
- It is ultraviolet (UV) and heat stable.
- It is non-leachable.
- It has a safe chemistry.

- It requires no specialized equipment for application.
- It reduces erodibility and improves waterproofing of the surface it is applied to.
- It significantly increases the California bearing ratio (CBR) and unconfined compression strength (UCS) of the surface it is applied to.

Sasbind, which was originally formulated for the durability treatment of roads and other paved surfaces, is a translucent liquid / product which means that it will not change the aesthetics of the Kimberley "Big Hole" Mine if applied to the sidewalls of the Kimberley shales. It proved very effective in bonding to the surfaces of the various test shale samples it was applied to and acted as a sufficient water proof coat / base around the surface of the rocks to inhibit water infiltration and keep soil particles bonded tightly together. With regards to the various laboratory tests conducted on each individual DECL product, Sasbind treated shale samples produced the following results as presented in Table 23.

Table 23 - Test results for Sasbind treated shale samples.

Durability test	Test results					Remarks
Absorption test	Total moisture intake after one week (%):			Average moisture intake per interval (g):		No visibile cracks or fractures
	5%			1 g		
Cyclic wetting and drying test	Original weight (g):	End weight (g):		Percentage material loss (%):		No physical evidence of slaking or disintegration
	2531 g	2510 g		0.83%		
Comparative accelerated weathering test	Original dry mass (g):	Degraded after 3rd cycle (g):	Residual after 3rd cycle (g):	Percentage degraded (%):	Percentage retained (%):	Very little physical breakdown and weathering (i.e. angialr form)
	249 g	163 g	70 g	65.46%	28.12%	
Slake-durability index test	Durability class			Slake-durability index		Completely intact
	Very high			> 98 %		

Sasbind treated shale samples allowed only 5 % moisture uptake of the original dry mass during one week of being submerged underwater, whilst during the cyclic wetting and drying tests, the Sasbind treated shale sample experienced only 0.83% material loss during the full six months of being exposed to natural weathering conditions and a frequent cycle of wetting and drying. These results, especially when compared to the test results of the other four DECL products, is considered as insignificantly small and extremely successful in terms of increasing rock durability and weathering resistance of the Kimberley shales. During the cyclic wetting and drying tests, Sasbind treated shale samples were also one of the few DECL treated shale samples that showed no evidence for the development of cracks or fractures on the surface of the rocks, which strongly suggests that the Sasbind DECL product proved very successful against combating the effects of constant temperature changes and a fluctuating water content. With regards to the comparative accelerated weathering tests, which included a component of mechanical agitation (i.e. rotation of the bins), Sasbind treated shale samples managed to retain a total of 28.12% of its original dry mass material, which is 7.66% better than the nearest performance of one of its DECL counterparts. It also showed the lowest percentage of degraded material at only 65.46%. Due to the fact that the Sasbind DECL product prevailed as the most effective and successful DECL product with regards to increasing rock durability and weathering resistance of the Kimberley shales during the preceding durability and weathering tests (as discussed above), it was subsequently also chosen as the representative DECL product to be tested against an untreated reference sample during the ensuing slake-durability index test done at Rocklab in Pretoria. During the slake-durability index test of a Sasbind treated shale sample and an untreated reference shale sample, the Sasbind treated shale sample performed exceptionally well and received a very high durability classification on the slake durability index, whilst an untreated reference shale sample of the Kimberley shales only ranked on the medium durability side of the slake durability index scale. This suggests that the Sasbind DECL product acts as an extremely effective waterproof base / coat around the surface of the rock or the surface it is applied to, allowing for very little to no water ingress through the surface of the rock and hence, a delayed effect of weathering. It dramatically slows down the weathering and deterioration rate of the Kimberley shales when exposed to natural weathering conditions and considerably decreases its susceptibility to slake and disintegrate when exposed to a continuous cycle of wetting and drying. The Sasbind liquid coat can be seen as a protective layer around the rock, inhibiting water ingress through the surface of the rock, which in turn binds the soil / rock particles closer together and increases the inner rock strength parameters of the shale by increasing overall rock durability and weathering resistance. If water is inhibited (for the most part) to enter the structure of the rock, then weathering of the material in the form of physical and chemical weathering, will occur on a much smaller scale and to a much lesser extent, causing the rock to become more durable.

Possible disadvantages that might be associated and need to be considered with the application of the Sasbind DECL product as a viable solution towards the defined slope stability problem at the Kimberley “Big Hole” Mine are very few, but still worth mentioning. As with any chemical treatment of a rock face, by means of either shotcrete, grouting or gunite for example, the risk exists that a buildup of pore water pressure behind the surface of the slope would become so intense that slope instabilities start to develop as a matter of time. This is no different when considering the spray-on application of the Sasbind DECL product to the surface of the rocks, which still leads to some degree of concern. The only reason for considering the Sasbind DECL product as a more effective and well-equipped solution towards the defined slope stability problem at the Kimberley “Big Hole” Mine (as oppose to previously mentioned surface chemical treatment procedures) is that the Sasbind DECL product is “breathable”, meaning that it eliminates capillary rise and water ingress from the top (i.e. reduces water permeability of the base it is applied to), whilst completely maintaining vapor permeability. In other words, water is not allowed to infiltrate the surface of the rock, but moisture is allowed to leave the structure of the rock through the process of evaporation. This means that ponding and buildup of pore water pressure behind the surface of the slope is less likely to occur and if so, to a lesser extent than what would have been expected with other conventional surface chemical treatments. In addition to this, the Sasbind DECL product is also very light in weight when applied to the surface of the rocks, which means that it would not add drastically to the overburden of the slope, whilst also being aesthetically pleasing (i.e. translucent in appearance). As a final remark, application of the Sasbind DECL product to the slopes of the Kimberley “Big Hole” Mine might be quite labour intensive and require a well-executed and detailed plan of the application procedure, which is why further investigation on this matter is strongly recommended.

To conclude the discussion of the results, it is worth mentioning that the Sasbind DECL product performed much better than the author had anticipated prior to commencement of the testing program. It showed an excellent durability performance against natural weathering conditions and an influence of external agitating factors such as mechanical agitation and accelerated weathering test conditions. This proved that the Sasbind DECL product provides sufficient external protection and support to the structure of the Kimberley shales and as such, further investigation into the suitability of this product as a viable solution towards the defined slope stability problem at the Kimberley “Big Hole” Mine is justified.

Chapter 8: Conclusion and Recommendations

8.1 Introduction

After completion of a full desk study, a comprehensive literature review, a practical case study and the necessary field and laboratory work as conducted for the purpose of this project and to find a viable solution towards the defined slope stability problem at the Kimberley “Big Hole” Mine, this chapter presents the conclusion and recommendations relevant to the completed research. Conclusions related to the slope instability problem at the Kimberley “Big Hole” Mine and a possible solution is presented forthwith, followed by the recommendations.

8.2 Conclusions

8.2.1 Current state and stability of the Kimberley “Big Hole” Mine

To unambiguously prove that the sidewalls of the Kimberley “Big Hole” Mine are still actively migrating in an unstable manner towards their natural angle of repose (i.e. natural equilibrium), a full desktop study in the form of direct visual inspections / site walkovers, aerial photography and pixel tracking were undertaken. All three research methods concluded enough visual evidence to suggest that the sidewalls of the Kimberley “Big Hole” Mine, including the outer perimeter, are still actively moving and that a slope slip / failure is inevitable. Direct visual inspections for example, delivered plentiful evidence of tension cracks, landslides and block toppling slope failures in and around the sidewalls of the Kimberley “Big Hole” Mine to suggest that slope instabilities are still frequently occurring, whilst aerial photography and pixel tracking exhibited excellent examples of sidewall migration patterns from the inside of the pit, outward, between the years 1968 and 2017. All three movement measuring techniques were considered to show sufficient evidence of sidewall migration up until the year 2017 and the conclusion was made that a nearby slope slip / failure in and around the sidewalls of the Kimberley “Big Hole” Mine is imminent.

8.2.2 Laboratory tests and proposed solution

Various durability and weathering tests were conducted within the scope of this project to test and evaluate the effectiveness of different dust and erosion control liquids on the durability and weathering resistance of the Kimberley shales when exposed to natural weathering conditions. From these tests and with specific reference to the slake-durability index test, three significant conclusion were drawn:

(1) The first being that a safe slope angle (or natural angle of repose) of 34° is expected on the sidewalls of the Kimberley “Big Hole” Mine. This means that the sidewalls of the pit are still expected to regress / degrade another 4° before a safe slope angle or natural angle of repose is

reached and maintained. When converting this to actual horizontal ground movement around the pit, it equates to 17.21 meters back (or outward) from the current mine pit perimeter. This means that all infrastructure, including buildings, businesses and roads, that fall within the vicinity of 17.21 meters from the current mine pit perimeter needs to be evacuated and cleared as a high risk zone for potential slope slips or failures in the nearby future.

(2) Secondly, dust and erosion control liquids (DECL) as introduced and tested within the scope of this project, effectively contributed towards increasing the durability and weathering resistance of the Kimberley shales after each and every laboratory test. In other words, the use or application of DECL products to reduce weathering and increase durability of the Kimberley shales when exposed to natural weathering conditions was considered successful and concluded an implementable solution towards the original problem statement as defined for this project. The findings of this project therefore justifies further research and testing on DECL products as a viable solution towards the defined slope stability problem at the Kimberley “Big Hole” Mine, with the added mention and consideration of the recommendations as made below.

(3) Finally, of the five DECL products that were introduced and tested within the scope of this project, it was concluded that the Sasbind DECL product performed best under the various testing conditions. Sasbind effectively managed to preserve and protect the rock structure of the Kimberley shales whilst being exposed and tested against various durability and weathering tests. The Sasbind DECL product was therefore considered as the most effective DECL product with regards to the slope stability problem at the Kimberley “Big Hole” Mine and proved, by means of the undertaken slake-durability index test, that a safe slope angle of 63° would be expected if the product had to be applied to the sidewalls of the Big Hole Mine. This concludes a considerable improvement from the 34° safe slope angle of an untreated shale slope.

8.3 Recommendations

Following the above made conclusions surrounding the slope stability problem at the Kimberley “Big Hole” Mine and the undertaken testing program, numerous recommendations can be made in terms of the results obtained directly from this thesis and any and all future research that is concerned with the state and stability of the sidewalls at the Kimberley “Big Hole” Mine.

8.3.1 Recommendations from own research

The following application procedure is recommended based on the weathering and durability test findings and conclusions as experienced during experimental tests with Sasbind:

- Spay diluted mixture of product by means of using a knapsack sprayer, water tanker or any suitable equipment that can hold a diluted mixture of the Sasbind DECL product provided that the solution per m^2 can be ensured and the area is saturated.
- A minimum of two coats should be applied in the form of a spray-dry-spray application procedure (however, it is worth mentioning that because there is no upper limit to the amount of layers / coats that can be applied to the surfaces of the rocks, it is generally accepted that the more coats, the better, depending on the cost limit of the project).
- A 1:2 water to product ratio (i.e. 200ml of water mixed with 400ml of the Sasbind product to give a 600ml diluted mixture for example) should be followed, mixing thoroughly between applications.
- It should be ensured that the initial application procedure of the Sasbind DECL product is applied to a dry clean surface (i.e. free of excess moisture and loose material), thereafter waiting at least 2 to 3 hours before applying of the second layer / coat.
- Any excess runoff or pooling of the diluted Sasbind mixture on the surfaces of the rock surface should be avoided.

This project was only considered an introductory research initiative for using dust and erosion control liquids (DECL), which are most frequently used by mines and roadwork specialist to suppress dust, as an effective slope stabilizing technique by increasing rock durability and weathering resistance of the Kimberley shales. Therefore, future research considering the same topic might need some further recommendations as seen below.

8.3.2 Recommendations for future research

- The effects of more than two layers / coats of various DECL products on the effectiveness of the rocks to withstand weathering and deterioration under natural weathering conditions should be tested (i.e. apply more coats / layers of the DECL products to the surfaces of the rocks to evaluate the significance thereof towards increasing durability and weathering resistance).
- The coat thicknesses of the various DECL products to the applied surfaces should be measured (if possible), as to evaluate whether the liquid products wash off / disintegrate as a function of time. A possible means of doing this is to use laser sensors (i.e. laser interferometry) as a suitable coat thickness measuring technique and further investigation on this matter is strongly recommended. Unfortunately, due to a lack of equipment at Stellenbosch University and cost constraints associated with this project, this could not be tested.
- Testing the effectiveness of the DECL products on a much larger scale by using in-situ rocks, such as that found on the sidewalls of the Kimberley “Big Hole” Mine for example, can be explored.

- Assess the possibility of pore water pressure buildup behind the surface of the slope and possible ways to prevent this (e.g. drainage pipes / holes).
- Implementing pixel tracking in combination with satellite interferometry as a mass movement monitoring technique should be explored. The combined effect of measuring ground movement via pixel deformation and supporting the results with satellite interferometric data would give compelling evidence for slope movements and mass deformation.
- Repeat absorption tests on a second set of samples, under the exact same conditions, as to ensure accuracy and consistency within the obtained results.
- Conduct cyclic wetting and drying tests by simulating the weathering conditions of the focus area as closely as possible (i.e. consider testing the rock samples in Kimberley, under the same climatic conditions, as oppose to conducting the experiments in Stellenbosch where the climate and weathering conditions are somewhat different).
- Develop more methods of measuring weathering and deterioration in shale type rocks (or mudrocks), besides the weight and visual inspections as conducted within the scope of this project, by looking at volume decreases or abrasion rates for example.
- Conduct cyclic wetting and drying tests over a longer period of time (i.e. over 1 year for example) as to more accurately determine the lifespan of DECL products and their exact durability properties.
- Equate an actual time series to the test conditions of the comparative accelerated weathering tests, as to make it more practical and relevant to the actual conditions experienced by rocks of the study area.
- Test the slake-durability index of all DECL products against an untreated reference sample and try and apply a practical conclusion to the obtained results.

8.4 Final remarks

It is ultimately recommended however, that a fresh coat of the DECL product, Sasbind, be applied frequently or annually to the surface of the rock as to ensure the most effective outcome and waterproofing effect. Logically, a spray-on product such as Sasbind for example, will inevitably always start to disintegrate and wash off after a certain period of time (or to a certain extent at least). This is why a frequent (or annual) re-application of the Sasbind DECL product is crucial if the effectiveness of the product as a protective waterproofing coat against weathering and natural weathering conditions wants to be maintained. Even though using a DECL product, such as Sasbind, is preliminary considered a viable solution towards the defined slope stability problem at the Kimberley “Big Hole” Mine, further testing and trail applications on a much larger scale is highly recommended and requires a lot more research and thought, especially considering the exact application procedure of the product to the sidewalls of the open mine pit itself.

To summarize, the Sasbind DECL product is, within the scope of this project, considered a viable solution towards the defined slope stability problem at the Kimberley “Big Hole” Mine as it proved very successful and effective towards decreasing the weathering and deterioration rate of the Kimberley shales when exposed to a continuous cycle of wetting and drying as well as the effects of natural weathering conditions. It successfully increased the inner rock strength parameters, rock durability and weathering resistance properties of the Kimberley shales after each durability and weathering test as conducted within the scope of this project and is therefore considered a viable solution towards slowing down the regression / undermining processes experienced by the sidewalls of the Kimberley “Big Hole” Mine and as a result, should also combat block toppling slope failure events and subsequent sidewall migration outward from the center of the pit.

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nano BOND

WORLD CLASS LEADERS IN DUST SUPPRESSION USING NANOTECHNOLOGY

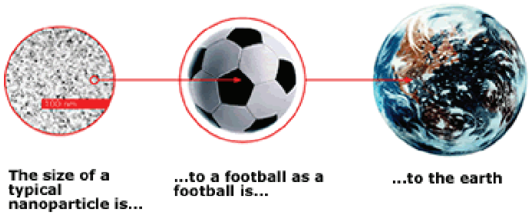
Nanobond is arguably the world's most effective surface spray dust palliative. It has been developed to supersede existing technologies from an efficiency, durability, particle-adhesion and commercial perspective. Nanobond has been designed by taking existing environmental conditions (below and above ground) into consideration by removing application obstacles thus improving dust control and reducing vehicle maintenance costs.

NANOBOND BENEFITS

- Improved coating due to smaller particle sizes and particle-adhesion chemistry
- Water soluble, spray application
- UV and heat stable
- Chemically converts water absorbing silanol groups to water resistant alkyl siloxane surfaces at room temperature
- Si-O-Si Siloxane bond (sand) survives for centuries
- Works with all types of soils
- One time full drying essential for performance
- Non leachable, Safe Chemistry, REACH & TSCA registered

PARTICLE SIZE COMPARASIONS

Nanobond will coat the extremely fine dust particles that other technologies battle to capture. This is due to the particle size of the Nanobond is 50nm in size which is 100 times smaller than a bitumen particle which is 5000nm in size.



DOSAGE RATE AND APPLICATION

1 liter : 300 liters H2O
3 liters / m2 (to a point of saturation)

Nanobond must be mixed with potable water that must be as close to neutral as possible. Once combined the solution must be thoroughly mixed.

The Nanobond solution can be sprayed onto the surface by knap-sack sprayers or water tankers provided the quantity of the solution / m2 can be ensured and the area is SATURATED.

STORAGE AND LIFE

Nanobond should be stored between 5 - 45 °C (41 - 113 °F) in a shaded, dry area away from sunlight, heat, ignition, source of sparks, rain and standing water. The container lid should be securely fastened every time it is used.
Its shelf life is 24 months.

Nanobond's efficiency of chemically coating the dust particle as well as its particle-adhesion improvement property, allows the dust particle to remain heavier and in much closer proximity to other dust particles for longer periods of time. This will reduce the frequency of application and thus maintenance costs. Site visibility and health conditions will vastly improve.
Nanobond is possibly the worlds first dust suppressant incorporating nanotechnology.

Tel: +27 (0)11 050 0705 • Email: info@cruzeholdings.co.za • Website: www.cruzeholdings.co.za

Material Safety Data Sheet

Product

Product Name : NANOBOND

Acrylic Co-polymer Based Composition in Water

Possible Hazards

HMIS Rating

Health	1
Flammability	0
Reactivity	0
Physical Hazards	1

Potential Health Effect

Eye :	May cause irritation
Skin :	May cause irritation
Injection :	May cause gastrointestinal discomfort
Inhalation:	May cause irritation to respiratory tract

First aid Measures

The person should be removed from the source of exposure.

If product is spilled on clothing or skin, remove soiled clothing, wash the affected area with lukewarm water for at least 10 - 15 minutes and seek medical advice.

If product is splashed in eyes, remove contact lenses, irrigate the affected eye with lukewarm water for at least 10 - 15 minutes and seek medical advice.

If product is inhaled or ingested seek medical advice.

Fire-fighting methods

FLASH POINT : Not Flammable

BOILING POINT : Approx.100°C (212°F) at 1013 hPa

FIRE EXTINGUISHING MATERIALS:

General Information

The product is soluble in water. Containers can build up pressure if exposed to heat and/or fire. As in any fire, wear a self-contained breathing apparatus in pressure-demand, MSHA/NIOSH (approved or equivalent), and full protective gear. Vapors may form an explosive mixture with air. Vapors can travel to a source of ignition and flash back. It will burn if involved in a fire. Flammable liquid can release vapors that form explosive mixtures at temperatures above the flashpoint. Use water spray to keep fire exposed containers cool. Containers may explode in the heat of a fire.

Extinguishing Media

For small fires, use dry chemical, carbon dioxide, water spray or alcohol-resistant foam. For large fires, use water spray, fog, or alcohol-resistant foam. Use water spray to cool fire-exposed containers.

Accidental release measures

Environmental precaution	Do not let product enter drains and water sources.
Methods for cleaning up federal regulation.	Contain with absorbent material and dispose. Clean with water. Discard material according to local state and
Precautions	Use Hand gloves and Safety glass for handling spill.
Handling	Ensure thorough ventilation of stores and work areas.
Protection against fire and explosion	Keep away from heat and ignition source, Keep away from sparks.
Handling and storage	
Exposure to Moisture	No effect on Moisture Exposure.
Handling	Wash thoroughly after handling. Use only in a well-ventilated area. Ground and bond containers when transferring material. Use spark-proof tools and explosion proof equipment. Avoid contact with eyes, skin, and clothing. Empty containers retain product residue, (liquid and/or vapor), andcan be dangerous. Keep container tightly closed. Keep away from heat, sparks and flame. Avoid ingestion and inhalation. Do not pressurize, cut, weld, braze, solder, drill, grind, or expose empty containers to heat, sparks or open flames.
Storage	Keep away from heat, sparks, and flame. Keep away from sources of ignition. Store in a tightly closed container. Keep from contact with oxidizing materials. Store in a cool, dry, well- ventilated area away from incompatible substances. Flammables-area. Do not store near perchlorates, peroxides, chromic acid or nitric acid.

Material Safety Data Sheet

Exposure controls and personal protection

Engineering Controls

Use explosion-proof ventilation equipment. Facilities storing or utilizing this material should be equipped with an eyewash facility and a safety shower. Use adequate general or local exhaust ventilation to keep airborne concentrations below the permissible exposure limits

Personal Protective Equipment

Eyes	Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA's eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.
Skin	Wear appropriate protective gloves to prevent skin exposure.
Clothing	Wear appropriate protective clothing to prevent skin exposure.
Respirators	A respiratory protection program that meets OSHA's 29 CFR 1910.134 and ANSI Z88.2 requirements or European Standard EN 149 must be followed whenever workplace conditions warrant a respirator's use.

Physical and chemical properties

Appearance	White Liquid
Odor	Mild
Chemical Type	Acrylic Co-polymer
Physical State	Liquid
Solubility	Dispersible in Water
Density	1.01-1.02 g/ml
pH value	Approx. 6.5-8
Stability and Reactivity	
Chemical Stability	Stable under normal temperatures & Pressures
Conditions to avoid	Incompatible materials, ignition sources, excess heat, oxidizers
Incompatibilities with other Materials	Strong oxidizing agents, acids, alkali
Hazardous Polymerization	Hazardous polymerization will not occur

Toxicological information

Effects of Overexposure	Carcinogenicity	Ecotoxicity	Neurotoxicity
No information available	No information is available	No specific information. is available	No information available.

Ecological Information

Environmental Fate and Distribution : When released to the soil and water, solvent Benzyl alcohol and ethylene glycol and alcohol generated due to reaction with water may evaporate to moderate extent. When released into the soil, this ethanol may leach into groundwater. When released into the water, these materials are expected to have a half life between 1 and 3 days. The active ingredient Organo silicon compound will react chemically with inorganic substrates such as soil, aggregates, or sand before any possibility of leaching out to ground water.

Disposal consideration

Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste according to the local, state and federal regulation. Additionally, disposal of the waste generators must follow local, state and federal hazardous waste regulations to ensure complete and accurate compliance.

Transport Information

The product do not constitute a hazardous substance in national/international road, rail, sea and air transportDOT regulations Hazard class Not regulated

Land transport ADR/RID (Cross-border) ADR/RID Class	Not regulated
Maritime transport IMDG, IMDG Class	Not regulated
Air transport ICAO-TI and IATA-DGR , ICAO/IATA Class	Not regulated
U.S. Department of Transportation Hazard Class:	Not Regulated

Regulatory information

USA

TOXIC SUBSTANCES CONTROL ACT (TSCA): All ingredients are on the TSCA inventory.

SARA section 313 Notification: This material does not contain any SARA 313 chemical in above de minimus levels.

Other Information

These data are offered in good faith as typical values and not as product specifications. No warranty, either expressed or implied, is hereby made. The recommended industrial hygiene and safe handling procedures are believed to be generally applicable. However, each user should review these recommendations in the specific context of the intended use and determine whether they are appropriate.

NANOBOND

Issue Date: May 24, 2014

Material Safety Data Sheet

Product

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Acrylic Co-polymer Based Composition in Water

Possible Hazards

HMIS Rating

Health	1
Flammability	0
Reactivity	0
Physical Hazards	1

Potential Health Effect

Eye :	May cause irritation
Skin :	May cause irritation
Injection :	May cause gastrointestinal discomfort
Inhalation:	May cause irritation to respiratory tract

First aid Measures

The person should be removed from the source of exposure.

If product is spilled on clothing or skin, remove soiled clothing, wash the affected area with lukewarm water for at least 10 - 15 minutes and seek medical advice.

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The product is soluble in water. Containers can build up pressure if exposed to heat and/or fire. As in any fire, wear a self-contained breathing apparatus in pressure-demand,MSHA/NIOSH (approved or equivalent), and full protective gear. Vapors may form an explosive mixture with air. Vapors can travel to a source of ignition and flash back. It will burn if involved in a fire. Flammable liquid can release vapors that form explosive mixtures at temperatures above the flashpoint. Use water spray to keep fire exposed containers cool. Containers may explode in the heat of a fire.

Extinguishing Media

For small fires, use dry chemical, carbon dioxide, water spray or alcohol-resistant foam. For large fires, use water spray, fog, or alcohol-resistant foam. Use water spray to cool fire-exposed containers.

Accidental release measures

Environmental precaution	Do not let product enter drains and water sources.
Methods for cleaning up	Contain with absorbent material and dispose. Clean with water. Discard material according to local state and federal regulation.
Precautions	Use Hand gloves and Safety glass for handling spill.
Handling	Ensure thorough ventilation of stores and work areas.
Protection against fire and explosion	Keep away from heat and ignition source, Keep away from sparks.
Handling and storage	
Exposure to Moisture	No effect on Moisture Exposure.
Handling	Wash thoroughly after handling. Use only in a well-ventilated area. Ground and bond containers when transferring material. Use spark-proof tools and explosion proof equipment. Avoid contact with eyes, skin, and clothing. Empty containers retain product residue, (liquid and/or vapor), andcan be dangerous. Keep container tightly closed. Keep away from heat, sparks and flame. Avoid ingestion and inhalation. Do not pressurize, cut, weld, braze, solder, drill, grind, or expose empty containers to heat, sparks or open flames.
Storage	Keep away from heat, sparks, and flame. Keep away from sources of ignition. Store in a tightly closed container. Keep from contact with oxidizing materials. Store in a cool, dry, well- ventilated area away from incompatible

substances. Flammables-area. Do not store near perchlorates, peroxides, chromic acid or nitric acid.

Exposure controls and personal protection

Engineering Controls

Use explosion-proof ventilation equipment. Facilities storing or utilizing this material should be equipped with an eyewash facility and a safety shower. Use adequate general or local exhaust ventilation to keep airborne concentrations below the permissible exposure limits

Personal Protective Equipment

Eyes	Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA's eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.
Skin	Wear appropriate protective gloves to prevent skin exposure.
Clothing	Wear appropriate protective clothing to prevent skin exposure.
Respirators	A respiratory protection program that meets OSHA's 29 CFR 1910.134 and ANSI Z88.2 requirements or European Standard EN 149 must be followed whenever workplace conditions warrant a respirator's use.

Physical and chemical properties

Appearance	White Liquid
Odor	Mild
Chemical Type	Acrylic Co-polymer
Physical State	Liquid
Solubility	Dispersible in Water
Density	1.01-1.02 g/ml
pH value	Approx. 6.5-8
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Chemical Stability	Stable under normal temperatures & Pressures
Conditions to avoid	Incompatible materials, ignition sources, excess heat, oxidizers
Incompatibilities with other Materials	Strong oxidizing agents, acids, alkali
Hazardous Polymerization	Hazardous polymerization will not occur

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Effects of Overexposure	Carcinogenicity	Ecotoxicity	Neurotoxicity
No information available	No information is available	No specific information. is available	No information available.

Ecological Information

Environmental Fate and Distribution : When released to the soil and water, solvent Benzyl alcohol and ethylene glycol and alcohol generated due to reaction with water may evaporate to moderate extent. When released into the soil, this ethanol may leach into groundwater. When released into the water, these materials are expected to have a half life between 1 and 3 days. The active ingredient Organo silicon compound will react chemically with inorganic substrates such as soil, aggregates, or sand before any possibility of leaching out to ground water.

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The product do not constitute a hazardous substance in national/international road, rail, sea and air transportDOT regulations Hazard class Not regulated

Land transport ADR/RID (Cross-border) ADR/RID Class	Not regulated
Maritime transport IMDG, IMDG Class	Not regulated
Air transport ICAO-TI and IATA-DGR , ICAO/IATA Class	Not regulated
U.S. Department of Transportation Hazard Class:	Not Regulated

Regulatory information

USA

TOXIC SUBSTANCES CONTROL ACT (TSCA): All ingredients are on the TSCA inventory.

SARA section 313 Notification: This material does not contain any SARA 313 chemical in above de minimus levels.

Other Information

These data are offered in good faith as typical values and not as product specifications. No warranty, either expressed or implied, is hereby made. The recommended industrial hygiene and safe handling procedures are believed to be generally applicable. However, each user should review these recommendations in the specific context of the intended use and determine whether they are appropriate.

BREATHABLE SOIL WATERPROOFING OF ROAD BASES & SLOPES

Nanosil technology is water-soluble, UV and heat stable, reactive soil modifier with the ability to retain strength of road bases and resistance to deformation.

SX 100
NANO SILICONE

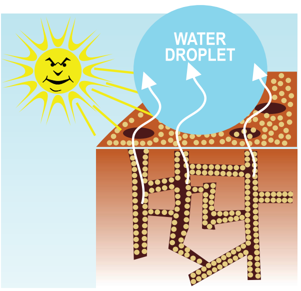
SX 100 nano silicone emulsion extends performance of Terrasil up to 100%. It is mixed with Nanosil solution and sprayed on compacted soils.

nano BOND

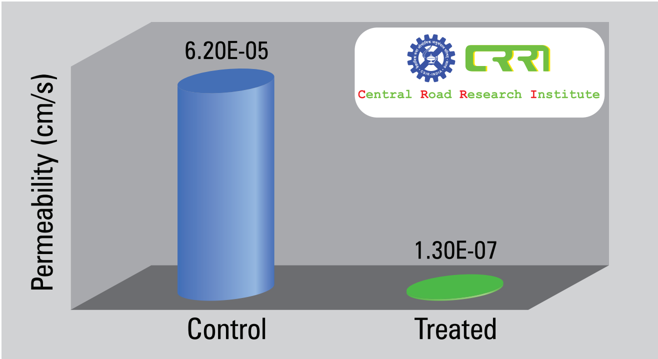
Nanobond acrylic co-polymer emulsion bonds the soil particles to resist soil erosion in side shoulders and slopes. It is mixed with Nanosil solution for one step waterproofing and bonding of compacted soils.

NANOSIL BENEFITS

- **Eliminates Capillary rise and water ingress from top**



- **Reduce water permeability of soils bases (10^{-5} cm/s to 10^{-7} cm/s) while maintaining 100% vapor premeability**



- **Maintains Dry CBR under wet conditions**
  Retains strength of road bases and increases resistance to deformation by maintaining frictional values between slit, sand and clay particles.

Soil Type	Untreated (4 Day soak % CBR)	Treated with Nanosil (%CBR)	
		4 Day dry	4 Day Dry + 4 Day Soak
Bihar, India Soil	1.1	9.7	6.5
Black Cotton Soil	1.0	5.8	4.1

- **Controls erosion of soils in side shoulders and slopes**

SUBGRADE MULTILAYER ENVELOPE

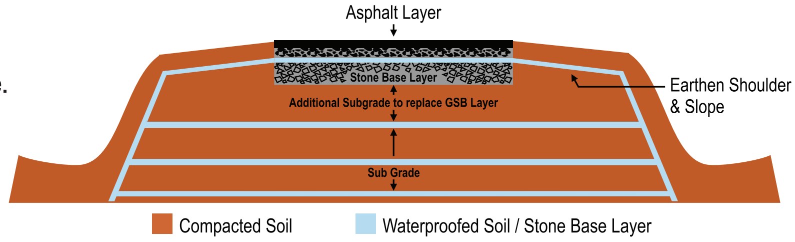
Apply Nanosil solution through two application cycles of Spray-Dry-Spray on compacted soil (Proctor density above 95% optimum moisture content).

First spray cycle waterproofs almost 90-95% of soil surface.

Second spray cycle ensures 100% saturation of the soil surface, penetration and waterproofing of micro-cracks.

Shoulders & Side Slopes
Use regular soil to cover the treated slopes and build shoulders. For extra binding of the side slopes, mix 10kgs of Nanobond with Nanosil solution.

PAVEMENTS ON EMBANKMENT



DOSAGE

Soil Layer		Nanosil : Water (<1000 ppm TDS) Ratio	SX 100 in kg	Nanobond in kg	Spray Rate Liters/m² upto saturation	No. of Applications
Bottom, Intermediate and Top		1 kg : 800 liters	0.5	–	1-3	2
Shoulders & Side Slopes		1 kg : 800 liters	0.5	10*	2-3	2
Stone pitching	Soil	1 kg : 800 liters	0.5	10	1-2	1
	Cement mortar	1 kg : 40 liters	0.5	10	0.5	1

* Nanobond binds side slopes to be used for stone pitching

APPLICATIONS

- Road Bases - Asphalt and Concrete Pavements
- Dirt Roads - Rural, Mining, Waste Sites
- Landfills / Construction Sites, Ponds, Canals, Levees (Bunds) etc.
- Solar Farms & Reclamations

STORAGE AND SHELF LIFE

Nanosil should be stored between 5 - 45 °C (41 - 113 °F) in a shaded, dry area away from sunlight, heat, ignition, source of sparks, rain and standing water. The container lid should be securely fastened every time it is used. Its shelf life is 24 months.

Tel: +27 (0)11 050 0705
Email: info@cruzeholdings.co.za
Website: www.cruzeholdings.co.za

Material Safety Data Sheet

SECTION 1: Identification of the substance/mixture and of the company/undertaking

1.1. Product identifier

Product form : Mixture

Product name : Nanosil ™

1.2. Relevant identified uses of the substance or mixture and uses advised against

Uses: Bitumen (Asphalt) binder additive

Uses advised against: None identified

1.3. Supplier's details

Cruze (Pty) Ltd.
Block C, Coachmans Crossing Office Park,
4 Brian street, Bryanston, 2052
T +27-0110500705
mark@cruzeholdings.co.za

1.4. Emergency telephone number

Emergency number : +27 (83) 6752438

SECTION 2: Hazards identification

2.1. Classification of the substance or mixture (Benzyl alcohol)

Product classification according to Regulation (EC) 1272/2008 (CLP):
Acute toxicity, Inhalation - Category 4, H332.
Acute toxicity, Oral - Category 4, H302.
Eye irritation - Category 2, H319.
Product classification according to Directive 67/548/EEC or 1999/45/EC: Harmful

R20/22 Harmful by inhalation and if swallowed.
R36 Irritating to eyes.

2.2. Label elements

Product labeling according to Regulation (EC) 1272/2008 (CLP):

Hazard Pictogram

Signal word: Warning.

Hazard statements:
H302 Harmful if swallowed.
H319 Causes serious eye irritation.
H332 Harmful if inhaled.

Precautionary statements:
P261 Avoid breathing dust/fume/gas/mist/vapours/spray.
P264 Wash thoroughly after handling.
P270 Do not eat, drink or smoke when using this product.
P271 Use only outdoors or in a well-ventilated area.
P280 Wear eye protection/face protection.
P301+P312 IF SWALLOWED: Call a POISON CENTER or doctor/physician if you feel unwell.
P330 Rinse mouth.
P304+P340 IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing.
P305+P351+P338 IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing.
P337+P313 If eye irritation persists: Get medical advice/attention.
P312 Call a POISON CENTER or doctor/physician if you feel unwell.
P501 Dispose of contents/container in accordance with local, regional and international regulations.

Supplemental information: Not Applicable

Notes: No Additional Information.

Product labeling according to Directive 67/548/EEC or 1999/45/EC:

Indications of danger: Harmful

Risk phrases:
R20/22 Harmful by inhalation and if swallowed.
R36 Irritating to eyes.

Material Safety Data Sheet

Safety phrases: S26 In case of contact with eyes, rinse immediately with plenty of water and seek medical advice.

2.3. Other hazards:

PBT/vPvB criteria: This product does not meet the PBT and vPvB classification criteria.

SECTION 3: Composition/information on ingredients

3.1. Substance

Proprietory Organosilane compound

3.2. Mixture

Name	Product identifier	%	Classification according to the United Nations GHS (Rev. 4, 2011)
Benzyl Alcohol	CAS 100-51-6	25-27	Inhalation 4, Acute Tox. (oral) 4, Eye Irrit. 2
Ethylene Glycol	CAS 107-21-1	3-5	Acute Tox., 4, H302 STOT RE, 2, H373

SECTION 4: First aid measures

4.1. Description of first aid measures

First-aid measures general : Never give anything by mouth to an unconscious person. If you feel unwell, seek medical advice (show the label where possible).

First-aid measures after inhalation : Remove to fresh air and keep at rest in a position comfortable for breathing. Call a POISON CENTER/doctor/physician if you feel unwell.

First-aid measures after skin contact : Remove/Take off immediately all contaminated clothing. Wash with plenty of soap and water. Immediately call a POISON CENTER or doctor/physician. Wash contaminated clothing before reuse.

First-aid measures after eye contact : Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing. Obtain medical attention if pain, blinking or redness persist.

First-aid measures after ingestion : Rinse mouth. Do NOT induce vomiting. Obtain emergency medical attention.

4.2. Most important symptoms and effects, both acute and delayed

Dizziness, Drowsiness, Headache, Irritation, Nausea. Preexisting sensitization, skin and/or respiratory disorders or diseases may be aggravated. See section 11 for additional information.

4.3. Indication of any immediate medical attention and special treatment needed

Treat symptomatically.

SECTION 5: Firefighting measures

5.1. Extinguishing media

Suitable extinguishing media : Foam. Dry powder. Carbon dioxide. Water spray.

Unsuitable extinguishing media : Not Known.

5.2. Special hazards arising from the substance or mixture

Fire hazard : Can form highly flammable liquid and vapour.

Explosion hazard : May form flammable/explosive vapour-air mixture.

Reactivity : Stable under normal conditions.

5.3. Advice for firefighters

Firefighting instructions : Use water spray or fog for cooling exposed containers. Exercise caution when fighting any chemical fire. Do not allow run-off from fire fighting to enter drains or water courses.

Protection during firefighting : Do not enter fire area without proper protective equipment, including respiratory protection. Wear self-contained breathing apparatus (SCBA) equipped with a full facepiece and operated in a pressure-demand mode (or other positive pressure mode) and approved protective clothing.

SECTION 6: Accidental release measures

6.1. Personal precautions, protective equipment and emergency procedures

General measures : Remove ignition sources. Use special care to avoid static electric charges. No naked lights. No smoking.

6.1.1. For non-emergency personnel

Emergency procedures : Evacuate unnecessary personnel. Stop leak without risks if possible. Avoid contact with skin, eyes and clothing. Avoid inhalation of vapours.

6.1.2. For emergency responders

Protective equipment	:	Equip cleanup crew with proper protection. Avoid inhalation of vapours. Avoid contact with skin and eyes.
Emergency procedures	:	Ventilate area.

6.2. Environmental precautions

Prevent entry to sewers and public waters. Notify authorities if liquid enters sewers or public waters.

6.3. Methods and material for containment and cleaning up

Methods for cleaning up	:	Soak up spills with inert solids, such as clay or diatomaceous earth as soon as possible. Collect spillage. Store aways from other materials.

SECTION 7: Handling and storage

7.1. Precautions for safe handling

Additional hazards when processed	:	Handle empty containers with care because residual vapours may be flammable.
Precautions for safe handling	:	Wash hands and other exposed areas with mild soap and water before eating, drinking or smoking and when leaving work. Provide good ventilation in process area to prevent formation of vapour. No naked lights. No smoking. Use only non-sparking tools. Use only outdoors or in a well-ventilated area. Do not breathe vapours. Avoid contact with skin, eyes and clothing.
Hygiene measures	:	Do not eat, drink or smoke when using this product. Wash hands thoroughly after handling.

7.2. Conditions for safe storage, including any incompatibilities

Technical measures	:	Ground/bond container and receiving equipment.
Storage conditions	:	Keep only in the original container in a cool, well ventilated place away from : Sources of ignition. Keep container tightly closed.
Incompatible products	:	Strong bases. Strong acids.

SECTION 8: Exposure controls/personal protection

8.1. Control parameters

Chemical Name	EU OELV	EU IOELV	ACGIH - TWA	ACGIH - STEL	UKWELs
Benzyl alcohol	N/E	N/E	N/E	N/E	N/E
Ethylene Glycol	40 ppm	40 ppm	100mg/M^3	40 ppm	TWA 52 ppm, STEL 104 ppm

N/E=Not established (no exposure limits established for listed substances for listed country/region/organization).

8.2. Exposure controls

Personal protective equipment	:	Avoid all unnecessary exposure.
Hand protection	:	Wear protective gloves.
Eye protection	:	Chemical goggles or safety glasses.
Skin and body protection	:	Wear suitable protective clothing.
Respiratory protection	:	Where exposure through inhalation may occur from use, respiratory protection equipment is recommended.
Thermal hazard protection	:	Not required for normal conditions of use.
Environmental exposure controls	:	Avoid release to the environment.
Other information	:	Do not eat, drink or smoke during use.

SECTION 9: Physical and chemical properties

9.1. Information on basic physical and chemical properties

Physical state	:	Liquid
Colour	:	Pale yellow.
Odour	:	Slight Aromatic
Odour threshold	:	No data available
pH	:	No data available
Relative evaporation rate (butylacetate=1)	:	No data available
Melting point	:	6°C
Freezing point	:	No data available
Boiling point	:	Approx. 200 °C
Flash point	:	90 °C (closed cup)
Self ignition temperature	:	No data available
Decomposition temperature	:	No data available
Flammability (solid, gas)	:	No data available
Vapour pressure	:	No data available

Relative vapour density at 20 °C	:	No data available
Relative density	:	No data available
Density	:	1.04 g/ml
Solubility	:	Miscible with : Ethanol. Methanol. alcoholic. Acetone.
Log Pow	:	No data available
Log Kow	:	No data available
Viscosity, kinematic	:	No data available
Viscosity, dynamic	:	100 - 500 cP @ 25°C
Explosive properties	:	Not Explosive
Oxidising properties	:	Not Oxidizing
Explosive limits	:	No data available

9.2. Other information

No additional information available

SECTION 10: Stability and reactivity

10.1. Reactivity

Stable under normal conditions.

10.2. Chemical stability

Stable under normal conditions. Moisture exposure may form flammable/explosive vapour-air mixture.

10.3. Possibility of hazardous reactions

Under fire conditions closed containers may rupture or explode. Can form explosive mixture with air.

10.4. Conditions to avoid

Direct sunlight. Extremely high or low temperatures.

10.5. Incompatible materials

Water. Acids. Oxidizing agents.

10.6. Hazardous decomposition products

Carbon monoxide. Carbon dioxide.

SECTION 11: Toxicological information

11.1. Information on toxicological effects

Acute toxicity : Not classified

Information on likely routes of exposure:

General: Overexposure by inhalation or ingestion may cause dizziness, drowsiness, headache, nausea, vomiting, diarrhea, convulsions, central nervous system depression and loss of consciousness.
Eyes: Causes eye irritation.
Skin: May cause skin irritation. Repeated or prolonged contact may cause irritation, dermatitis, defatting and drying or cracking of the skin. Repeated or prolonged skin contact may cause allergic reactions with susceptible persons.
Inhalation: Harmful by inhalation. Inhalation at high vapor concentrations may cause respiratory tract irritation and central nervous effects.
Ingestion: Harmful if swallowed. Ingestion may cause nausea, vomiting and diarrhea.

Acute toxicity information: Harmful if inhaled - Category 4. Harmful if swallowed - Category 4.

Chemical Name	LC50 Inhalation	Species	LD50 Oral	Species	LD50 Skin	Species
Benzyl alcohol	>4178/M^3 4 hrs Aerosol	Rat/adult	1620mg/kg	Rat/adult	N/E	

Corrosion/Irritation/Sensitization information:
Skin corrosion/irritation: Not classified (based on available data, the classification criteria are not met).
Serious eye damage/irritation: Causes serious eye irritation - Category 2.
Respiratory or skin sensitization: Not classified (based on available data, the classification criteria are not met).
BENZYL ALCOHOL: This material has a low potential to cause allergic skin reactions, however cases of skin sensitization have been reported.

Chemical Name	Eye Irritation	Species/Dose	Skin Irritation	Species/Dose	Skin Sensitization	Species/Dose
Benzyl alcohol	Irritant (OECD 405)	Rabbit/adult	Non irritant (OECD 404)	Rabbit/adult	Non Sensitizer	Guinea Pig and Human Patch

Carcinogenicity/Mutagenicity/Reproductive toxicity information:

Carcinogenicity: Not classified (based on available data, the classification criteria are not met).
BENZYL ALCOHOL: Under conditions of a two-year NTP gavage study, there was no evidence of carcinogenic activity for rats or mice

receiving 200 or 400 mg/kg.

Germ cell mutagenicity: Not classified (based on available data, the classification criteria are not met).
BENZYL ALCOHOL: Ames testing showed no mutagenic activity and mixed results both positive and negative were observed from other in-vitro genotoxicity assays. Benzyl alcohol showed no genotoxicity during in-vivo testing. The weight of the evidence indicates this material is not mutagenic or clastogenic.

Reproductive toxicity: Not classified (based on available data, the classification criteria are not met).
BENZYL ALCOHOL: No effects on reproductive organs were observed in subchronic and long-term studies with rates and mice. Developmental toxicity oral study, mouse: NOAEL (no-observed-adverse-effect level), maternal toxicity=550 mg/kg bw/day; NOAEL, developmental toxicity=550 mg/kg bw/day. No developmental effects were observed in absence of maternal toxicity.

Specific target organ toxicity (STOT):

STOT-single exposure: Not classified (based on available data, the classification criteria are not met).
STOT-repeated exposure: Not classified (based on available data, the classification criteria are not met).

BENZYLALCOHOL: Long term animal studies indicate a gavage NOAEL (no-observed-adverse-effect-level) >=400 mg/kg/day for rats and >=200 mg/kg/day for mice. At higher doses, effects on bodyweights, brain lesions, thymus, skeletal muscle, kidneys, liver and central nervous system were observed. In a 4-week inhalation study in rats on Benzyl Alcohol, no adverse effects were observed with a no-observed-adverse-effect level (NOAEC) of 1,072 mg/m^3.

SECTION 12: Ecological information

12.1. Toxicity

Chemical Name	Fish 96 hour LC50	Species	Fish 96 hour LC50	Species Fish	Chronic NOEC	Species
Benzyl alcohol	**460mg/L**	Pimephalis promelas (Fathead minnow)	>100 mg/L	Oryzias latipes (Medaka)	N/E	

Chemical Name	Invertebrates 48 hour EC50	Species	Invertebrates 24 hour EC50	Species	Invertebrates Chronic NOEC	Species
Benzyl alcohol	230mg/L	Daphnia magna	440mg/ L	Pseudokirchneriella subcapitata	310 mg/L (72 hours	Pseudokirchneriella subcapitata

Chemical Name	Algal 96 hour EC50	Species	Algal 72 hour EC50 groath rate)	Species	Algal Chronic NOEC	Species
Benzyl alcohol	N/E		770 mg/L	Pseudokirchneriella subcapitata,	310 mg/L (72 hours	Pseudokirchneriella subcapitata

12.2. Persistence and degradability

NANOSIL	
Persistence and degradability	Not established.

12.3. Bioaccumulative potential

NANOSILL	
Bioaccumulative potential	Not established.

12.4. Mobility in soil

No additional information available

12.5. Other adverse effects

Other information : Avoid release to the environment.

SECTION 13: Disposal considerations

13.1. Waste treatment methods

Waste disposal recommendations : Dispose in a safe manner in accordance with local/national regulations. Dispose of this material and its container to hazardous or special waste collection point.

Additional information : Handle empty containers with care because residual vapours are flammable.

Ecology - waste materials : Hazardous waste due to toxicity. Avoid release to the environment.

SECTION 14: Transport information

14.1. UN number

UN-No (Land transport) : Not Regulated

14.2. UN proper shipping name

Proper Shipping Name (Land transport) : Not Regulated

Proper Shipping Name (IATA) : Not Regulated

Proper Shipping Name (IMDG) : Not Regulated

14.3. Transport hazard class(es)

Class (Land transport)	:	Not Applicable
Class (IATA)	:	Not Applicable
Class (IMDG)	:	Not Applicable

14.4. Packing group

Packing group (Land transport)	:	II

14.5. Environmental hazards

Other information	:	Not classified.

14.6. Special precautions for user

Special transport precautions	:	- Ensure there is adequate ventilation.

14.6.1. Overland transport

Not Regulkated

14.6.2. Transport by sea

Not Regulated

14.6.3. Air transport

14.7. Transport in bulk according to Annex II of MARPOL 73/78 and the IBC Code

Not applicable

SECTION 15: Regulatory information

15.1. Safety, health and environmental regulations/legislation specific for the substance or mixture

EU Authorizations and/or restrictions on use:	Not Applicable
Other EU information:	REACH Registration Numbers, 17-21-20000364-74-0000, 17-2119878844-19-0000, 17-210000366-70-0000
National regulations:	No Additional Information

Chemical inventories:

Regulation Status
Canadian Domestic Substances List (DSL): Y
Canadian Non-Domestic Substances List (NDSL): N
European Inventory of Existing Chemical Substances (EINECS): Y
European List of Notified Chemical Substances (ELINCS): Y
Europe REACH (EC) 1907/2006: N
U.S. Toxic Substances Control Act (TSCA): Y

SECTION 16: Other information

Other information	:	None.

This information is based on our current knowledge and is intended to describe the product for the purposes of health, safety and environmental requirements only. It should not therefore be construed as guaranteeing any specific property of the product

TECHNICAL DATA SHEET

Road Material Stabilisers (Pty) Ltd
1986/004184/07
PO Box 84513 Greenside
2034 Johannesburg Gauteng
Republic of South Africa
Tel 27 (0)11 390 3499
Fax 27 (0)11 390 3284
E-mail info@roadmaterial.co.za
Website www.roadmaterial.co.za

SASBIND

DATE: 03/06/2004
REVISED: 19/01/2005

DESCRIPTION:
SASBIND is a uniquely formulated water based emulsion of modified acrylic polymers suitable for the binding and stabilisation of layers for use in the construction of all types of roads. SASBIND is also suitable for application to the surface of already constructed roads requiring dust palliation.

APPLICATION RATES:

Stabilisation:	0.4-0.7% MDD
Seal coat:	0.1 ℓ/m^2

(Application rates are offered as a guide, use as directed)

BENEFITS:
- Water-based (mixes in with compaction water)
- Suitable for application to a wide variety of soil types
- No specialised equipment required
- Minimal disruption to traffic
- Reduces erodibility and improves waterproofing of unsurfaced roads
- Increases CBR and UCS significantly

PREPARATION:
- Establish the suitability of the soil for use with SASBIND
- Add the required quantity of SASBIND directly to the water bowser with the compaction water

APPLICATION:
Mix-in
- Rip the layer to 100-150 mm and break large agglomerations to max 50 mm
- Calculate the approximate volume of water required to reach OMC
- Add the required quantity of SASBIND to required quantity of water
- Apply the solution onto prepared surface in 2-4 applications, mixing thoroughly between applications
- Shape to required camber and compact with pneumatic or vibratory roller to required density
- Apply the seal coat if required to the road surface while still damp and allow to dry (approx 1-2 hours)

Surface treatments (spray-on application)
- Road structure: well compacted base or wearing coarse layer; density >93%.
- Ensure the road surface is firm, free of excess loose material and with sufficient camber to ensure proper drainage
- Apply the product in multiple applications using the prescribed dilution ratio. Avoid run-off and pooling

CHARACTERISTICS:

Appearance	milky white liquid
Specific gravity	1.04 @ 25°C
pH	7 ±1
Odour	mild Acrylic
Solids %m/m	46-55
Diluent	water

HAZARDS:		PRECAUTIONS:	FIRST AID:
Fire	non-flammable	–	–
Explosion:	non-explosive	–	–
Skin	slightly Irritating when undiluted	Wear protective clothing for sensitive skins	Rinse with water
Ingestion	irritant	Do not ingest	Do not induce vomiting*
Eyes	slightly irritating	Avoid splashing	Flush with water for min 20 min*
			(Seek prompt medical advice)

STORAGE:

Maximum handling temperature	75°C
Storage temperature	5-60°C
Transport temperature	5-60°C

PACKAGING / LABELLING:

Packed:	200 kg mild steel drums
Label:	including description, application, first aid and batch number

TECHNICAL DATA SHEET

Road Material Stabilisers (Pty) Ltd
1986/004184/07
PO Box 84513 Greenside
2034 Johannesburg Gauteng
Republic of South Africa
Tel 27 (0)11 390 3499
Fax 27 (0)11 390 3284
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SASBIND

DATE: 03/06/2004
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DESCRIPTION:
SASBIND is a uniquely formulated water based emulsion of modified acrylic polymers suitable for the binding and stabilisation of layers for use in the construction of all types of roads. SASBIND is also suitable for application to the surface of already constructed roads requiring dust palliation.

APPLICATION RATES:

Stabilisation: 0.4-0.1% MDD
Seal coat: 0.1 ℓ/m^2

(Application rates are offered as a guide, use as directed)

BENEFITS:

- Water-based (mixes in with compaction water)
- Suitable for application to a wide variety of soil types
- No specialised equipment required
- Minimal disruption to traffic
- Reduces erodibility and improves waterproofing of unsurfaced roads
- Increases CBR and UCS significantly

PREPARATION:

- Establish the suitability of the soil for use with SASBIND
- Add the required quantity of SASBIND directly to the water bowser with the compaction water

APPLICATION:

Mix-in

- Rip the layer to 100-150 mm and break large agglomerations to max 50 mm
- Calculate the approximate volume of water required to reach OMC
- Add the required quantity of SASBIND to required quantity of water
- Apply the solution onto prepared surface in 2-4 applications, mixing thoroughly between applications
- Shape to required camber and compact with pneumatic or vibratory roller to required density
- Apply the seal coat if required to the road surface while still damp and allow to dry (approx 1-2 hours)

Surface treatments (spray-on application)

- Road structure: well compacted base or wearing coarse layer; density >93%.
- Ensure the road surface is firm, free of excess loose material and with sufficient camber to ensure proper drainage
- Apply the product in multiple applications using the prescribed dilution ratio. Avoid run-off and pooling

CHARACTERISTICS:

Appearance	-	milky black liquid
Specific gravity	-	1.04 @ 25°C
pH	-	7 ±1
Odour	-	mild Acrylic
Solids %m/m	-	46-55
Diluent	-	water

HAZARDS:		PRECAUTIONS:	FIRST AID:
Fire	- non-flammable	–	–
Explosion:	- non-explosive	–	–
Skin	- slightly Irritating when undiluted	Wear protective clothing for sensitive skins	Rinse with water
Ingestion	- irritant	Do not ingest	Do not induce vomiting*
Eyes	- slightly irritating	Avoid splashing	Flush with water for min 20 min*
			(Seek prompt medical advice)

STORAGE:

Maximum handling temperature	-	75°C
Storage temperature	-	5-60°C
Transport temperature	-	5-60°C

PACKAGING / LABELLING:

Packed:	-	200 kg mild steel drums
Label:	-	including description, application, first aid and batch number

Appendix B

Petrographic analysis (thin section description)

Sample: KSU-1

Macroscopic rock description

Very fine grained, dark grey colored rock with alternating light and dark layers.

Microscopic rock description

Composition: Quartz (55%), Clay minerals (30%), Mica (5%), Iron oxide (3%), Feldspar (7%), Rock fragments (<1%), Carbon (0%) (extremely fine grained nature of rock makes petrographic description particularly difficult).

Grain size: Very fine grained (<40μmm).

Sorting: Very well sorted.

Rounding: Very well rounded.

Clast / Matrix supported: Predominantly matrix supported layers.

Other textures: Horizontal layers (i.e. rhythmite).

Description: The rock is a rhythmically layered sedimentary rock consisting of lighter and darker brown interlayers as seen in Figure 53. The rock is extremely fine grained, which makes the petrographic analysis extremely difficult.

Sample: KSAG-1

Macroscopic rock description

Very fine grained, dark grey colored rock with alternating light and dark layers.

Microscopic rock description

Composition: Quartz (48%), Clay minerals (34%), Mica (7%), Iron oxide (3%), Feldspar (8%), Rock fragments (<1%), Carbon (0%) (extremely fine grained nature of rock makes petrographic description particularly difficult).

Grain size: Very fine grained (<30μmm).

Sorting: Very well sorted.

Rounding: Very well rounded.

Clast / Matrix supported: Predominantly matrix supported layers.

Other textures: Horizontal layers (i.e. rhythmite).

Description: The rock is a rhythmically layered sedimentary rock consisting of lighter and darker brown interlayers as seen in Figure 53. The rock is extremely fine grained, which makes the petrographic analysis extremely difficult.

Appendix C

PANalytical
Results quantitative - MajorBasic32+Zn
Major element analysis by XRF, Rh Tube, 3kWatt
BDL = Below Detection Limit
Note: LOI = weight loss or gain at 1000°C.
LOI (loss on ignition) includes the total of volatiles content of the rock (including the water combined to the lattice of silicate minerals) and the gain on ignition related to the oxidation of the rock (mostly due to Fe).

Row	Sample name			Meas. date/time	Al2O3 (%)	CaO (%)	Cr2O3 (%)	Fe2O3 (%)	K2O (%)	MgO (%)	MnO (%)	Na2O (%)	P2O5 (%)	SiO2 (%)	TiO2 (%)	L.O.I. (%)	Sum Of Conc. (%)
12	WILMAR	KBU1	Majors Interm32	17/03/2017 20:17	16.91	0.58	0.01	6.54	2.43	1.55	0.05	0.64	0.08	52.01	0.79	16.43	98.01
13	WILMAR	KB2	Majors Interm32	17/03/2017 20:26	17.59	0.57	0.02	6.54	2.63	1.62	0.05	0.62	0.08	52.13	0.81	15.45	98.11
16	BE-N																
17	Basalt Reference values				10.05	14.03		12.84	1.40	13.15	0.20	3.18	1.06	38.38	2.59		96.88
19	BE-N	STD	Majors Interm32	15/01/2016 16:01	10.05	14.06	0.01	12.88	1.41	13.23	0.20	3.16	1.08	38.25	2.69		97.02
20	BEN	std	MajorBasic32+Zn	02/02/2016 22:16	10.06	14.02	0.05	12.82	1.41	13.18	0.20	3.11	1.09	37.95	2.64		96.53
21	BE-N	STD	Majors Interm32	12/02/2016 19:49	9.96	14.06	0.01	12.85	1.40	13.23	0.20	3.15	1.07	38.14	2.69		96.76
22	BE-N	STD	MajorBasic32+Zn	12/02/2016 19:56	10.09	14.02	0.05	12.80	1.41	13.20	0.20	3.16	1.09	37.92	2.63		96.57
23	BE-N	std	MajorBasic32+Zn	08/03/2016 16:42	10.10	14.05	0.05	12.85	1.42	13.28	0.19	3.11	1.09	38.18	2.66		96.98
24	BE-N	STD	Majors Interm32	09/03/2016 16:42	9.87	14.06	0.05	12.90	1.41	13.01	0.20	3.05	1.10	37.83	2.67		96.15
25	BE-N	std	MajorBasic32+Zn	18/03/2016 23:56	10.05	14.03	0.05	12.84	1.42	13.26	0.19	3.11	1.09	37.99	2.65		96.68
26	BE-N	STD	MajorBasic32+Zn	23/03/2016 14:08	10.08	14.04	0.05	12.87	1.40	13.23	0.20	3.12	1.10	38.10	2.67		96.86
27	BE-N	STD	MajorBasic32+Zn	15/04/2016 06:31	10.10	14.02	0.05	12.85	1.42	13.13	0.19	3.11	1.09	37.99	2.65		96.60
28	BE-N	STD	MajorBasic32+Zn	19/04/2016 08:41	10.04	14.03	0.05	12.80	1.40	13.12	0.20	3.13	1.10	38.08	2.67		96.62
29	BE-N	STD	MajorBasic32+Zn	20/04/2016 00:50	10.10	14.03	0.05	12.88	1.42	13.12	0.20	3.13	1.10	37.94	2.64		96.61
30	BE-N	STD	MajorBasic32+Zn	05/05/2016 01:05	10.01	14.06	0.05	12.84	1.42	13.08	0.20	3.18	1.09	38.19	2.65		96.77
31	BE-N	STD	MajorBasic32+Zn	05/05/2016 21:37	10.09	14.03	0.05	12.83	1.42	13.14	0.21	3.18	1.09	37.97	2.64		96.65
32	BE-N	std	MajorBasic32+Zn	17/05/2016 13:43	10.04	14.04	0.05	12.79	1.41	13.07	0.20	3.17	1.08	37.98	2.66		96.49
33	BEN	STD	MajorBasic32+Zn	20/05/2016 10:34	10.04	14.01	0.05	12.87	1.42	13.13	0.19	3.16	1.08	37.89	2.64		96.48
34	BE-N	STD	MajorBasic32+Zn	07/06/2016 00:54	10.06	14.06	0.05	12.82	1.42	13.13	0.20	3.18	1.08	38.11	2.65		96.76
35	BE-N	STD	MajorBasic32+Zn	07/06/2016 23:52	10.05	14.03	0.05	12.82	1.41	13.11	0.20	3.19	1.09	38.16	2.65		96.76
36	BE-N	std	MajorBasic32+Zn	20/06/2016 15:58	10.14	14.03	0.05	12.88	1.41	13.07	0.20	3.07	1.08	38.19	2.66		96.78
37	BE-N	STD	MajorBasic32+Zn	11/07/2016 14:36	10.04	13.94	0.05	12.83	1.42	13.18	0.19	2.42	1.10	38.64	2.65		96.46
38	BE-N	STD	MajorBasic32+Zn	22/07/2016 20:59	10.08	14.04	0.05	12.79	1.41	13.14	0.20	3.17	1.10	38.30	2.66		96.94
39	BE-N	std	MajorBasic32+Zn	02/08/2016 23:54	10.04	14.02	0.05	12.79	1.41	13.13	0.20	3.12	1.09	37.99	2.66		96.50
40	BE-N	std	MajorBasic32+Zn	24/08/2016 21:10	10.01	14.05	0.05	12.80	1.41	13.12	0.19	3.12	1.10	37.94	2.64		96.43
41	BE-N	std	MajorBasic32+Zn	02/09/2016 12:51	10.03	14.00	0.05	12.79	1.41	13.20	0.20	3.21	1.09	37.81	2.65		96.44
42	BE-N	STD	MajorBasic32+Zn	07/09/2016 17:19	10.06	14.12	0.04	12.89	1.42	13.18	0.20	3.16	1.09	38.17	2.66		96.99
43	BE-N	STD	MajorBasic32+Zn	07/10/2016 23:04	10.08	14.13	0.05	12.84	1.37	13.12	0.20	3.14	1.07	38.26	2.64		96.90
44	BE-N	STD	MajorBasic32+Zn	19/10/2016 18:55	10.01	14.11	0.05	12.84	1.37	13.06	0.20	3.15	1.07	37.92	2.64		96.42
45	BE-N	STD	MajorBasic32+Zn	20/10/2016 23:07	10.09	14.10	0.05	12.78	1.37	13.15	0.20	3.10	1.07	37.97	2.62		96.50
46	BE-N	STD	MajorBasic32+Zn	08/11/2016 22:32	9.99	14.11	0.05	12.84	1.41	13.13	0.19	3.11	1.10	38.11	2.64		96.68
47	BE-N	STD	MajorBasic32+Zn	28/11/2016 20:16	10.04	14.14	0.05	12.82	1.41	13.08	0.20	3.19	1.09	37.90	2.65		96.57
48	BE-N	STD	MajorBasic32+Zn	10/12/2016 00:23	10.05	14.09	0.05	12.83	1.41	13.08	0.00	3.12	1.08	37.92	2.65		96.28
49	BE-N	STD	MajorBasic32+Zn	08/03/2017 14:47	10.08	14.04	0.05	12.78	1.42	13.19	0.20	3.16	1.08	38.28	2.63		96.91
50	BE-N	STD	Majors Interm32	17/03/2017 13:03	9.90	14.01	0.05	12.86	1.41	12.93	0.20	3.01	1.10	37.90	2.64		96.01
51	BE-N	std	MajorBasic32+Zn	17/03/2017 12:55	10.07	14.07	0.05	12.86	1.41	13.04	0.20	3.05	1.10	38.08	2.64		96.57
52	BE-N	STD	Majors Interm32	17/03/2017 13:03	9.90	14.01	0.05	12.86	1.41	12.93	0.20	3.01	1.10	37.90	2.64		96.01
55	Average				10.03	14.04	0.04	12.85	1.41	13.20	0.20	3.12	1.09	38.05	2.66	#DIV/0!	96.72
56	Relative standard deviation (%)				0.17	0.10		0.09	0.75	0.40	1.25	1.81	2.27	0.88	2.85	#DIV/0!	0.17
60	JB-1				14.53	9.29	0.07	8.97	1.43	7.73	0.16	2.79	0.26	52.17	1.34		98.74
61	Basalt (depleted) Reference values																
63	JB-1	STD	Majors Interm32	15/01/2016 15:52	14.62	9.27	0.01	8.87	1.44	7.84	0.16	2.79	0.26	52.61	1.33		99.20
64	JB-1	STD	Majors Interm32	12/02/2016 19:15	14.58	9.30	0.01	8.86	1.44	7.80	0.16	2.80	0.27	52.45	1.32		98.99
65	JB-1	STD	MajorBasic32+Zn	12/02/2016 19:23	14.66	9.26	0.06	8.84	1.44	7.71	0.17	2.83	0.26	52.43	1.31		98.97
66	JB-1	std	MajorBasic32+Zn	08/03/2016 17:06	14.72	9.29	0.06	8.84	1.45	7.82	0.16	2.79	0.26	52.82	1.31		99.52
67	JB-1	STD	Majors Interm32	09/03/2016 16:34	14.48	9.30	0.07	8.89	1.43	7.69	0.16	2.75	0.27	52.20	1.32		98.56
68	JB-1	std	MajorBasic32+Zn	19/03/2016 00:20	14.82	9.29	0.06	8.85	1.44	7.82	0.16	2.77	0.26	52.76	1.32		99.55
69	JB-1	STD	MajorBasic32+Zn	23/03/2016 14:39	14.66	9.29	0.06	8.86	1.44	7.82	0.16	2.77	0.26	53.02	1.31		99.65
70	JB-1	STD	MajorBasic32+Zn	15/04/2016 06:41	14.70	9.29	0.06	8.87	1.45	7.73	0.17	2.84	0.26	52.71	1.31		99.39
71	JB-1	STD	MajorBasic32+Zn	19/04/2016 08:50	14.64	9.26	0.06	8.85	1.44	7.72	0.16	2.81	0.27	52.94	1.31		99.46
72	JB-1	STD	MajorBasic32+Zn	20/04/2016 00:59	14.71	9.25	0.06	8.84	1.43	7.73	0.16	2.79	0.26	52.80	1.31		99.34
73	JB-1	STD	MajorBasic32+Zn	05/05/2016 01:14	14.74	9.28	0.06	8.87	1.46	7.72	0.17	2.81	0.27	52.85	1.31		99.54
74	JB-1	STD	MajorBasic32+Zn	05/05/2016 21:46	14.68	9.24	0.07	8.86	1.44	7.74	0.16	2.82	0.26	52.71	1.32		99.30
75	JB-1	std	MajorBasic32+Zn	17/05/2016 13:53	14.67	9.31	0.06	8.84	1.44	7.76	0.16	2.83	0.27	52.76	1.31		99.41
76	JB-1	STD	MajorBasic32+Zn	20/05/2016 10:51	14.69	9.28	0.06	8.86	1.43	7.69	0.16	2.80	0.27	52.80	1.32		99.36
77	JB-1	STD	MajorBasic32+Zn	07/06/2016 01:03	14.71	9.30	0.07	8.85	1.44	7.74	0.16	2.81	0.27	52.74	1.31		99.40
78	JB-1	STD	MajorBasic32+Zn	08/06/2016 00:01	14.64	9.30	0.06	8.86	1.44	7.69	0.16	2.78	0.27	52.75	1.32		99.27
79	JB-1	std	MajorBasic32+Zn	20/06/2016 16:07	14.80	9.25	0.06	8.84	1.45	7.69	0.16	2.80	0.27	53.03	1.31		99.66
80	JB-1	std	MajorBasic32+Zn	11/07/2016 14:53	14.65	9.15	0.06	8.80	1.45	7.67	0.16	2.15	0.26	52.46	1.31		98.12
81	JB-1	STD	MajorBasic32+Zn	22/07/2016 21:15	14.61	9.30	0.06	8.86	1.45	7.73	0.16	2.88	0.27	53.00	1.31		99.63
82	JB-1	std	MajorBasic32+Zn	03/08/2016 00:03	14.73	9.28	0.06	8.85	1.45	7.73	0.16	2.81	0.26	53.01	1.32		99.66
83	JB-1	std	MajorBasic32+Zn	24/08/2016 21:19	14.72	9.27	0.06	8.85	1.46	7.79	0.16	2.81	0.27	52.95	1.30		99.64
84	JB-1	std	MajorBasic32+Zn	02/09/2016 13:08	14.67	9.29	0.06	8.84	1.44	7.74	0.16	2.84	0.27	52.84	1.31		99.46
85	JB-1	STD	MajorBasic32+Zn	07/09/2016 17:28	14.64	9.35	0.06	8.87	1.45	7.78	0.16	2.83	0.27	52.91	1.31		99.63
86	JB-1	STD	MajorBasic32+Zn	07/10/2016 23:13	14.72	9.33	0.06	8.90	1.40	7.72	0.16	2.80	0.26	53.10	1.29		99.74
87	JB-1	STD	MajorBasic32+Zn	19/10/2016 18:13	14.74	9.36	0.06	8.86	1.41	7.72	0.17	2.78	0.26	52.79	1.29		99.44
88	JB-1	STD	MajorBasic32+Zn	20/10/2016 23:16	14.71	9.34	0.06	8.87	1.40	7.74	0.16	2.86	0.27	52.95	1.28		99.64
89	JB-1	STD	MajorBasic32+Zn	08/11/2016 22:41	14.63	9.32	0.06	8.86	1.44	7.71	0.16	2.81	0.27	52.76	1.31		99.33
90	JB-1	STD	MajorBasic32+Zn	28/11/2016 20:25	14.64	9.33	0.07	8.85	1.43	7.73	0.16	2.81	0.26	52.96	1.32		99.56
91	JB-1	STD	MajorBasic32+Zn	10/12/2016 00:32	14.70	9.27	0.07	8.83	1.44	7.74	0.00	2.81	0.27	52.62	1.31		99.06
92	JB-1	STD	MajorBasic32+Zn	08/03/2017 15:12	14.80	9.29	0.06	8.84	1.45	7.82	0.16	2.85	0.28	52.94	1.31		99.80
93	JB-1	STD	Majors Interm32	17/03/2017 13:19	14.55	9.28	0.07	8.88	1.42	7.66	0.16	2.71	0.27	52.54	1.31		98.85
94	JB-1	std	MajorBasic32+Zn	17/03/2017 13:11	14.70	9.35	0.06	8.86	1.44	7.76	0.17	2.79	0.28	52.81	1.31		99.53
95	JB-1	STD	Majors Interm32	17/03/2017 13:19	14.55	9.28	0.07	8.88	1.42	7.66	0.16	2.71	0.27	52.54	1.31		98.85

Average			14.60	9.29	0.01	8.87	1.44	7.82	0.16	2.80	0.27	52.53	1.33	#DIV/0!	99.10
Relative standard deviation (%)			0.48	0.05	85.29	1.17	0.70	1.16	0.00	0.18	1.92	0.69	1.12		0.36
SY-3															
Syenite Reference values			**11.60**	**8.31**		**6.49**	**4.10**	**2.72**	**0.32**	**3.97**	**0.55**	**59.62**	**0.15**		**97.83**
sy3 std	Majors Interm32	04/05/2015 20:39	11.44	8.17	0.00	6.33	4.15	2.62	0.33	3.98	0.54	59.23	0.16		96.95
SY-3	Majors Interm32	27/08/2015 16:00	11.44	8.11	0.00	6.31	4.17	2.60	0.33	4.01	0.53	58.78	0.17		96.45
Standard SY-3	Majors Interm32	14/09/2015 17:04	11.58	8.13	0.00	6.30	4.18	2.61	0.32	4.09	0.53	59.20	0.17		97.11
SY-3 STD	Majors Interm32	14/10/2015 19:57	11.52	8.11	0.00	6.30	4.18	2.65	0.31	4.03	0.53	59.03	0.16		96.82
SY-3 STD	Majors Interm32	15/10/2015 20:03	11.57	8.11	0.00	6.31	4.17	2.62	0.32	4.04	0.53	59.09	0.16		96.92
SY-3 STD	Majors Interm32	20/10/2015 14:33	11.44	8.10	0.00	6.28	4.14	2.62	0.32	4.02	0.53	58.69	0.17		96.31
SY-3 STD	Majors Interm32	29/10/2015 13:12	11.51	8.14	0.01	6.32	4.19	2.64	0.31	4.05	0.54	59.16	0.17		97.04
SY-3 STD	Majors Interm32	15/01/2016 16:20	11.54	8.16	0.00	6.33	4.20	2.65	0.32	4.00	0.53	59.17	0.17		97.07
sy-3 STD	Majors Interm32	08/03/2017 17:11	11.65	8.15	0.00	6.33	4.16	2.66	0.32	4.03	0.53	59.45	0.17		97.45
SY-3 STD	Majors Interm32	17/03/2017 13:56	11.38	8.16	0.00	6.31	4.15	2.55	0.32	3.89	0.54	58.66	0.17		96.13
Average			11.51	8.13		6.31	4.17	2.62	0.32	4.01	0.53	59.05	0.17		96.83
Relative standard deviation (%)			0.80	2.12		2.74	1.68	3.60	0.00	1.11	3.09	0.96	11.33		1.03
NIM-S															
Syenite Reference values			**17.34**	**0.68**		**1.40**	**15.35**	**0.46**	**0.01**	**0.43**	**0.12**	**63.60**	**0.04**		**99.43**
NIM-S STD	Majors Interm32	31/07/2015 19:07	17.23	0.66	0.00	1.39	15.41	0.44	0.01	0.47	0.12	63.99	0.05		99.77
NIM-S STD	Majors Interm32	14/10/2015 20:16	17.28	0.67	0.00	1.38	15.26	0.42	0.01	0.47	0.12	63.58	0.04		99.23
NIM-S STD	Majors Interm32	15/10/2015 20:22	17.25	0.68	0.00	1.38	15.26	0.44	0.01	0.47	0.12	63.34	0.04		98.99
NIM-S STD	Majors Interm32	29/10/2015 13:21	17.30	0.67	0.01	1.39	15.37	0.44	0.01	0.47	0.12	63.76	0.04		99.58
NIM-S STD	Majors Interm32	15/01/2016 16:10	17.25	0.67	0.01	1.39	15.37	0.44	0.01	0.44	0.12	63.79	0.04		99.53
nim-s STD	Majors Interm32	08/03/2017 17:20	17.51	0.67	0.00	1.39	15.22	0.44	0.01	0.46	0.12	64.02	0.04		99.88
NIM-S STD	Majors Interm32	17/03/2017 14:05	17.03	0.67	0.00	1.39	15.23	0.43	0.01	0.45	0.12	63.26	0.04		98.63
Average			17.27	0.67		1.39	15.33	0.44	0.01	0.47	0.12	63.67	0.04	#DIV/0!	99.39
Relative standard deviation (%)			0.43	1.47		1.07	0.16	5.43	0.00	9.30	0.00	0.11	6.25		0.04
Quality control for 2010-2011															
Average HUSG		############	**13.75**	**1.52**	**0.00**	**3.78**	**4.66**	**1.04**	**0.06**	**2.57**	**0.21**	**69.77**	**0.54**	**0.73**	**98.65**
STDEV		############	**0.20**	**0.04**	**0.00**	**0.14**	**0.06**	**0.04**	**0.01**	**0.18**	**0.01**	**0.54**	**0.02**	**0.05**	**0.71**
MIN		############	**13.04**	**1.48**	**0.00**	**3.64**	**4.55**	**0.94**	**0.05**	**2.30**	**0.20**	**68.42**	**0.52**	**0.53**	**97.23**
MAX		############	**14.30**	**1.63**	**0.01**	**4.56**	**4.80**	**1.22**	**0.08**	**3.30**	**0.23**	**70.96**	**0.60**	**0.80**	**100.40**
HUSG STD	Majors Acid32	15/01/2016 11:44	13.87	1.58	0.00	3.75	4.68	1.11	0.06	2.74	0.22	70.73	0.56	0.90	100.20
HUSG STD	Majors Interm32	15/01/2016 11:52	13.87	1.56	0.01	3.75	4.65	1.11	0.06	2.69	0.23	70.81	0.56	0.90	100.20
HUSG-1 std	Majors Acid32	01/02/2016 14:31	13.84	1.57	0.00	3.74	4.67	1.11	0.05	2.73	0.22	70.51	0.56	0.90	99.90
HUSG-1 std	Majors Acid32	04/02/2016 21:12	13.84	1.56	0.01	3.73	4.65	1.11	0.06	2.71	0.22	70.37	0.56	0.90	99.72
HUSG-1 STD	Majors Interm32	12/02/2016 15:49	13.76	1.57	0.01	3.74	4.65	1.11	0.06	2.71	0.21	70.36	0.54	0.90	99.62
HUSG-1 std	Majors Acid32	08/03/2016 16:25	13.69	1.58	0.01	3.75	4.68	1.11	0.06	2.64	0.22	70.63	0.56	0.90	99.83
HUS-G std	Majors Acid32	14/03/2016 23:14	13.68	1.57	0.01	3.74	4.64	1.10	0.05	2.63	0.22	70.58	0.57	0.90	99.69
HUSG-1 STD	Majors Acid32	18/03/2016 23:39	13.59	1.58	0.01	3.74	4.65	1.11	0.06	2.61	0.23	70.61	0.57	0.90	99.66
HUSG-1 STD	Majors Acid32	12/04/2016 23:40	13.67	1.57	0.01	3.74	4.62	1.10	0.06	2.63	0.23	70.34	0.56	0.90	99.43
HUSG-1 STD	Majors Acid32	15/04/2016 05:56	13.69	1.57	0.01	3.75	4.65	1.10	0.06	2.63	0.23	70.39	0.56	0.90	99.54
HUSG-1 std	Majors Acid32	05/05/2016 00:24	13.69	1.57	0.01	3.76	4.65	1.10	0.06	2.61	0.22	70.41	0.57	0.90	99.55
HUSG-1 STD	Majors Acid32	07/06/2016 00:45	13.75	1.57	0.00	3.75	4.65	1.08	0.06	2.62	0.22	70.41	0.57	0.90	99.58
HUS-G std	MajorBasic32+Zn	20/06/2016 15:49	13.90	1.56	0.00	3.72	4.66	1.00	0.05	2.69	0.22	71.37	0.54	0.90	100.61
HUS-G STD	MajorBasic32+Zn	11/07/2016 14:11	13.87	1.54	0.00	3.71	4.65	1.02	0.05	2.03	0.22	70.36	0.55	0.90	98.90
HUSG-1 STD	Majors Acid32	27/07/2016 00:04	13.63	1.57	0.00	3.73	4.66	1.10	0.06	2.66	0.23	70.59	0.57	0.90	99.70
HUS-G std	Majors Acid32	22/08/2016 23:53	13.67	1.55	0.00	3.73	4.64	1.09	0.06	2.60	0.22	70.60	0.58	0.90	99.64
HUSG-1 std	Majors Acid32	24/08/2016 21:01	13.66	1.57	0.00	3.74	4.67	1.09	0.06	2.61	0.22	70.43	0.57	0.90	99.52
HUSG-1 std	Majors Acid32	25/08/2016 17:34	13.65	1.57	0.00	3.74	4.67	1.10	0.06	2.61	0.22	70.48	0.56	0.90	99.56
HUSG-1 std	Majors Acid32	31/08/2016 02:48	13.61	1.57	0.00	3.74	4.63	1.10	0.06	2.62	0.23	70.41	0.56	0.90	99.43
HUSG-1 STD	Majors Acid32	01/09/2016 04:17	13.67	1.56	0.00	3.74	4.63	1.10	0.06	2.64	0.22	70.52	0.56	0.90	99.60
HUSG-1 STD	Majors Acid32	02/09/2016 14:28	13.69	1.56	0.00	3.74	4.64	1.10	0.06	2.62	0.22	70.52	0.56	0.90	99.61
HUSG-1 STD	Majors Acid32	07/09/2016 16:54	13.66	1.57	0.00	3.74	4.64	1.11	0.06	2.60	0.22	70.39	0.56	0.90	99.45
HUS-G STD	Majors Acid32	17/10/2016 21:33	13.62	1.55	0.00	3.74	4.66	1.08	0.06	2.50	0.22	70.40	0.56	0.90	99.29
HUSG-1 STD	Majors Acid32	30/09/2016 05:48	13.53	1.54	0.00	3.73	4.66	1.10	0.06	2.54	0.22	70.55	0.56	0.90	99.39
HUSG-1 std	Majors Acid32	02/11/2016 20:58	13.53	1.55	0.00	3.73	4.63	1.08	0.06	2.47	0.22	70.52	0.56	0.90	99.25
HUSG-1 STD	Majors Acid32	28/11/2016 19:51	13.63	1.58	0.00	3.75	4.64	1.11	0.05	2.60	0.23	70.63	0.56	0.90	99.68
HUSG-1 std	Majors Acid32	17/03/2017 08:38	13.72	1.57	0.00	3.73	4.63	1.08	0.06	2.59	0.22	70.39	0.57	0.90	99.46
HUSG-1 STD	Majors Interm32	17/03/2017 12:46	13.75	1.56	0.01	3.74	4.61	1.08	0.05	2.59	0.22	70.55	0.54	0.90	99.60
Average			13.79	1.57	0.01	3.74	4.66	1.11	0.06	2.69	0.22	70.57	0.56	0.90	99.88
Relative standard deviation (%)			0.34	3.20	45.08	0.89	0.10	6.17	11.31	4.82	3.53	1.15	2.98	23.28	1.25