Comparison of the engineering geological properties of near surface and deep sedimentary rocks of the Karoo Supergroup, South Africa

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Declaration

I, **Hendre Human** (the undersigned), declare that the thesis/ dissertation, **Comparison of the engineering geological properties of near surface and deep sedimentary rocks of the Karoo Supergroup, South Africa,** which I herby submit for the degree **MSc Engineering Geology** at the **University of Pretoria,** is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

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Abstract

The sedimentary rocks of the Karoo Supergroup cover approximately 75% of the surface area of South Africa. Major projects have been constructed on and in these rocks with a number of tunnelling projects such as the Lesotho Highlands Water Project and the Orange-Fish Tunnel. The mechanical properties of these rocks have been well studied and recorded through research and construction projects. During the exploration phase for shale gas, two deep boreholes were drilled in the southern part of the Main Karoo Basin, near Willowvale and Ceres. This provided the opportunity to access rock samples from deep formations. Various laboratory tests were done on selected cores to be able to determine the engineering properties and strength characteristics of the deep Karoo Supergroup rocks, and these engineering properties and strength characteristics are compared to the shallow or near surface rocks, which is presented in this dissertation. Five core samples from the Willowvale borehole (KWV-01) were retrieved for laboratory testing, which include samples of a dolerite sill, sandstone from the Pluto's Vale Member, carbonaceous shale from the Whitehill Formation, massive shale from the Prince Albert Formation, and lastly, tillite from the Dwyka Group. Four core samples were retrieved from the Ceres borehole (KZF-01) and, included fine sandstone from the Tierberg Formation, carbonaceous shale from the Whitehill Formation, shale from the Prince Albert Formation and diamictite from the Dwyka Group. The density, porosity, water absorption, specific gravity, slake durability, free swelling and mineralogy of the different rock samples were determined and compared between the two boreholes (KZF-1 & KWV-1), as well as with those of the known properties of the near surface Karoo rocks published in literature, and also results from twelve surface samples collected during this research project. The Geodurability Classification system is used to classify the core samples, so as to determine its durability. The sandstone, shale and tillite show increased UCS, durability, density, and lower expansiveness when moving from surface deeper into the Main Karoo Basin rocks.

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1. Introduction

The sedimentary rocks of the Karoo Supergroup cover approximately 75% of the surface area of South Africa. Major projects have been constructed on and in these rocks with a number of tunnelling projects, such as the Lesotho Highlands Water Project and the Orange-Fish Tunnel. The mechanical properties of these rocks exposed to the natural environment and in near surface projects have been well studied and recorded via research and construction projects. During the exploration phase for shale gas, two deep boreholes were drilled in the southern part of the Main Karoo Basin, near Willowvale and Ceres. The Cimera-Karin research unit at University of Johannesburg, collaborating with seven other universities analysed data from the first borehole in the Tankwa Karoo in the Witzenberg (Ceres) District in order to explore the geology, and in particular the shale gas potential of the southern Karoo Basin. Another borehole was then drilled near Willowvale in the Eastern Cape Province in the south-eastern part of the Main Karoo Basin, in order to create a more clear view and expectation of the geology and rock properties. Core retrieved from the two boreholes provided the opportunity to access rock samples from deep formations.

This research project aims to compare the general engineering properties and strength characteristics of the Karoo Supergroup rocks at depth with the known properties at or near the surface. The main aim of this research project is to compare the engineering properties and strength characteristics, which are determined by various tests done on the selected core samples. Rocks of the Main Karoo Basin were tested, and the shallow near surface rock properties are compared with the deep Karoo rock properties. The geomechanical-, engineering properties and mineralogy of the sedimentary Karoo Supergroup rocks were then evaluated, and the near surface Karoo rocks were compared to the deep Karoo rocks of the same lithologies. The research project enables a determination as to whether the near surface and deep Karoo rocks of the same lithological deposition have similar properties and to identify the differences in engineering geological properties in terms of their localities to varying depth from surface.

Different tests were done on selected core samples that are located hundreds of metres below the surface, where these results are then compared to the properties of near or outcropping rocks, data from published literature and from surface sample information determined in the dissertation. The two deep boreholes, namely KZF-1 and KWV-1 were drilled in the southern and south-eastern part of the Main Karoo Basin, in order to explore the geology, which exposed the rock cores for the required testing. The geomechanical- engineering properties and mineralogy of the different lithologies of the two boreholes (KWV-01 and KZF-01) are also compared with one another. Further tests were also required to be done on samples collected on the surface, where the lithologies of interest outcropped and are exposed. The specific tests necessary to determine the engineering properties, strength characteristics such as hardness, density and durability of the samples for the dissertation are uniaxial compressive strength test, sonic wave velocity test, and slake durability test. The reactivity, physical properties and chemical composition of the samples are determined by the Duncan “Free” swell test, Ethylene Glycol soak test, porosity and water absorption tests, XRD and XRF tests. These tests will indicate easily degradable clay minerals, minerals prone for swelling and shrinking under prolonged changed environmental conditions contained in the samples.

The engineering properties and strength characteristics of each tested lithological unit consist of a range of values, however the purpose of the dissertation would contribute to the determination as to whether the current depth from surface of the specific lithologies have an effect on the properties. The dissertation would also indicate whether the engineering properties and strength characteristics of the specific lithologies consist of constant values over the entire Main Karoo Basin, or whether there is a large difference in the values determined based on the rock sample locality.

2. Literature Review

2.1.1. Depositional Environments

The Dwyka Group is the oldest unit of the Karoo Supergroup and reflects a Godwana glaciation from 302 to 290 Ma. The Dwyka Group is present over a large area of South Africa and contains both marine and continental facies. The Dwyka Group comprises of four upward-fining sequences of massive to stratified diamictites which reaches a thickness of up to 800m. The diamictites are composed from a silt-dominated matrix with dropstones of variable sizes, shapes, and compositions which has derived from floating ice (Fagereng, 2014).

The Main Karoo retro-arc basin dates to be deposited from the Late Carboniferous to the middle Jurassic years. The Karoo Supergroup attains a maximum thickness of 6 – 8 km in the south. In the Main Karoo Basin the lower Ecca Group shales (Prince Albert Formation) are interpreted to be a marine basin or shelf deposits. Little is known about the degree of metamorphism of the Karoo Supergroup, however the Cape Fold Belt have undergone, lower greenschist grade (approximately 200 ˚C) metamorphism at most. The Prince Albert Formation consists of cherty and phosphatic siltstone and mudstone beds as seen in Figure 1. The Prince Albert Formation was deposited as syn- to post-glacial suspension fall-out and flocculations of fines from large inflows of sediment-laden water with some input by periodic turbidites and mud flows of semi-consolidated sediments (Herbert & Compton, 2007). The upper part of the Ecca Group reflects a filled stage of shallow marine sedimentation followed by the overfilled style of fluvial sedimentation of the overlying Beaufort and Stormberg Groups (Catuneanu, et al., 2005).

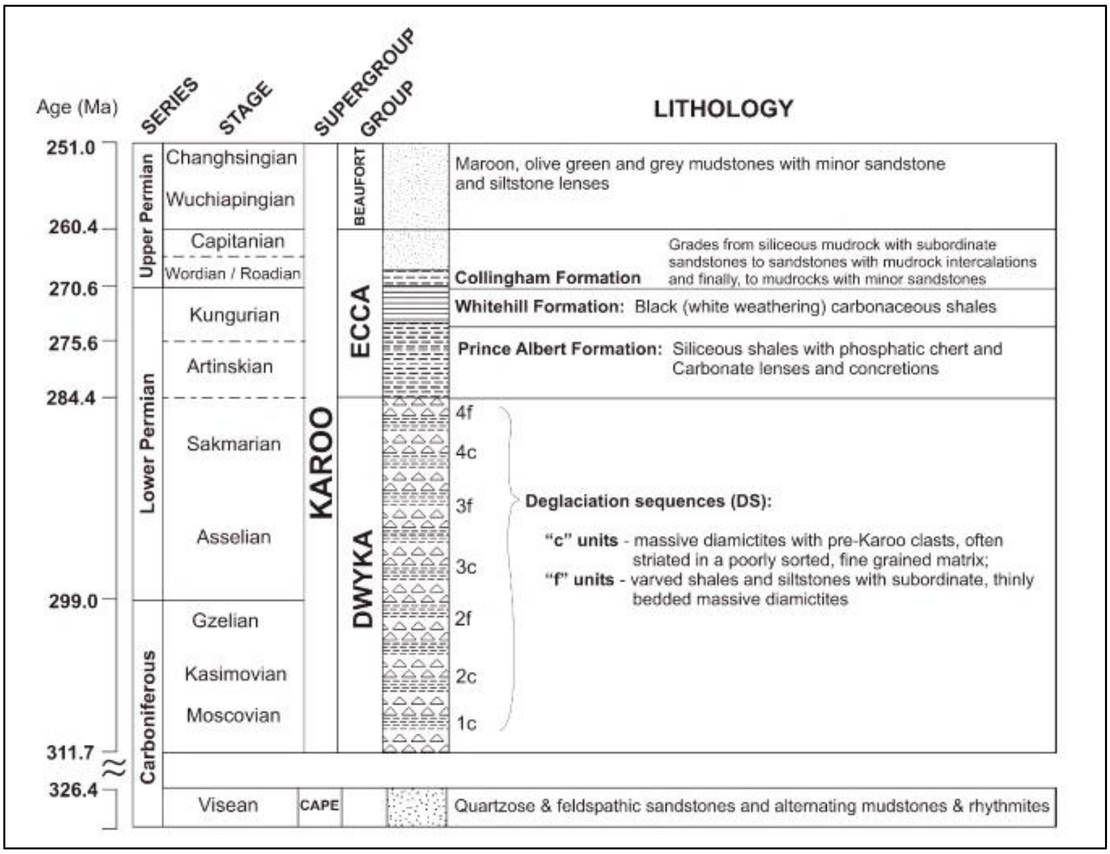


Figure 1: Stratigraphic column of the lowermost units in the Karoo Supergroup (Catuneanu, et al., 2005)

Dolerite is a mafic igneous rock related to basalt and gabbro that crystallised from molten magnesium-rich and iron-rich, but relative silica-poor magma trapped at relatively shallow depths (less than 8 km) in the earth's crust. The Karoo dolerite bodies were formed approximately 180 mya (million years ago) when mafic magma from the upper mantle was injected into the upper crust during volcanic activity. The dolerite intrusion form is related to the lithology of the host rock and the physical conditions prevailing at the time of the intrusion. The dolerite intrusions in the Dwyka Group are restricted to vertical sheets or dykes generally less than 5 m wide due to the high overburden pressure. However, in the Ecca and Beaufort Group with well-bedded sedimentary units, the overburden pressure was significantly lower and the magma was able to move laterally and form extensive horizontal sheets or sills. All varieties of dolerite (silica-undersaturated, silica-saturated and silica-oversaturated) contain silicate minerals that are chemically unstable on a geological time scale. Dolerites that have crystallized from molten material and are composed of an interlocking mass of crystals have a very low porosity and permeability, which indicates a high density. The water absorption of dolerite is therefore very low compared to most sedimentary rocks, however this is valid for unaltered dolerite (Dunlevey & Stephens, 1994).

2.1.2. Engineering properties of near surface Karoo rocks

Engineering properties and strength characteristics of rocks are determined from certain parameters which includes the compressive strength, density, porosity, durability and chemical compositions. Rock density is a function of individual grains, porosity and pore-fluid. Normally, density increases in igneous rocks with decreasing silica content. The densities of different rock-types varies due to the differences in mineralogy and degree of consolidation. The density of sedimentary rocks is affected by the composition, depth of burial, age, porosity, cementation, tectonic processes and pore-fluid type (Reynold, 1979). The porosity of a rock is the percentage of voids present. Porosity is dimensionless and is usually expressed as a percentage. The porosity of sedimentary rocks is usually higher than igneous rocks due to more open pores or voids between sediment grains than voids between minerals in igneous rocks. Rocks contain different types of porosity including primary, secondary, fracture, open, and closed porosities. Different factors including grain size, composition, cementation, rock types, burial depth, and diagenetic history affects rock porosity (Reynold, 1979). The density and porosity of rocks from the Karoo Supergroup are important physical properties that significantly affect the mechanical properties of the rocks. The uniaxial compressive strength (UCS) of rocks is also a key parameter in rock mechanics since it has a significant influence on the quality of rock masses and their behaviours. Parameters such as lithology, rock compaction, weathering and tectonic are likely to have a major influence on the results of the individual samples.

Dwyka Tillite

Tillite is the major component of the Dwyka Group, where the Formation varies with a maximum thickness of about 765 m in the Southern Cape, to 165 m in Northern KwaZulu-Natal. The Dwyka Group underlies the Ecca Group of the Main Karoo Basin. The tillites have been intruded by the Karoo dolerites in some localities, which caused low-grade contact metamorphism. Wedge-type failures have been known to occur in fresh tillite, which is generally restricted to sliding along saturated clays. Sliding may also take place along faults and joints. A range of values for engineering properties of the Dwyka tillite were determined when the Goedertrouw Dam was constructed, as shown in Table 1. Dwyka tillite at the Oppermansdrift Dam was tested on two samples, and indicated the following properties (George, 1983):

- UCS: 85 MPa
- Modulus of elasticity: 26.4 GPa
- Poisson's ratio: 0.16

Table 1: Engineering properties of tillite at Goedertrouw Dam (modified from George, 1983)

Type of tests	Unweathered (W1)	Slightly weathered (W2)	Moderately weathered (W3)	Highly weathered (W4)	Completely weathered (W5)
Seismic velocity (m/sec)	4 960 – 5 512	3 858 – 4 960	1 654 – 3 858	551 – 1 654	<551
Unconfined compressive strength (MPa)	122 – 298 (mean 225)	80 – 130 (mean 107)	10 – 40 (mean 28)	5 – 22	<1
Slake durability 7 cycles (%)	99.54	99.02	95.24	57.5	-
Porosity (%)	Range 0.0021 – 0.0076 (mean 0.0047)				
Density (kg/m^3)	Range 2 508 – 2 690 (mean 2 647)				
Swell (%)	Range 0.03 – 2.39 (mean 0.85)				

Tunnelling in tillite is generally trouble-free when compared with other rock types. Tillite is massive, and mostly medium to widely jointed, which result in sliding rock mass only along joint or wedge orientations that are very poor (Brink, 1983). Tillite seldom weathers to any great depths, where it is usually sufficient to remove the upper mantle of soft residual soil and to place the foundations or reinforcement directly on the partially weathered rock. The strength characteristics of unweathered tillite in a railway tunnel near Ulundi in KwaZulu-Natal are presented in Table 2 (Brink, 1983).

Table 2: Engineering properties of tillites in the railway tunnel near Ulindi (Brink, 1983)

Engineering Properties:	Compressive strength		Deformation parameters		
	UCS (MPa)		Modulus of elasticity		Poisson's ratio v
			Secant (GPa)	*Tangent (GPa)*	
Unweathered tillite (W1)	Maximum	194	68	70	0.33
	Minimum	142	39	39	0.22
	Mean	180	55	54	0.27
	Number of tests	4	4	4	4
	Standard deviation	25	15.30	16	0.06
	Coefficient of variation	0.14	0.28	0.29	0.22

Karoo Sandstone

Thin, poorly sorted sandstone occurs in the Ecca and Beaufort Groups, while quartzitic sandstone of the same age occurs in a neighbouring region. Higher up in the sequence, namely in the Molteno, Elliot and Clarens Formations, thick deposits of fine-grained to medium-grained sandstones are characteristic (Brink, 1983). Some strength and deformation characteristics of sandstones of the Vryheid and Estcourt Formations are provided in Table 3 (Brink, 1983).

Table 3: Strength and deformation characteristics of some Karoo sandstones (modified from Brink, 1983)

	Vryheid Formation			Estcourt Formation			
	UCS (MPa)	E_t (GPa)	Bulk density (kg/m^3)	UCS (MPa)	$E_{t(50)}$ (GPa)	Poisson's Ratio ν	Bulk density (kg/m^3)
Maximum	44.70	11.364	2 493	271	13.40	0.28	2 660
Minimum	8.60	0.621	2 356	57	5.90	0.06	2 350
Mean	27.00	2.426	2 421	116	9.90	0.14	2 473
Number of tests	17	17	17	20	9	9	3
Standard deviation	12.30	2.90	43.60	56.50	2.43	0.08	164
Coefficient of variation	0.45	1.18	0.02	0.49	0.25	0.57	0.07

Karoo Mudrocks

Mudrock is a sedimentary rock that is composed predominantly of silt-sized or smaller particles (Brink, 1983). The Elliot Formation, Beaufort and Ecca Groups contain mudrocks and can be classified into two groups, namely, fissile mudrocks (silt-shale, mud-shale, and clay-shale), and non-fissile mudrocks (siltstone, mudstone and claystone) (Brink, 1983). Eleven samples were collected from road cuttings at various localities in South Africa, and XRD tests were done to determine the mineralogy of each mudrock as seen in Table 4 (Brink, 1983).

Table 4: Mineralogy of shallow mudrock (Brink, 1983)

Mineral	*Sample Number and Formation or Group*										
	M1	**M2**	**M3**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**
	Ecca	**Beaufort**					**Elliot**	**Ecca**			**Beaufort**
Quartz	VLP	VLP	VLP	VLP	VLP	VLP	VLP	VLP	VLP	VLP	VLP
Feldspar	MA	MA	MA	MA	MA	MA-SA	LP		MA	MA	MA
Mica or illite	LP	MA	MA	MA	MA	MA-SA	SA	LP	SA	LP	SA
Chamosite	MA-SA	SA	Tr	SA	SA-Tr	SA-Tr		MA	SA	MA	SA
Kaolinite		Tr									
Chlorite		SA+1		SA+2	SA+3	Tr		MA+5		Tr	SA - Tr
Montmorillonite					SA		SA+4				
Vermiculite			SA-Tr		SA+3						
Sidents									LP		

Notes:
1. Chlorite montmorillonite interlayered
2. Fe-chlorite
3. Vermiculite or Fe-chlorite
4. Montmorillonite probably mixed with illite
5. Chlorite probably interlayered with illite

Symbols with quantities present:
VLP- Very Large Percentage
LP- Large Percentage
MA- Medium Amount
SA- Small Amount
Tr- Trace

A change in temperature and humidity are the main causes of disintegration of mudrocks (Olivier, 1979). It has been demonstrated that fresh Karoo mudrocks undergo dimensional changes on changes in moisture content. Free swelling ranging from 0.01 to 7.0% was reported by Oliver (1976) for samples of fresh Beaufort mudrock from the Tarkastad Subgroup. From the samples tested, it was determined that the well-stratified samples expanded much more in the direction perpendicular to bedding than in the direction parallel to bedding.

Karoo mudrocks absorb water to a varying degree. The water absorption characteristics of the Karoo mudrocks were tested by immersing sawn cubes in water (Brink, 1983). The absorption after oven-dried samples are emerged in water ranges from 0.80 – 5.10% (Brink, 1983). In Table 6, the percentage absorption of the different samples is shown for comparison.

The bulk densities and porosities of mudrocks were determined by (Rowsell & De Swardt, 1976) from boreholes drilled in the main Karoo basin. Densities in the northern and north-westernmost parts were consistently less than 2.4 g/cm^3, and the porosities were consistently higher than 10 percent. Where bulk densities in the Northern Karoo Supergroup region range from 2.4 to 2.6 g/cm^3 and porosities from 2% to 10%. In the Southern part, densities are consistently greater than 2.6 g/cm^3, with maximum porosities ranging from 0.9 to 6.8% (Brink, 1983).

Uniaxial compressive strength (UCS) tests were done on the Karoo mudrocks at their natural moisture content, the results are shown in Table 5. The compressive strength of the eleven samples varied from 33 MPa to 169 MPa. Values reported by Oliver (1976) in the Orange-Fish tunnel ranged between 40 MPa and 168 MPa for the Beaufort Mudrocks.

Mudrocks are more susceptible to weathering and breakdown than any other rocks when exposed to the environment (Oliver, 1976). The term 'slaking' is used to describe the breakdown of rocks by wetting and drying. When a mudrock is allowed to dry out, the air is then drawn into the outer pores, which creates a high suction pressure. If the same mudrock is allowed to be saturated, the entrapped air is being pressurised, as the water is drawn into the rock by capillary action. These slaking processes overstress the internal arrangements of the grains, which lead to breakdown. The slake durability tests are then used to estimate the resistance to breakdown by wetting and drying cycles (Bell, 2007).

Table 5: Results of some tests performed on 11 specimens of Karoo mudrocks (modified from Brink, 1983)

Sample nr.	Geological Formation and probable mudrock type	Locality	UCS (MPa)	Slake Durability Index (%)	Bulk Density (g/cm^3)	Absorption (%)	Cumulative Pore Volume (cm^3/g)
M1	Ecca clay-shale	Between Merrivale and Boston, Natal	112	99.10	2.67	1.36	0.020
M2	Beaufort claystone	Near Leeu-Gamka, Cape Province	117	99.60	2.69	0.89	0.020
M3	Beaufort claystone	Near Prince Albert Road, Cape Province	133	-	-	-	-
M6	Beaufort mudstone	Near Estcourt, Natal	36	98.20	2.43	4.17	0.057
M7	Beaufort clay-shale	Near Estcourt, Natal	49	91.00	2.34	6.15	0.046
M8	Beaufort claystone	Between Wakker-stroom and Dirkiesdorp, Transvaal	169	99.60	2.65	1.37	-
M9	Elliot sandstone	Near Clarens, Orange Vrystaat	33	56.60	2.33	7.01	0.045
M10	Ecca clay-shale	Durban Outer Ring Road, Durban	57	97.70	2.52	3.38	-
M11	Ecca mudstone	Durban Outer Ring Road, Durban	65	88.60	-	-	-
M12	Ecca Shale	Durban Outer Ring Road, Durban	83	97.90	2.48	2.49	-
M13	Beaufort claystone	Between Prince Albert Road and Leeu Gamka, Cape Province	118	99.70	2.71	0.42	-

Karoo Dolerite

Dolerite intruded amongst the Karoo rocks such as dykes and sills, which vary in thickness across the Main Karoo Basin (Brink, 1983). A large number of laboratory tests were done on the borehole cores (EX cores), which includes compressive strength tests on fresh dolerite at different sites as represented in Table 6. The specific gravity of dolerite was determined from 210 tests samples, and the values ranged from 3.05 to 2.85 g/cm^3, where the mean is taken as 2.94 g/cm^3 (Brink, 1983).

Table 6: Strength of fresh dolerite (modified from (Brink, 1983))

Locality		Unconfined compressive strength (MPa)					
		Maximum	Minimum	Mean	Number of tests	Standard deviation	Coefficient of variation
Site 1 Hilton quarry, Pietermaritzburg		540	426	472	6	42.32	0.090
Site 2 Mountain Rise quarry, Pietermaritzburg		368	269	336	9	33.77	0.100
Site3 Kinross road cutting		285	233	267	6	21.34	0.080
Site 4 Borchards Crushers quarry, Standerton		489	222	370	6	119.04	0.322
Site 5 South African Railways quarry, Cradock		363	173	293	15	53.51	0.183
Site 6 South African Railways National Roads quarry, Cradock		497	298	406	27	57.66	0.142
Site 7 Olive Hill quarry, Bloemfontein		386	254	303	15	42.50	0.140
Site 8 Hendrik Verwoerd Dam	A- Excavation for wall and abundments	551	133	388	82	66.56	0.172
	B- Quarry a	527	164	382	49	67.68	0.177
	C- Quarry b	465	285	391	28	45.28	0.116
Site 9 P.K. le Roux dam	A- Lower quarry	360	238	321	15	29.10	0.091
	B- Left flank	479	326	392	18	56.80	0.145
Site 10 Lesotho Highlands water project		283	103	201	10	63	0.32

There are few existing case studies on the Karoo Supergroup rocks in South Africa that involve the strength characteristics and engineering properties of the different rock types at the surface, and near surface. Two of the most significant civil engineering works ever undertaken in southern Africa, which are the Orange-Fish tunnel and the Drakensberg pumped storage scheme have added enormous knowledge to the geotechnical behaviour of the Karoo Supergroup rocks from the experience gained.

2.1.3. Orange-Fish tunnel Case Histories

The Orange-Fish tunnel is 82 km long which makes it the longest water tunnel in the world with a diameter of 5.3 m. The tunnel diverts stored water from the Gariep Dam (Hendrik Verwoerd Dam) on the Orange River to the upper reaches of the Great Fish River. The tunnel is constructed at a depth of 30-400 m below the surface, and runs southwards at a gradient of 1:2 000. A total of 280 boreholes were drilled and some boreholes were more than 450 m deep, which resulted in a total core recovery of nearly 29 kilometres (Olivier, 1983). Numerous investigations and tests were carried out on selected test specimens from the cores extracted so as to determine the engineering properties and mineralogical composition of the different rock types.

The tunnel intersected near-horizontal strata of alternating sandstone, siltstone, 'muddy' siltstone and mudstone, which belongs to the Tarkastad Subgroup and the Beaufort Group, with intersected dolerite dykes and sills. Approximately 55% of the tunnel was excavated in mudrocks or in alternating beds of 'sandy' and 'muddy' rock types, and approximately 35% was excavated in arenaceous rock types, where the remaining 10% tunnel length was excavated in dolerite (Olivier, 1983). Durable and non-durable compacted mudrock types were found, which consisted of dominant minerals like illite, quartz, and feldspar. A very small percentage of chlorite and a mixed layer of montmorillonite-illite were also found in some rock samples (Olivier, 1983).

Engineering properties such as the uniaxial compressive and tensile strengths, 'Duncan' free swelling coefficient, Poisson's ratio, porosity and permeability, which were determined in both research and field laboratories during site investigations and construction stages, showed a wide variation for any particular rock type. The majority of the sandstones and arenaceous siltstones showed a very low free-swelling potential, and the mudrocks revealed highly variable behaviour. The non-durable mudrock had a high free-swell (Olivier, 1983). The large variations in their mechanical and free-swelling characteristics were primarily caused by the difference in their texture (fabric), and not by their mineralogical differences.

A rock durability classification, the Geodurability Classification system (Olivier, 1979), is practical and simple, as it depends only on a minimum number of rock index properties. The classification system is based on different ranges of ratios of the uniaxial compressive strength (σ_c), and the "Duncan" free-swelling coefficient (ϵ_D). The free-swelling coefficient (ϵ_D) is then calculated by dividing the change in length after swelling (ΔL) with the initial length of specimen (L). This proposed Geodurability classification was used on the different rock types in the tunnel (Figure 2). Testing and classification on extracted core samples were done, from boreholes drilled vertically 3 m into the tunnel roof at longitudinal intervals of approximately 75 m. The classification results of the test localities explored along the tunnel route indicated that only 30% of the potential difficult rock types could be classified as poor to very poor rocks (Olivier, 1979).

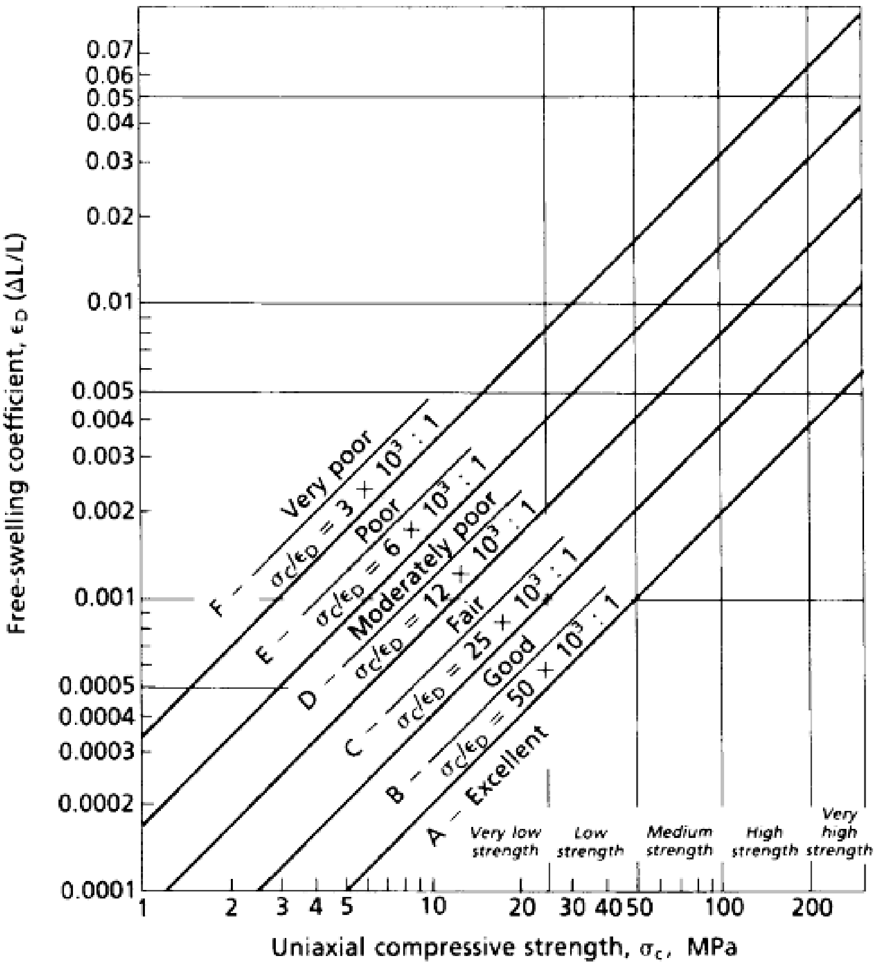


Figure 2: Geodurability classification of intact rock material (Bell, 2007)

The majority of sedimentary rocks reveal a prominent anisotropical swelling behaviour, with the values of the free swelling potential being several times greater in a direction perpendicular to the bedding than parallel to it (Duncan et al., 1968).

The results from the two-cycle durability tests carried out on selected rock samples according to the Durability-Plasticity Classification are determined to have a “high” or “very high” slake durability rating. Figure 3 indicates the different sections on a Durability-Plasticity Classification graph. For example a sample is plotted by using its plasticity index and slaking durability on the graph in a section indicating that the sample has a medium durability – low plasticity.

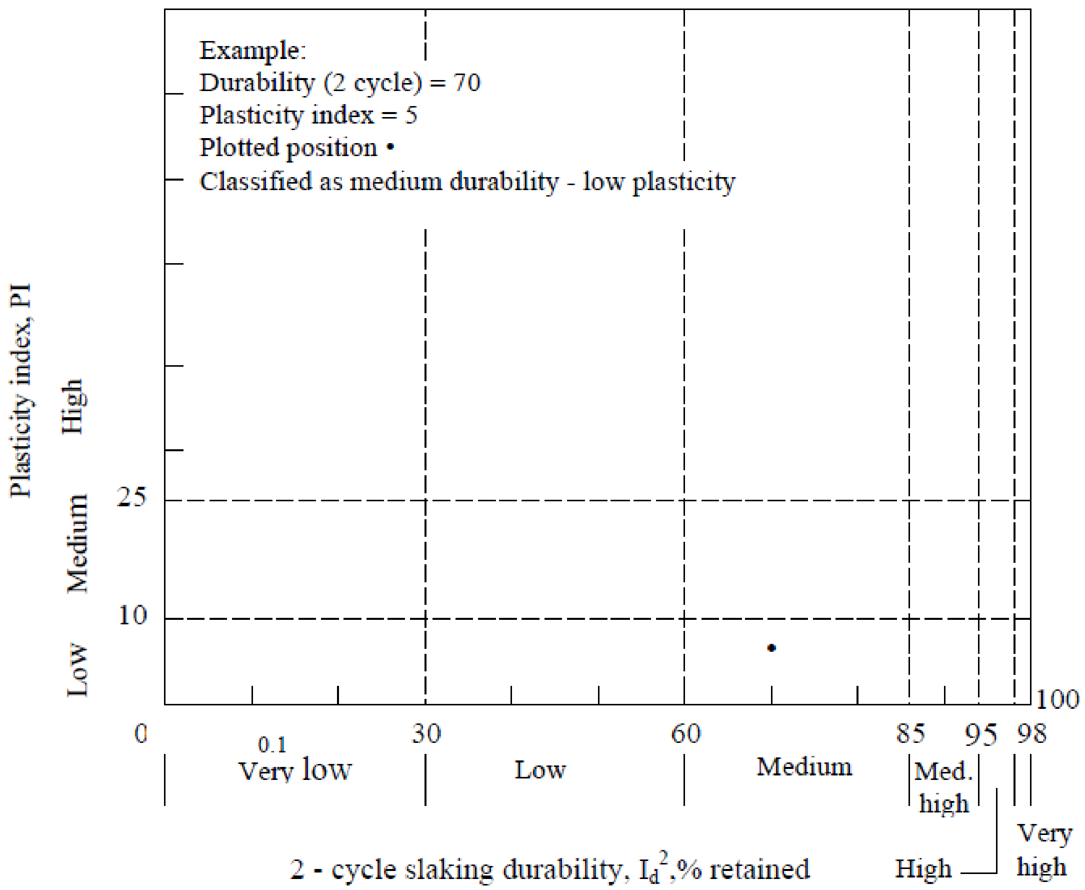


Figure 3: Durability-Plasticity Classification of intact rock material (Al-Rawas, et al., 2000)

2.1.4. The Drakensberg Pumped Storage Scheme Case History

The Drakensberg Pumped Storage Scheme serves a dual purpose by providing an inter-basin transfer link of water from the Tugela River to the Vaal River, and the generation of electricity at peak periods for distribution through Eskom's national power network. It is situated in the KwaZulu-Natal Province across the Drakensberg escarpment, approximately 67 km from Harrismith on the road to Bergville. The scheme is situated entirely on or within strata of the Karoo Supergroup, with most of the scheme situated amongst the Beaufort Group rocks. The lower elevated sections are in the Ecca Group rocks, and rocks of the Molteno Formation are present in the higher parts. For general lithological description purposes, the strata were divided into the upper and lower escarpment, where a prominent sandstone outcrop was taken as the boundary between the two broad categories. The lower escarpment consists of rocks of the Estcourt and Volksrust Formations, characterised by greenish-grey to bluish-grey sandstones, siltstones and mudstones. The upper escarpment consists mainly of Tarkastad Formation rocks, characterised by reddish-brown and greyish-green sandstones, siltstones, and mudstones. Dolerite dykes are present in both the upper and lower escarpments (Terblanche & Heidstra, 1983).

Extensive drilling was carried out, and trial shafts were sunk to execute numerous measurements for determining the in situ rock mass properties. The laboratory tests show a wide variation in the geomechanical parameters between the sandstones, siltstones and mudstones. The range of values are shown in Table 7, where it is important to note that the slake durability of the mudstones is poor. The slake durability values are quoted after the standard two cycle test. Some of the mudstones, which are subjected to four cycles of slake durability tests, gave very low values of 20-40%. The more cycles the samples undergo the more breakdown and disintegration of particles would occur, but the standard slake durability index values of samples are usually determined after two cycles. A variety of in-situ tests measurements was also carried out in the underground caverns, which includes a plate bearing test (Terblanche & Heidstra, 1983).

Table 7: Laboratory tests on rock at the Drakensberg pumped storage scheme (modified from Terblanche & Heidstra, 1983)

Test type		**Generalised Rock Type**		
		Sandstone	*Siltstone*	*Mudstone*
Unconfined compressive strength (MPa)		40 – 85	30 – 60	15 – 50
Point load index (MPa)	Diametral	1.50 – 3.00	1.00 – 2.00	0.50 – 1.00
	Axial	4.00 – 5.00	2.70 – 3.80	1.50 – 2.50
Density (kg/m^3)		2 520	2 600	2 620
Elastic modulus (GPa)		18 – 25	11 – 18	-
Poisson’s ratio		0.15 – 0.20	0.10 – 0.17	-
Slake durability (%)		98 – 100	95 – 99	73 – 90
RQD (%)		90 – 100	80 – 100	75 – 100

3. Sample Localities

The Karoo Supergroup ranges in age from Late Carboniferous to Middle Jurassic and attains a maximum cumulative thickness of approximately 12 km in the southeastern portion of the Main Karoo Basin towards the eastern end of the Karoo Trough (a linear east-west zone of maximum subsidence along the southern basin edge). The Main Karoo Basin is bounded along its southern margin by a fold-trust belt (Cape Fold Belt), which is a narrow zone of crustal shortening and thickening (Johnson, et al., 2006). The Main Karoo Basin dramatically thins in a northerly direction. The Karoo strata of the Main Basin covers an area of approximately 700 000 km^2. The Cape Fold Belt formed while the upper Karoo units were still in progress of sedimentation, resulting in the intense deformation of the Cape Supergroup, and lower units of the Karoo Supergroup along the southern Basin edge. These actions exposed the deep units of the Karoo Basin as seen in the cross-section from Figure 3 (Johnson, et al., 2006).

The localities of the two boreholes drilled in the Main Karoo Basin for geology exploration and shale gas potential determination can be seen in Figure 4.

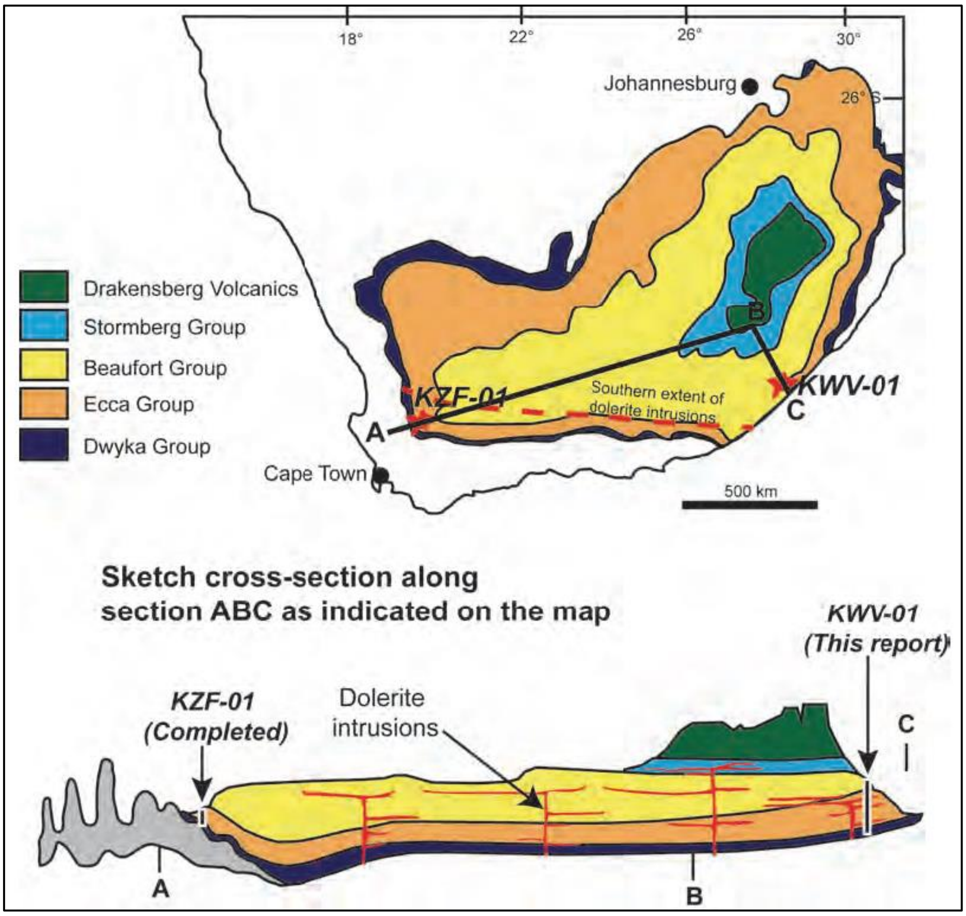


Figure 4: Localities of the two boreholes drilled in the Main Karoo Basin (de Kock, et al., 2015b)

Near Willowvale in the Eastern Cape Province, the deep borehole was drilled up to a depth of 2 353m, which terminated on the 11th of December 2015. The area is well known for its abundance of intrusive dolerites. The borehole from the drill site is situated immediately east of Willowvale in a defunct road quarry on the road to Dwesa Nature Reserve (S32 14' 41" E28 35' 08") which is named KWV-01. Figure 5 shows the drill site and the sealed borehole after drilling was completed. The locality was selected due to the dearth of information detailing the stratigraphy of the Karoo succession in the area, and also because for the investigation of the effect the dolerite intrusions have on the maturity of organic matter in the sedimentary rocks (de Kock, et al. 2015a).

Figure 5: Drilling site in the road quarry near Willowvale and the sealed borehole (de Kock, et al. , 2015a)

Various Formations of the Beaufort- and Ecca Group are identified by the core log, and abundant dolerite intrusions were also found as seen in Appendix B. Starting from the surface downwards, the stratigraphic units that were intersected in borehole KWV-01 are shown in Table 8 (de Kock, et al., 2015a).

Table 8: Intersected lithologies and their stratigraphic assignment in borehole KWV-01 (de Kock, et al., 2015a).

Depth (m)	Formation	Group	Geology
0 – 189.20	Koonap	Beaufort	Grey to dark grey mudstone & sandstone. Dolerite intersecting. Some clay-pellet conglomerates.
189.20 – 264.50	Waterford	Beaufort	Light grey, flat bedded fine sandstone with abundant mud flasers & interbedded massive mudstone.
264.50 – 919.20	Fort Brown	Ecca	Black and dark grey shale with abundant thin, fine sandstone beds that often contain clay-pellet beds.
919.20 – 1048.40	Trumpeters Member - Ripon FM	Ecca	Two prominent fine sandstones interbedded siltstone and fine carbonaceous shale.
1048.40 – 1346.16	Wonderfontein Member- Ripon FM	Ecca	Mostly shale with some sandstone and a dolerite intrusion intersecting.
1346.16 – 2276.13	Plutos Vale Member – Ripon FM	Ecca	Prominent carbonaceous black shale, thick layer of greywackes, tuff beds and sandstones with three thick layers of dolerite intrusions.
2276.13 – 2308.40	Whitehill	Ecca	Pyritic, dark, highly carbonaceous and finely laminated shale, with a intersected very fine-grained dolerite intrusion.
2308.40 – 2339.75	Prince Albert	Ecca	Very dark grey to grey shale, massive shale and siltstone.
2331.16 – 2352.39 EOH	-	Dwyka	Grey, coarse grained matrix with rounded and occasional sub-angular sandstone and quartz fragments – Tillite.

In a 10 km radius around the drilling site, only twenty-three groundwater sites were found, and these received a hydrocensus. The 10 km radius was chosen due to the maximum 5 km horizontal drill ability of a hydraulic fracturing rig. From six groundwater samples, two river samples and the drilling water (sourced also from the Shixi River), it can be noted that the groundwater and surface water are of good quality based on the pH and EC measurements. The pH ranged from 6.99 – 8.54. In the borehole KWV-01, no artesian water was intersected from a depth of 50 to 2 300m, and there were no noticeable changes in the drilling mud consistency throughout the drilling operation (de Kock, et al., 2015a).

The drill site for the borehole KZF-01 was selected south of the southern limit of Karoo Large Igneous Province (LIP) dolerite occurrences near the lower contact of the Ecca Group with the Dwyka Group, and within a prominent bend in the strike of the Cape Fold Belt, which is also known as the so-called Cape syntaxis (as seen in Figure 6 (A)). The borehole KZF-01 with coordinates S32 50' 30.43" E19 49' 33.02" is located on the farm named Zandfontein 89 (as seen in Figure 6 (B)) (de Kock, et al., 2015b).

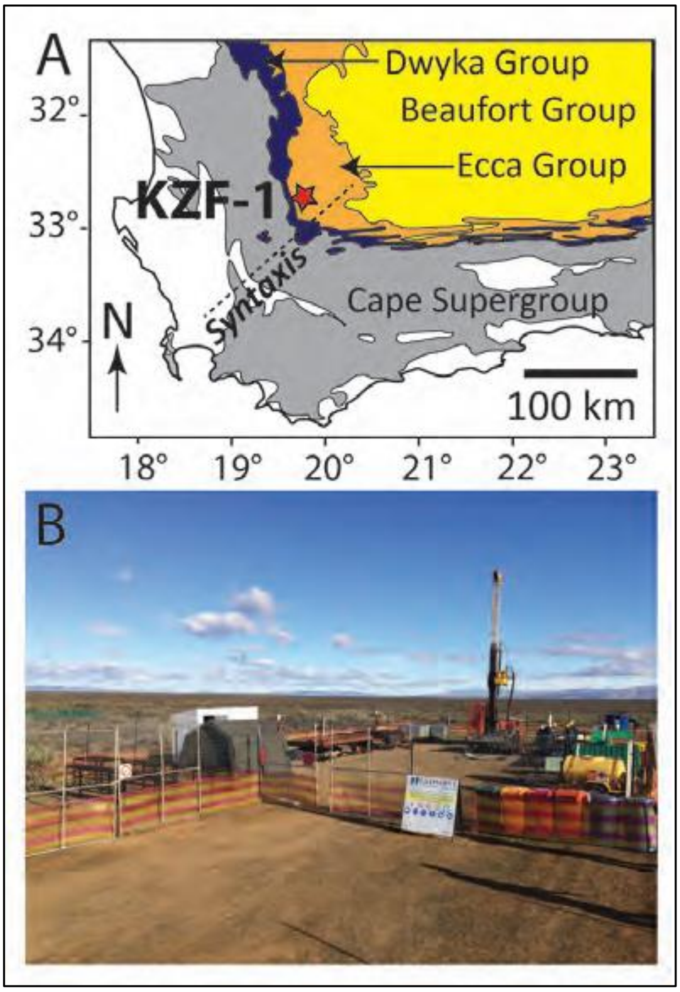


Figure 6: Locality of the KZF-01 borehole (A); on-site conditions of KZF-01 borehole (B) (de Kock, et al., 2015b)

The KZF-01 borehole was drilled from surface and intersected lithologies of the Ecca and Dwyka Group as shown in Appendix B, with a summarised description shown in Table 9 (de Kock, et al., 2015b).

Table 9: Intersected lithologies and their stratigraphic assignment in borehole KZF-01 (de Kock, et al., 2015b)

Depth (m)	Formation	Group	Geology
0 – 338.62	Tierberg	Ecca	Dark grey mudstone with siltstone beds and laminae and tuffaceous beds.
338.62 – 420.46	Collingham	Ecca	Numerous tuffaceous beds and laminae with chert beds. Prominent siltstones at top of FM.
420.46 – 439.95; 443.30 – 479.55; 489.15 - 498.45	Whitehill	Ecca	Predominance black mudstone and highly carbonaceous shale with abundance of pyrite.
439.95 – 443.30; 479.55 – 489.15; 498.45 – 657.12	Prince Albert	Ecca	Grey mudstone with numerous siltstone and tuffaceous horizons.
657.12 – 671.00	-	Dwyka	Siltstones with dropstones – Diamictite.

In a 10 km radius around the drill site, the data collected during the hydrocensus included static water levels, groundwater quality, and aquifer parameters. Forty-eight groundwater samples in total surrounding the borehole KZF-01, and eighteen samples of deep water intersected in borehole, KZF-01 were collected (de Kock, et al., 2015b). The findings are that the water in the KZF-01 borehole is less saline and less acidic than the shallow aquifers groundwater. The KZF-01 intersected several aquifers, where a shallow aquifer system was encountered before about a 60 m depth. After the shallow aquifer system, the borehole was dry up to around 550 m, where three artesian inflows were encountered at various depths. Fresh water was encountered at 558 m and at 671 m respectively, where sulphurous water was encountered at 625.5 m (de Kock, et al., 2015b).

Due to a lack of information on the detailed stratigraphy of the Karoo Supergroup succession in the southern area of the basin, testing was required on the surface outcrops. Samples were retrieved from the Eastern, Western, and Northern Cape. Sample retrieval started in the area north east of East London in the Eastern Cape then moving in an westerly direction, passing through Grahamstown then following the outcrops just north of Willowmore until Matjiesfontein in the Western Cape, where the collection route then turned towards the north up to Sutherland in the Northern Cape. The entire sample retrieval route from the Eastern Cape towards the Western Cape, and lastly in the Northern Cape, can be seen in Figure 7, 8 & 9 below. The samples retrieved are from lithologies within the Beaufort-, Ecca- and Dwyka Group.

Figure 7: Sample retrieval route in Eastern Cape (Google earth pro V 7.3.3.7786. (December 14, 2015). South Africa. Multiple coordinate points, Eye alt 198.82 km. SIO, NOAA, U.S. Navy, NGA, GEBCO. AfriGIS 2018, Google 2018. http://www.earth.google.com [March 13, 2018]).

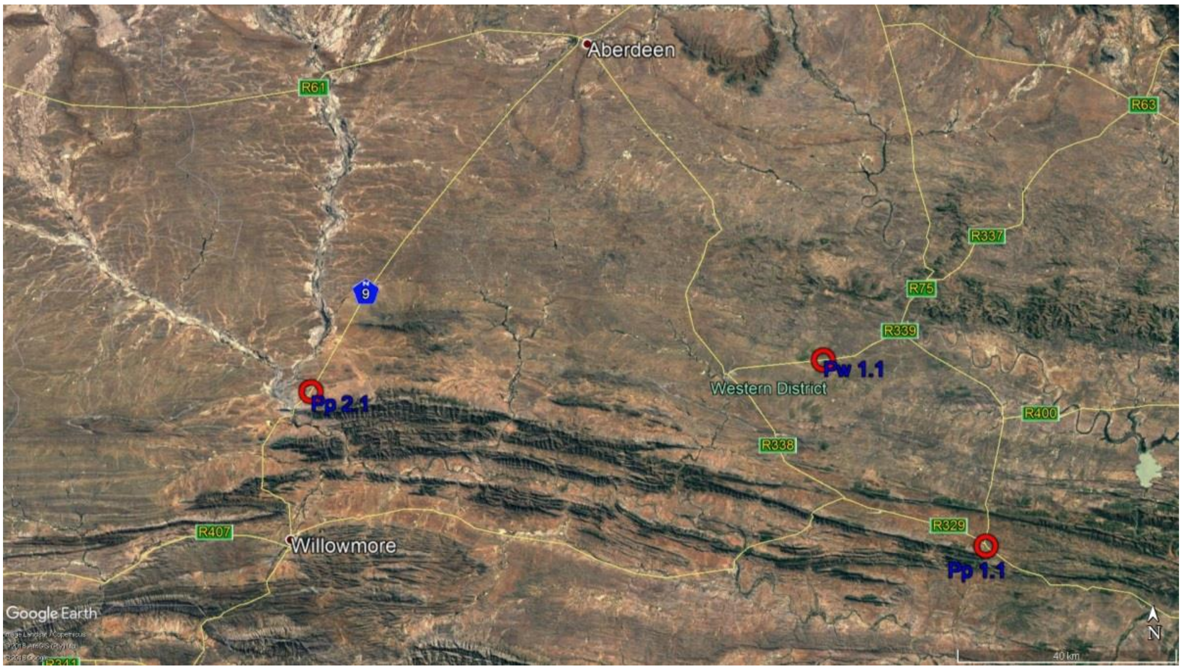


Figure 8: Sample retrieval route in Eastern Cape (Google earth pro V 7.3.3.7786. (December 14, 2015). South Africa. Multiple coordinate points, Eye alt 198.82 km. SIO, NOAA, U.S. Navy, NGA, GEBCO. AfriGIS 2018, Google 2018. http://www.earth.google.com [March 13, 2018]).

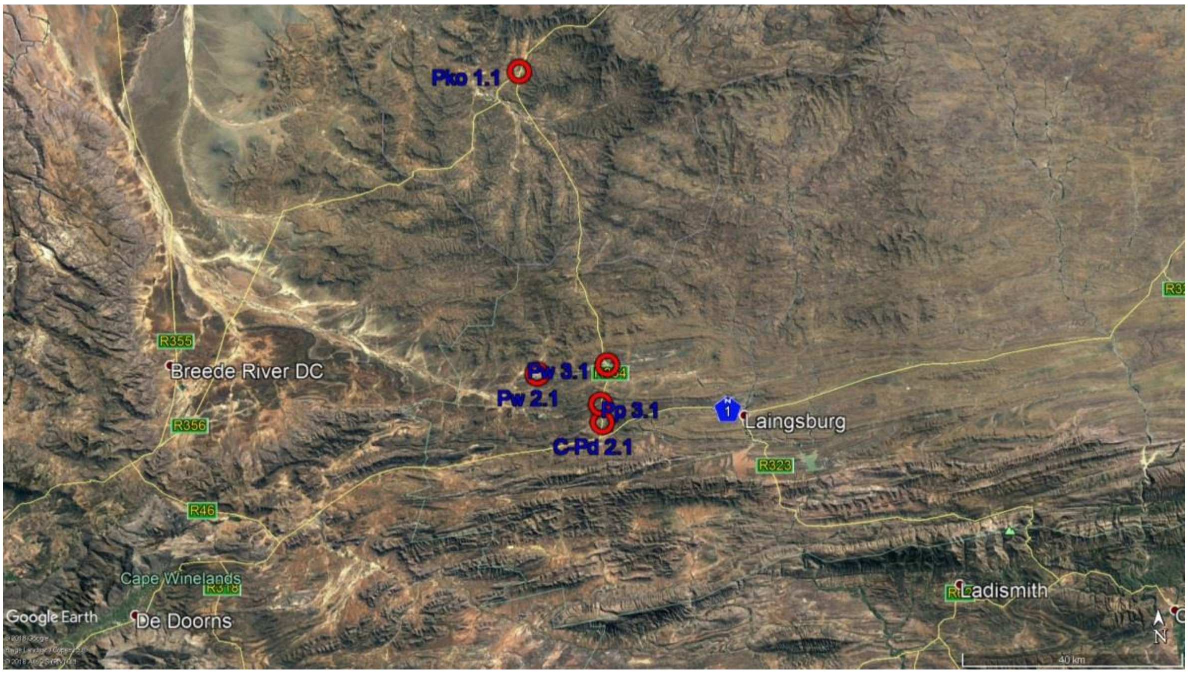


Figure 9: Sample retrieval route in Western and Northern Cape (Google earth pro V 7.3.3.7786. (December 14, 2015). South Africa. Multiple coordinate points, Eye alt 198.82 km. SIO, NOAA, U.S. Navy, NGA, GEBCO. AfriGIS 2018, Google 2018. http://www.earth.google.com [March 13, 2018]).

4. Methodology

The lack of geological information with sufficient depth and the prospecting of possible shale gas contained in the deep carbonaceous shales, lead to the drilling of two deep boreholes in the Main Karoo Basin. One borehole has been drilled near Willowvale in the Eastern Cape Province, with the other borehole near Ceres in the Western Cape Province. The drilling contractor for both boreholes was Geoserve Exploration Drilling (Pty) Ltd. For the borehole near Willowvale (KWV-01), a PQ core was drilled to a depth of 300 m, then followed by a HQ core to a 1000 m depth, and lastly a NQ core to the end of the hole at 2 352.39 m (de Kock, et al., 2015a). The borehole near Ceres (KZF-01) was also started with a PQ core and was drilled to approximately 60 m deep, where from this point a HQ core was used to drill further up to the end of the hole at 671 m deep (de Kock, et al., 2015b). The entire borehole length of the intersected stratigraphy units of both boreholes are shown in Appendix B. The cores of the KWV-01 borehole and KZF-01 borehole were transported to, and are kept at the National Core Library of the CGS at Donkerhoek, east of Pretoria. A variety of tests were done on different selective core samples that came from the two deep boreholes so as to be able to determine the specific lithologies' engineering properties and their characteristics.

From the KWV-01 borehole (near Willowvale), five representative samples were selected and taken at varying depths and Formations or Groups. The five samples taken from borehole KWV-01 are described and shown in Figure 10:

- *Sample 1*: Dolerite sill intrusion (2 073.55 – 2 073.88 m)
- *Sample 2*: Sandstone from the Pluto's Vale Member (2 259.06 – 2 259.46 m)
- *Sample 3*: Carbonaceous shale from the Whitehill Formation (2 303.70 – 2 303.98 m)
- *Sample 4*: Massive shale from the Prince Albert Formation (2 326.29 – 2 326.70 m)
- *Sample 5*: Tillite from the Dwyka Group (2 351.34 – 2 351.66 m).

1	2	3	4	5

Figure 10: Five representative core samples taken from the borehole KWV-01. (From left to right - dolerite, sandstone, carbonaceous shale, massive shale and tillite)

In Table 10 the lithology and lithological description of the five samples are given.

Table 10: KWV-01 Lithology and lithological description of the samples (logged by: A Birch) (de Kock, et al, 2015a)

Sample number	Lithology	Lithological descriptions and Remarks	Stratigraphic unit
1.	Dolerite	Grey green very fine crystalline. With high angle basal contact. Traces disseminated pyrite.	Dolerite sill
2.	Sandstone	Grey to dark grey very fine grained sandstone with faint pinkish iron staining in places. Bedding discernable.	Pluto's Vale Member
3.	Carbonaceous shale	Black near massive carbonaceous shale. 10% disseminated pyrite.	Whitehill Formation
4.	Massive shale	Massive dark grey to black shale.	Prince Albert Formation
5.	Tillite	Grey coarse grained matrix with rounded and occasional sub angular sandstone and quartz fragments.	Dwyka Group

As described above, the samples were taken at varying depths, where the core boxes of the different lithology can be seen below, from Figure 11 to Figure 15 (with an increase in depth from ground level, starting from upper left corner to ending at lower right corner in each core box).

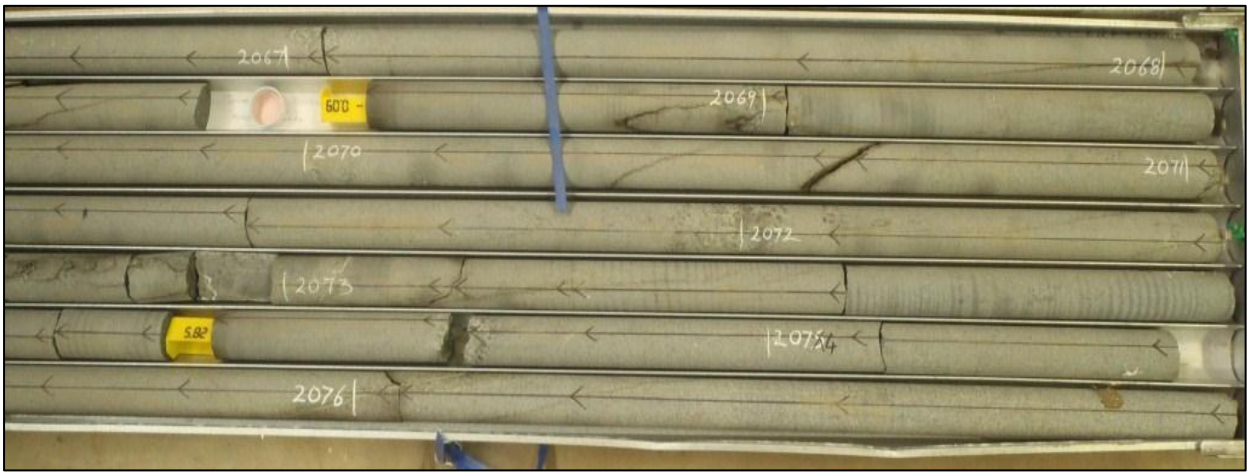


Figure 11: KWV-01 Dolerite in the core box

Figure 12: KWV-01 Sandstone in the core box

Figure 13: KWV-01 Carbonaceous shale individually wrapped in plastic bags in the core box

Figure 14: KWV-01 Massive shale in the core box

Figure 15: KWV-01 Tillite in the last core box of the borehole KWV-01

From the KZF-01 borehole (near Ceres), four representative samples were taken at varying depths and Formations, or in varying Groups. The dolerite is not present in the KZF-01, because the borehole is located at the southern section of the Karoo dolerite intrusion boundary.

The four selective samples were taken also from varying depths of the borehole KZF-01 as shown and in Figure 16:

- *Sample C1*: Fine Sandstone from the Tierberg Formation (240.46 – 240.81 m)
- *Sample C2*: Carbonaceous Shale from the Whitehill Formation (433.02 – 433.42 m)
- *Sample C3*: Shale from the Prince Albert Formation (440.51 – 440.87 m)
- *Sample C4*: Diamictite from the Dwyka Group (661.50 – 661.86 m)

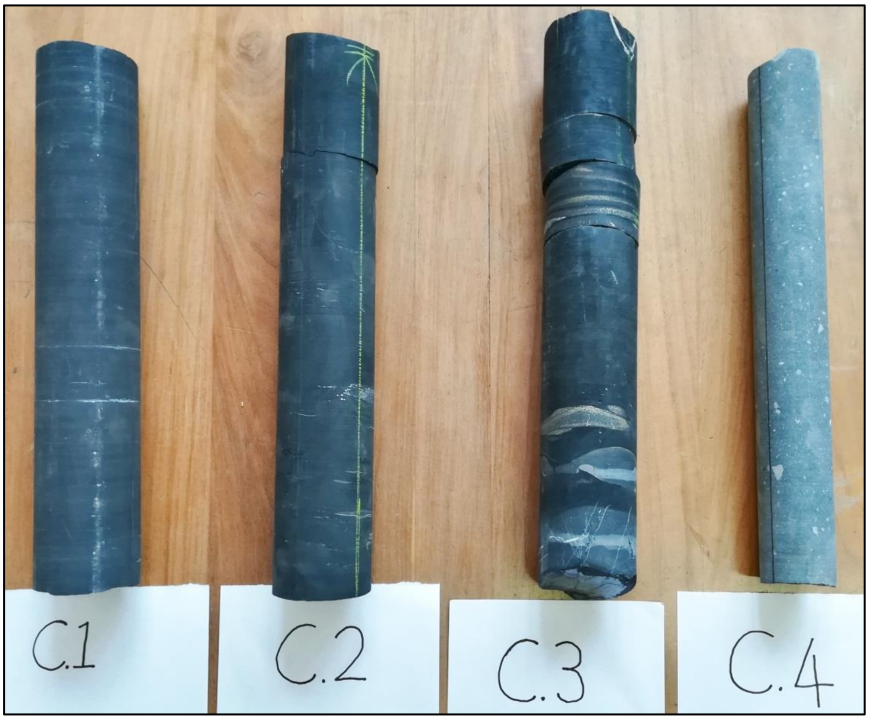


Figure 16: The four representative core samples taken from the borehole KZF-01. (From left to right (C.1-C.4) - fine sandstone, carbonaceous shale, shale and diamictite)

In Table 11 the lithology and lithological description of the four samples are given.

Table 11: KZF-01 Lithology and lithological description of the samples (de Kock, et al., 2015b)

Sample number	Lithology	Lithological descriptions and Remarks	Stratigraphic unit
C1.	Fine Sandstone	Dark grey very fine grained sandstone.	Tierberg Formation
C2.	Carbonaceous Shale	Massive dark grey to black carbonaceous shale.	Whitehill Formation
C3.	Shale	Black near massive shale. 10% disseminated pyrite.	Prince Albert Formation
C4.	Diamictite	White angular to sub-angular gravel in a light grey fine matrix.	Dwyka Group

As described above, the selective samples of borehole KZF-01 were taken at varying depths, where the core boxes of the different lithology can be seen in Figure 17 to Figure 20 (with an increase in depth from ground level, starting from upper left corner to ending at lower right corner).

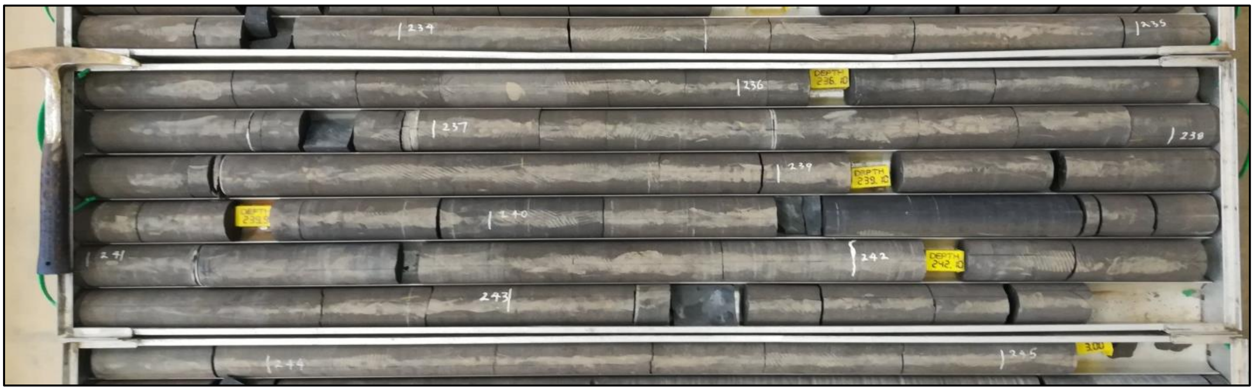


Figure 17: KZF-01 Fine sandstone in the core box

Figure 18: KZF-01 Carbonaceous shale in the core box

Figure 19: KZF-01 Shale in the core box

Figure 20: KZF-01 Diamictite retrieved in the second last core box of the borehole KZF-01

Testing was done on the Karoo outcrops, as necessary to be able to correlate the engineering properties and strength characteristics of the near surface rocks from the same lithologies as the deep core samples. At certain localities, where there were no existing or readily available information on the outcropped lithologies, tests could be done on these selective samples in order to determine new information of the Main Karoo Basin surface rocks. Samples were collected at the southern boundary of the Main Karoo Basin from outcrops located next to paved or main roads. The construction of paved roads through these outcrop ridges exposed the different lithologies, which made retrieving intacted samples possible. Examples of these outcrops are shown in Figure 21 and Figure 22.

Figure 21: Dolerite outcrop located next to paved road

Figure 22: Shale outcrop located next to paved road

Twelve representative samples were retrieved on surface through outcrops from different lithologies at the southern section of the Main Karoo Basin. Details of the samples retrieved are listed in Table 12, and the localities of the samples are indicated on the Figure 23.

Table 12: Surface samples retrieved

Sample number	Lithology	Lithological descriptions and Remarks	Stratigraphic unit
Jd 1.1	Dolerite	Black to grey speckled white dolerite	Karoo Dolerite
Jd 2.1	Dolerite	Grey speckled white dolerite	Karoo Dolerite
Pa 1.1	Sandstone	Grey, medium grained sandstone	Adelaide Subgroup – **Beaufort Group**
Pko 1.1	Sandstone	Greyish-brown streaked black sandstone	Koedoesberg Formation – **Ecca Group**
Pp 1.1	Shale	Brown stained black and orange shale	Collingham-, Whitehill- and Prince Albert Formation – **Ecca Group**
Pp 2.1	Shale	Greenish-grey shale	Prince Albert Formation – **Ecca Group**
Pp 3.1	Shale	Reddish-brown streaked black shale	Prince Albert Formation – **Ecca Group**
Pw 1.1	Shale	Grey-stained brown shale	Waterford Formation – **Ecca Group**
Pw 2.1	Shale	Light grey-stained orange shale	Whitehill Formation – **Ecca Group**
Pw 3.1	Shale	Grey-stained brown shale	Whitehill Formation – **Ecca Group**
C-Pd 1.1	Tillite	Dark grey matrix with rock fragments	Dwyka Tillite – **Dwyka Group**
C-Pd 2.1	Tillite	Grey matrix with rock fragments	Dwyka Tillite – **Dwyka Group**

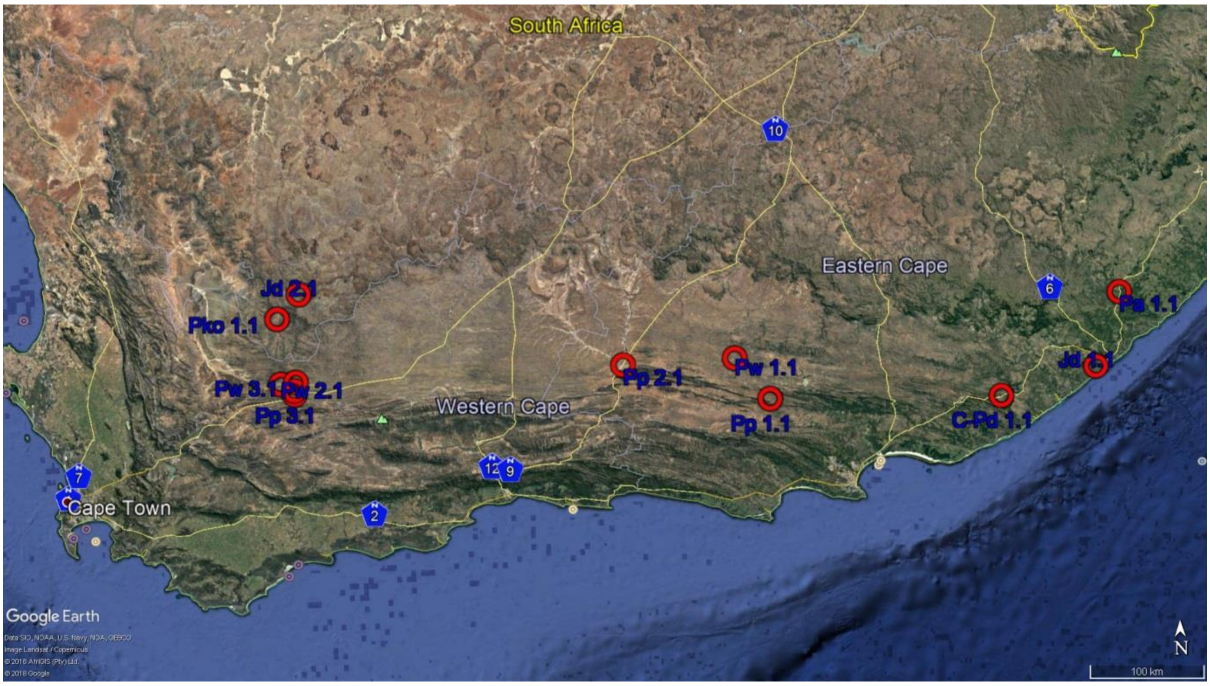


Figure 23: Localities of the surface samples retrieved (Google earth pro V 7.3.3.7786. (December 14, 2015). South Africa. Multiple coordinate points, Eye alt 855.90 km. SIO, NOAA, U.S. Navy, NGA, GEBCO. AfriGIS 2018, Google 2018. http://www.earth.google.com [March 13, 2018]).

A variety of tests were done on the samples retrieved from both boreholes KWV-01 and KZF-01, and on the samples retrieved from surface, to determine the different engineering and mechanical properties of each sample. The tests done on the samples on both borehole cores and surface samples are as follows:

- Sonic Wave Velocity Test;
- Uniaxial Compressive Strength Test;
- Porosity and Water Absorption Test;
- Slake-Durability Test;
- Duncan "Free" Swell Test;
- Ethylene Glycol Soak Test; and
- XRD and XRF tests.

The Uniaxial Compressive Strength and Seismic Velocity tests were performed on different core samples at Rocklab (Pty) Ltd. in Pretoria. The tests were carried out according to the ISRM's Specifications (1979). The parameters that are obtained by means of strain gauges include strength (UCS), sonic wave velocity, dynamic Young's modulus, elastic modulus, and Poisson's ratio.

The remainder of the laboratory tests were done to determine the porosity, density, bulk specific gravity, water absorption, swelling and Slake-Durability Index properties at the University of Pretoria's Department of Geology. The mineralogy of the samples was also determined in the laboratory at the University of Pretoria's Department of Geology by XRD and XRF tests.

The specific gravity and water absorption of coarse and fine aggregate were done according to standard test method ASTM C 127 – 81 (ASTM D 570). The sample is immersed in water for approximately 24 hours to essentially fill the pores. It is then removed from the water, the water dried from the surface of the particles and then weighed. Subsequently, the sample is weighed while submerged in water. Finally, the sample is oven-dried and weighed a third time. Using the weights obtained and formulas in the method, it is possible to calculate the specific gravity and water absorption (ISRM, 1979).

The bulk volume (V) was determined by using the *Buoyancy method*. Archimedes' Principle was used by determining the difference between the saturated-surface-dry and saturated-submerged sample weights (ISRM, 1979). It is then assumed that the density of water (p_w) is 1.0 g/cm^3. The volume of voids is then determined by using the differences between the saturated-surface-dry and oven-dry masses. If the bulk volume and volume voids are known, the porosity can then be calculated. The sample volume was calculated as shown in Equation (1) according to the buoyancy method, and some symmetrical circular core sample's volume were also calculated with a caliper:

Volume (cm^3) (buoyancy method):

$$V = \frac{Msat - Msub}{p_w} \tag{1}$$

Msat- saturated surface dry mass
Msub- submerged mass
p_w- density of water (assume 1g/cm^3)

The pore volume, porosity, dry density, bulk specific gravity and water absorption of the samples were calculated as shown in Equation 2-6:

Pore Volume (cm^3):

$$Vv = \frac{Msat - Ms}{p_w} \tag{2}$$

Msat- saturated surface dry mass
Ms- dry mass
p_w- density of water (assume 1g/cm^3)

Porosity (%):

$$n = \frac{100 \times Vv}{V} \tag{3}$$

Vv- pore volume (cm^3)
V- volume (cm^3)

Dry density (g/cm^3):

$$p_d = \frac{Ms}{V} \tag{4}$$

Bulk specific gravity:

$$Bulk\ Sp.Gr = \frac{Ms}{Msat - Msub} \tag{5}$$

Absorption (%):

$$Abs. = \frac{Msat - Ms}{Ms} \times 100 \tag{6}$$

The Slake-Durability Index test was done to assess the resistance offered by a rock sample to weakening and disintegration when subjected to two standard cycles of drying and wetting. The standard procedure is based on ASTM D 4644-87 (reapproved 1992) Standard Test Method for Slake Durability. The apparatus for the test consists of a test drum comprising a 2.00 mm standard mesh cylinder of unobstructed spaces, with a 100 mm length and a 140 mm diameter. The drum has a removable lid so that samples are able to be placed inside it. The drum containing the samples is then attached to a motor drive that is capable of rotating it at a constant speed of 20 rpm for 10 min in a slaking fluid (e.g. tap water). A representative sample is selected comprising of 10 rock lumps to give a total sample mass of 450-550 g (ISRM, 1979). The Slake-Durability Index is obtained by dividing the weight of the sample retained by its original weight, which is expressed as percentage. The following scale is used to determine the slake durability (Bell, 2007):

- Very low Under 25 %
- Low 25 – 50 %
- Medium 50 – 75 %
- High 75 – 90 %
- Very high 90 – 95 %
- Extremely high Over 95 %

By using the mass of the samples and the drum mass, the slake-durability index can be determined for a standard two cycle test with the equation (7).

Slake-durability Index (two-cycle):

$$Id_2 = \frac{(Mass\ C - Mass\ D) \times 100\%}{Mass\ A - Mass\ D} \tag{7}$$

Mass A, Mass C, and Mass D as in Table 16.

The Duncan or "Free" Swell Test was done on the two samples from borehole KWV-01, which contained the higher clay content, namely on *Sample 3 (carbonaceous shale)* and *Sample 4 (massive shale)*, two samples from the KZF-01 borehole, namely *Sample C.2 (carbonaceous shale)* and *Sample C.3 (shale),* and also on six surface shale samples of different formations. The swelling strain index for a radially confined specimen was determined by using a micrometer dial gauge, mounted to measure the swelling displacement at the central axis of the specimen (Duncan et al., 1968). The samples are immersed in distilled water and swelling displacement is measured. The tests were done over a period of 60 days, and the results were then noted. The first apparatus set up is shown in Figure 24:

Figure 24: Free Swelling Test setup

An Ethylene Glycol soak test was done on all the samples of both boreholes as well as the surface samples, where the reagent (Ethylene Glycol) meets the requirements of ASTM Designation: D 2693. Ethylene Glycol is a material that reacts with swelling clays of the montmorillonite group which causes the clay to form a larger basal spacing than that of the clay mineral itself. If the samples contain swelling clays of the montmorillonite group, the samples will be expected to undergo expansive breakdown which proves that when samples are exposed to prolonged wetting and drying or freezing and thawing conditions that they will be expected to break down eventually. The Ethylene Glycol Soak test were done on all the samples to determine if there is any swelling clays present, especially in the shale and dolerite samples. A glass container was used to submerge the oven-dried samples in the Ethylene Glycol. The first observations of the samples were made after 21 days of submersion, with follow up observations after 40 days.

The XRD tests were done at the Analytical Laboratory in the Department of Geology at the University of Pretoria. The samples were prepared according to the standardised Panalytical backloading system, which provides nearly random distribution of the particles. The samples were analysed using a PANalytical X'Pert Pro powder diffractometer in θ–θ configuration, with an X'Celerator detector and variable divergence and fixed receiving slits with Fe filtered Co-Kα radiation (λ=1.789Å). The phases were identified using X'Pert Highscore® plus software. Graphical representations of the qualitative results follow below. The relative phase amounts (weight %) was estimated using the Rietveld method (Autoquan Programme).

The XRF tests were also done at the Analytical Laboratory in the Department of Geology at the University of Pretoria. The sample preparation was as follows: core samples were milled in a tungsten-carbide milling pot to achieve particle sizes <75 microns, then dried at 100 ^{o}C and roasted at 1000 ^{o}C to determine the Loss On Ignition (LOI) values. A one gram sample was then mixed with 6 g Lithiumterborate flux and fused at 1050 ^{o}C to make a stable, fused glass bead.

For trace element analyses, the sample was mixed with a PVA binder and pressed in an aluminium cup at 10 tons. The Thermo Fisher ARL Perform 'X Sequential XRF instrument with OXSAS software was used for analysis.

5. Data

5.1. Willowvale borehole core samples (KWV-01)

The specimen particulars and specimen dimensions of the five selective core samples from the Willowvale borehole for the Sonic Wave Velocity and Dynamic Young's Modulus tests are shown in Table 13. The same five specimens were used for further tests, e.g. the Uniaxial Compressive Test with Elastic Modulus and Poisson's Ratio measurements, by means of strain gauges, as shown in Table 14 and 15.

Table 13: KWV-01 Specimen Dimensions for the UCS Test

Specimen particulars				Specimen Dimensions				
Rocklab Specimen No. 6693-	Sample No.	Depth m	Rock Type	Diameter mm	Height mm	Ratio of Height to Diameter	Mass g	Density g/cm^3
SVT-01/	1	2073.55	Dolerite	47.40	118.6	2.5	625.3	2.99

UCM-01								
SVT-02/ UCM-02	2	2259.06	Sandstone	47.36	119.7	2.5	582.6	2.76
SVT-03/ UCM-03	3	2303.70	Carbonaceous Shale	47.31	112.1	2.4	539.9	2.74
SVT-04/ UCM-04	4	2326.29	Massive Shale	46.67	112.5	2.4	534.8	2.78
SVT-05/ UCM-05	5	2351.66	Tillite	47.37	109.3	2.3	523.7	2.72

Table 14: KWV-01 Specimen test results from Sonic Wave Velocity Test

Sample No.	**Specimen Test Results**						
	P-Wave Travel Time (ũs)	S-Wave Travel Time (ũs)	P-Wave Velocity m/s	S-Wave Velocity m/s	Dynamic Young's Modulus GPa	Dynamic Shear Modulus GPa	Poisson's Ratio N
1	19.1	44.5	6202	2662	59.1	21.3	0.39
2	21.5	46.8	5567	2558	49.5	18.1	0.37
3	27.8	60.7	4032	1846	25.6	9.4	0.37
4	22.1	47.6	5088	2362	42.5	15.6	0.36
5	18.2	43.6	6001	2505	47.7	17.1	0.39

Table 15: KWV-01 Specimen test results from the UCS Test

Sample No.	Specimen Test Results							
	Failure Load kN	Strength (UCS) MPa	Tangent Elastic Modulus @50% UCS GPa	Secant Elastic Modulus @50% UCS GPa	Poisson's Ratio Tangent @50% UCS	Poisson's Ratio Secant @50% UCS	Linear Axial Strain at Failure mm/mm	Failure Code
1	529.2	299.9	102.0	94.2	0.29	0.24	0.003137	YA
2	596.1	338.4	63.3	69.3	0.27	0.24	0.005378	YA
3	130.2	74.1	34.6	34.6	0.21	0.19	0.002130	7B
4	290.4	169.8	52.4	54.9	0.22	0.20	0.003221	YA
5	757.7	429.9	80.5	82.5	0.31	0.27	0.005997	YA

Determining the porosity, water absorption and specific gravity in the laboratory, the following results in Table 16 were required for calculations of the rock properties.

Table 16: KWV-01: Dry-, saturated- and submerged masses of the five core samples

Sample:		**1- Dolerite**	**2- Sandstone**	**3- Carbonaceous Shale**	**4- Massive Shale**	**5- Tillite**
Dry Mass (g)	Ms1:	98.51	101.41	108.62	76.6	103.36
	Ms2:	89.24	107.84	118.57	89.26	99.45
	Ms3:	77.21	127.13	115.77	80.96	101.81
	Ms Tot:	264.96	336.38	342.96	246.82	304.62
Saturated Mass (g)	Msat1:	98.77	101.43	109.2	76.69	103.53
	Msat2:	89.42	107.87	119.32	89.36	99.59
	Msat3:	77.41	127.15	116.36	81.02	101.84
	Msat Tot:	265.6	336.45	344.88	247.07	304.96
Submerged Mass (g)	Msub1:	65.89	64.78	69.27	49.51	65.79
	Msub2:	59.48	68.86	75.57	57.52	63.3
	Msub3:	51.29	81.27	73.77	52.28	64.31
	Msub Tot:	176.66	214.91	218.61	159.31	193.4

The calculations done according to Equation 1 are shown in Table 1A in the Appendix A and the results in Table 17 by using the dry -, saturated- and submerged mass of three specimens of each rock sample.

Table 17: KWV-01 Porosity, dry density and water absorption for the five core samples

Calculations		1- Dolerite	2- Sandstone		3- Carbonaceous Shale		4- Massive Shale		5- Tillite
Volume calculation method		*Buoy-ancy Method*	*Caliper Method*	*Buoy-ancy Method*	*Caliper Method*	*Buoy-ancy Method*	*Caliper Method*	*Buoy-ancy Method*	*Buoy-ancy Method*
Porosity (%)	**n Avg:**	**0.719**	**0.056**	**0.058**	**1.491**	**1.518**	**0.272**	**0.285**	**0.305**
Dry Density (g/cm^3)	**p_d Avg:**	**2.978**	**2.678**	**2.767**	**2.670**	**2.716**	**2.688**	**2.813**	**2.731**
Bulk Specific Gravity	**Sp. Gr. Avg:**	**2.978**	**2.767**	**-**	**2.716**	**-**	**2.813**	**-**	**2.731**
Absorp-tion (%)	**Abs.Avg :**	**0.242**	**0.021**	**-**	**0.559**	**-**	**0.101**	**-**	**0.112**

The Slake-durability index test required five representative specimens of each rock type sample for testing by subjecting them to a two standard cycle of wetting and drying. The results obtained by the tests are shown in Table 2A in the Appendix.

By using the mass of the samples and the drum mass, as shown in the Appendix in Table 2A, the Slake-durability index can be determined for a standard two-cycle test with the equation (7). The Slake-durability Index of the five samples is shown in Table 18 below:

Table 18: KWV-01 Slake-Durability Index of the different rock types

Sample:	1- Dolerite	2- Sandstone	3- Carbonaceous Shale	4- Massive Shale	5- Tillite
Slake-Durability Index (two-cycle) Id_2:	99.55	99.78	99.40	99.71	99.80

The XRD results indicate the amount of weight percentage of each mineral present in the five rock specimens of borehole KWV-01. The results from the laboratory are shown in Table 19.

Table 19: KWV-01 XRD results of the five rock specimens

1-1 Dolerite			2-1 Sandstone			3-1 Carbonaceous Shale		
	weight%	3 σ error		weight%	3 σ error		weight%	3 σ error
Actinolite	2.85	0.78	Actinolite	1.12	0	Kaolinite	6.57	1.41
Diopside	30.06	1.5	Biotite	13.31	0.87	Muscovite	36.29	1.2
Enstatite	6.16	1.32	Muscovite	34.11	0.75	Pyrrhotite	13.55	0.6
Ilmenite	1.02	0.3	Plagioclase	15.64	1.11	Quartz	43.6	1.26
Kaolinite	1.77	0.93	Quartz	35.82	0.81			
Muscovite	3.46	0.84						
Plagioclase	49.92	1.56						
Quartz	2.63	0.33						
Talc	2.13	1.2						

4-1 Massive Shale			5-1 Tillite		
	weight%	3 σ error		weight%	3 σ error
Chlorite	22.25	0.87	Chlorite	10.43	0.9
Muscovite	34.28	0.75	Microcline	3.95	0.99
Quartz	43.47	0.72	Muscovite	10	0.66
			Plagioclase	27.47	1.05
			Quartz	48.15	1.05

The X-Ray Fluorescence Test (XRF) was conducted to determine the major and trace elements in the five different rock specimens of borehole KWV-01. The results obtained from the XRF Test are shown in Table 20 and 21.

Table 20: KWV-01 XRF Major Element Analyses Results

% Major Elements	Sample				
	1.1- Dolerite	2.1- Sandstone	3.1- Carbonaceous Shale	4.1- Massive Shale	5.1- Tillite
SiO_2	49.40	60.70	51.40	57.70	67.50
TiO_2	0.86	0.74	0.73	0.62	0.67
Al_2O_3	15.00	21.00	18.30	19.40	13.60
Fe_2O_3	10.60	5.47	10.40	11.40	5.24
MnO	0.14	0.17	0.03	0.19	0.20
MgO	7.99	1.45	2.31	1.17	1.91
CaO	12.50	1.15	1.37	0.72	2.55
Na_2O	2.08	1.50	0.22	*<0.01*	2.55
K_2O	0.66	5.06	4.04	4.38	2.89
P_2O_5	0.16	0.08	0.34	0.08	0.19
Cr_2O_3	0.05	*<0.01*	*<0.01*	0.03	0.03
NiO	0.03	0.02	0.02	0.00	*<0.01*
V_2O_5	0.05	0.08	*<0.01*	0.03	0.01
ZrO_2	*<0.01*	0.03	*<0.01*	0.01	0.03
CuO	0.01	*<0.01*	*<0.01*	*<0.01*	*<0.01*
SO3	0.02	*<0.01*	0.12	*<0.01*	0.04
BaO	*<0.01*	0.12	0.04	0.08	*<0.01*
RbO2	*<0.01*	0.04	0.03	0.04	0.02
WO3	*<0.01*	*<0.01*	0.04	*<0.01*	0.33
LOI	0.38	2.41	10.60	4.09	2.21
TOTAL	**99.92**	**100.01**	**99.98**	**99.93**	**99.97**

Table 21: KWV-01 XRF Trace Elements Analyses Results

ppm Trace Elements	Sample				
	1.1- Dolerite	2.1- Sandstone	3.1- Carbonaceous Shale	4.1- Massive Shale	5.1- Tillite
As	0	0	0	0	21
Cu	64	56	63	35	20
Ga	20	29	28	27	22
Mo	1	5	13	2	4
Nb	10	23	17	17	15
Ni	76	12	35	15	23
Pb	0	18	52	1	6
Rb	18	210	194	185	121
Sr	231	417	217	110	192
Th	0	20	17	15	8
U	0	1	0	0	0
W	244	94	66	29	686
Y	16	48	40	36	37
Zn	76	125	122	103	81
Zr	90	265	143	214	249

According to the Duncan or "Free" Swell Test done on the representative samples, no swelling displacement was indicated for both the carbonaceous-and massive shale during a 60-day submersion period. This leads to the conclusion that both the carbonaceous shale and massive shale from the KWV-01 borehole has little to no swelling potential.

According to the Ethylene Glycol Soaking Test on each of the five rock samples, no spalling, splitting or disintegration of the rock samples have been observed. When the samples were submerged for an extended period of 40 days in total, another observation was to be made, and still no spalling, splitting, or disintegration was noted. Figure 25 shows the oven-dried samples before the test was carried out, and Figure 26 shows the submerged samples after 21 days. The test indicates that no expansive breakdown occurred in the shale and tillite samples and also supported the fact that no montmorillonite group clays are present in the sandstone and dolerite samples.

Figure 25: KWV-01 Oven-dried samples before Ethylene Glycol Soaking Test

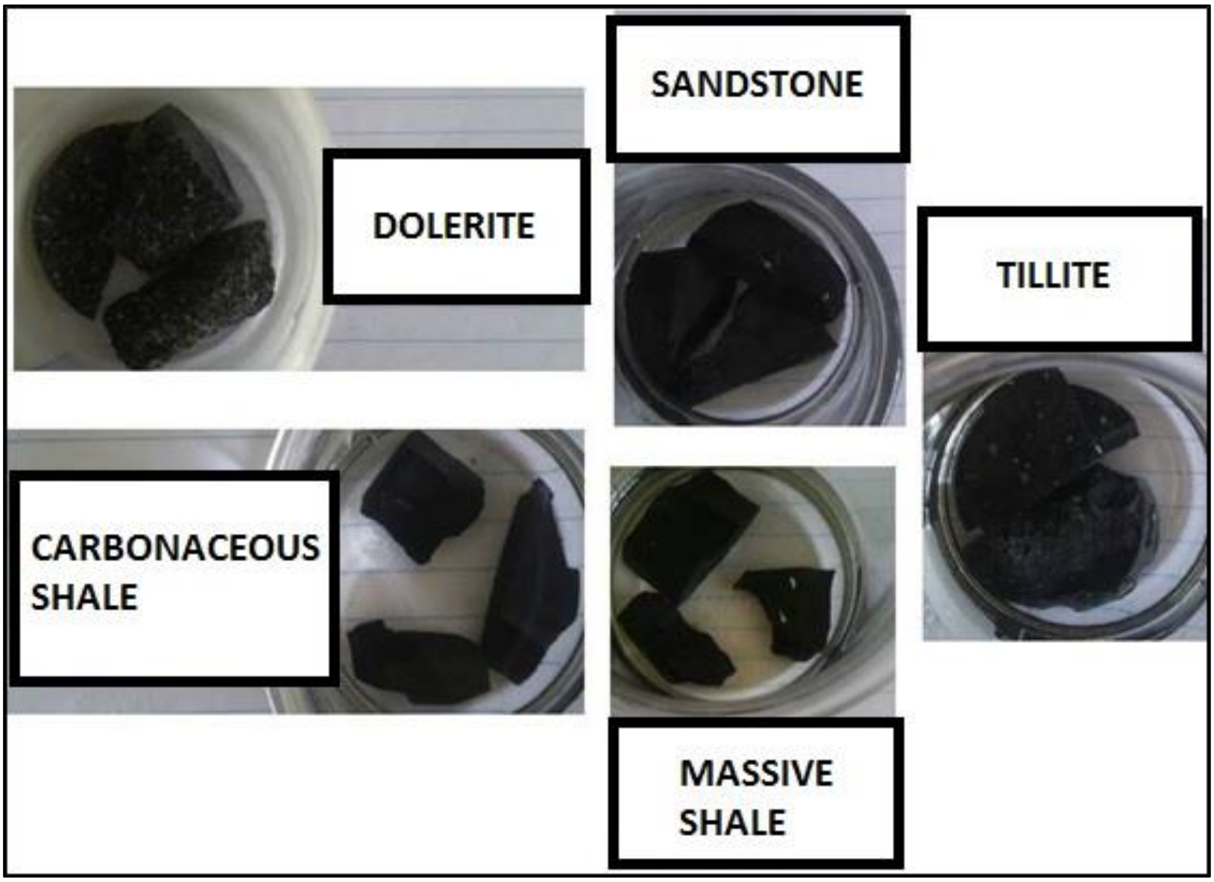


Figure 26: KWV-01 Ethylene Glycol submerged samples after 21 days

5.2 Ceres borehole core samples (KZF-01)

The specimen particulars and specimen dimensions of the four KZF-01 (Ceres) core samples from the Sonic Wave Velocity and Dynamic Young's Modulus tests are shown in Table 22. The four specimens were also used for further tests as the Uniaxial Compressive Test with Elastic Modulus and Poisson's Ratio measurements by means of strain gauges, as shown in Table 23 and 24.

Table 22: KZF-01 Specimen Dimensions for the UCS test

Specimen particulars				**Specimen Dimensions**				
Rocklab Specimen No. 7234-	Sample No.	Depth m	Rock Type	Diameter mm	Height mm	Ratio of Height to Diameter	Mass g	Density g/cm^3
SVT-01/ UCM-01	C1	240.46	Fine Sandstone	63.20	133.6	2.1	1112.9	2.65
SVT-02/ UCM-02	C2	433.07	Carbonaceous Shale	63.23	154.9	2.4	1286.3	2.64
SVT-03/ UCM-03	C3	440.51	Shale	63.15	108.5	1.7	890.0	2.62
SVT-04/ UCM-04	C4	661.50	Diamictite	47.47	103.0	2.2	494.7	2.71

Table 23: KZF-01 Specimen test results from Seismic Wave Velocity test

Sample No.	Specimen Test Results						
	P-Wave Travel Time (ũs)	S-Wave Travel Time (ũs)	P-Wave Velocity m/s	S-Wave Velocity m/s	Dynamic Young's Modulus GPa	Dynamic Shear Modulus GPa	Poisson's Ratio N
C1	46.7	83.2	2861	1606	17.4	6.8	0.27
C2	58.6	94.0	2643	1648	17.0	7.2	0.18
C3	43.2	72.8	2511	1490	14.3	5.8	0.23
C4	18.2	33.2	5657	3101	67.1	26.1	0.29

Table 24: KZF-01 Specimen test results from the UCS Test

Sample No.	Specimen Test Results							
	Failure Load kN	Strength (UCS) MPa	Tangent Elastic Modulus @50% UCS GPa	Secant Elastic Modulus @50% UCS GPa	Poisson's Ratio Tangent @50% UCS	Poisson's Ratio Secant @50% UCS	Linear Axial Strain at Failure mm/mm	Failure Code
C1	440.6	140.4	25.6	24.4	0.21	0.16	0.005732	YA
C2	313.7	99.9	23.8	25.2	0.21	0.18	0.004170	YA
C3	221.0	70.6	15.7	14.2	0.22	0.15	0.004948	YA
C4	358.1	202.3	50.8	53.6	0.25	0.23	0.004069	YA

To determine the porosity, water absorption and specific gravity in the laboratory, the mass were required from the KZF-01 core samples for calculating the rock properties as shown in Table 3A in Appendix A.

The results of the calculations as shown in Appendix A in Table 4A were also determined by using the dry, saturated, and submerged mass of three specimens of each rock sample. The sample volume, pore volume, porosity, dry density, bulk specific gravity and water absorption of the samples were calculated by using Equations (1-6), as previously indicated. Below in Table 25 are the porosity, dry density, bulk specific gravity and absorption results of the four core samples.

Table 25: KZF-01 Porosity, dry density, and water absorption for the four core samples

Calculations		C1- Fine Sandstone	C2- Carbonaceous Shale	C3- Shale	C4- Diamictite
Porosity (%)	**n Avg:**	**2.431**	**4.181**	**3.975**	**0.339**
Dry Density (g/cm^3)	**p_d Avg:**	**2.632**	**2.563**	**2.588**	**2.720**
Bulk Specific Gravity	**Sp. Gr. Avg:**	**2.632**	**2.563**	**2.588**	**2.720**
Absorption (%)	**Abs.Avg:**	**0.924**	**1.631**	**1.542**	**0.125**

According to the Slake-Durability Index test on the KZF-01 core samples, ten representative specimens of each lithological sample were tested by subjecting them to a two standard cycle of wetting and drying. The results obtained by the tests are shown in Appendix A in Table 5A.

By using the equation (7) as previously indicated, the Slake-Durability Index can be calculated for the core samples of the different rock types as shown in Table 26.

Table 26: KZF-01 Slake-Durability Index of the different rock types

Sample:	**C1- Fine Sandstone**	**C2- Carbonaceous Shale**	**C3- Shale**	**C4- Diamictite**
Slake-durability index (two-cycle) Id_2:	99.72	99.23	98.70	99.57

The XRD results indicating the amount of weight percentage of each mineral present in the four rock specimens of borehole KZF-01 are shown in Table 27.

Table 27: KZF-01 XRD results of the four rock specimens

C.1- Fine Sandstone		**C.2- Carbonaceous Shale**	
	weight%		weight%
Calcite	2.91	Ankerite	8.9
Chlorite	10.98	Chlorite	11.72
Microcline	4.89	Muscovite	22.79
Muscovite	16.92	Plagioclase	13.16
Plagioclase	18.19	Pyrite	4.12
Quartz	40.05	Quartz	30.72
Siderite	6.05	Siderite	8.59
C.3- Shale		**C.4- Diamictite**	
	weight%		weight%
Ankerite	4.07	Calcite	5.14
Calcite	0	Chlorite	6.58
Muscovite	33.03	Microcline	3.37
Plagioclase	18.51	Muscovite	13.37
Pyrite	10.38	Plagioclase	23.99
Quartz	34.01	Quartz	47.54

The X-Ray Fluorescence Test (XRF) was conducted to determine the major elements in each of the four different rock specimens of borehole KZF-01. The results obtained are shown below in Table 28.

Table 28: KZF-01 XRF Major Element Analyses Results

% Major Elements	Sample			
	C1- Fine Sandstone	C2- Carbonaceous Shale	C3- Shale	C4- Diamictite
SiO_2	60.20	60.30	53.20	55.40
TiO_2	0.56	0.53	0.65	0.48
Al_2O_3	14.40	11.90	17.00	15.70
Fe_2O_3	7.89	4.79	6.69	10.00
MnO	0.28	0.23	0.02	0.16
MgO	1.29	1.37	1.82	3.98
CaO	1.47	2.80	0.95	3.39
Na_2O	2.54	2.34	1.58	1.53
K_2O	3.30	2.12	4.34	3.96
P_2O_5	0.24	0.18	0.24	0.51
Cr_2O_3	<0.01	<0.01	<0.01	<0.01
NiO	<0.01	<0.01	<0.01	<0.01
V_2O_5	0.02	<0.01	0.02	0.01
ZrO_2	0.01	0.02	<0.01	0.01
SO_3	<0.01	<0.01	0.07	0.36
WO_3	0.10	0.13	0.12	0.11
BaO	0.12	<0.01	<0.01	<0.01
SrO	0.04	0.03	0.04	0.07
LOI	7.53	13.20	13.20	4.27
Total	**99.98**	**99.93**	**99.92**	**99.93**

According to the Duncan or "Free" Swell Test done on the four representative samples from the KZF-01 borehole, no swelling displacement was indicated for both shale samples during a 60-day submersion period. This leads to the conclusion that both the carbonaceous shale and massive shale from the KZF-01 borehole has little to no swelling potential. This also indicates the absence large quantities of swelling clays in the samples.

The Ethylene Glycol Soaking Test done on each of the four rock samples resulted in no spalling, splitting, or disintegration of any of the rock samples submerged. An extended submerging of 40 days in total still didn't cause any spalling, splitting, or disintegration of the samples.

5.3 Karoo surface samples

The specimen particulars and specimen dimensions for the twelve retrieved surface samples from the Sonic Wave Velocity and Dynamic Young's Modulus tests are shown in Table 29 and 30. The Uniaxial Compressive Test with Elastic Modulus and Poisson's Ratio measurements by means of strain gauges of the twelve retrieved samples are shown in Table 31 and 32.

Table 29: Surface Samples- Specimen Dimensions for the UCS Test

Specimen Particulars			Specimen Dimensions				
Rocklab Specimen No. 7429-	Sample No.	Rock Type	Diameter mm	Height mm	Ratio of Height to Diameter	Mass g	Density g/cm^3
UCM-01	Pa 1.1	Sandstone	46.05	121.5	2.6	517.05	2.55
UCM-02	Jd 1.1	Dolerite	29.38	59.5	2.0	120.96	3.00
UCM-03	C-Pd 1.1	Tillite	42.62	97.6	2.3	373.21	2.68
UCM-04A	Pp 1.1	Shale	29.19	21.9	0.8	38.68	2.64
UCM-04B	Pp 1.1	Shale	29.07	33.1	1.1	58.51	2.66
UCM-05	Pw 1.1	Shale	42.81	49.8	1.2	189.80	2.65
UCM-06	Pp 2.1	Shale	42.83	87.7	2.0	336.01	2.66
UCM-07	Pw 2.1	Shale	28.71	46.2	1.6	60.81	2.03
UCM-08	Pw 3.1	Shale	35.05	51.2	1.5	117.35	2.37
UCM-09	Pp 3.1	Shale	-	-	-	-	-
UCM-10	C-Pd 2.1	Tillite	35.38	62.7	1.8	166.13	2.70
UCM-11	Jd 2.1	Dolerite	35.43	74.9	2.1	221.83	3.00
UCM-12	Pko 1.1	Sandstone	35.33	62.6	1.8	159.61	2.60

Table 30: Surface Samples- Specimen Dimensions for the SVT Test

Specimen particulars			Specimen Dimensions			
Rocklab Specimen No. 7429-	Sample No.	Rock Type	Diameter mm	Height mm	Mass g	Density g/cm^3
SVT-01	Pa 1.1	Sandstone	46.21	94.4	395.4	2.50
SVT-02	Jd 1.1	Dolerite	28.92	52.7	106.2	3.07
SVT-03	C-Pd 1.1	Tillite	42.42	93.1	355.3	2.70
SVT-04	Pp 1.1	Shale	29.06	33.1	59.5	2.71
SVT-05	Pw 1.1	Shale	42.83	56.5	214.5	2.63
SVT-06	Pp 2.1	Shale	42.83	46.5	175.9	2.63
SVT-07	Pw 2.1	Shale	28.19	46.3	61.3	2.12
SVT-08	Pw 3.1	Shale	35.19	51.2	117.8	2.36
SVT-09	Pp 3.1	Shale	-	-	-	-
SVT-10	C-Pd 2.1	Tillite	35.42	62.8	166.1	2.69
SVT-11	Jd 2.1	Dolerite	35.42	77.8	229.0	2.99
SVT-12	Pko 1.1	Sandstone	35.38	62.6	159.6	2.59

Table 31: Surface Samples - Specimen test results from Seismic Wave Velocity Test

Sample No.	Specimen Test Results						
	P-Wave Travel Time (ũs)	S-Wave Travel Time (ũs)	P-Wave Velocity m/s	S-Wave Velocity m/s	Dynamic Young's Modulus GPa	Dynamic Shear Modulus GPa	Poisson's Ratio N
Pa 1.1	22.0	47.7	4292	1980	26.7	9.8	0.36
Jd 1.1	8.1	15.5	6509	3401	93.1	35.5	0.31
C-Pd 1.1	45.6	73.4	2041	1268	10.3	4.3	0.19
Pp 1.1	7.3	13.2	4538	2510	43.6	17.0	0.28
Pw 1.1	15.4	28.9	3670	1956	26.2	10.1	0.30
Pp 2.1	9.8	17.3	4744	2687	47.9	19.0	0.26
Pw 2.1	24.4	49.5	1898	936	5.0	1.9	0.34
Pw 3.1	17.2	33.1	2979	1548	14.9	5.7	0.32
Pp 3.1	-	-	-	-	-	-	-
C-Pd 2.1	16.3	30.2	3852	2079	30.0	11.6	0.29
Jd 2.1	12.3	23.1	6324	3367	88.2	33.9	0.30
Pko 1.1	13.8	24.2	4539	2588	43.7	17.4	0.26

Table 32: Surface Samples - Specimen test results from the UCS Test

Sample No.	Specimen Test Results							
	Failure Load kN	Strength (UCS) MPa	Tangent Elastic Modulus @50% UCS GPa	Secant Elastic Modulus @50% UCS GPa	Poisson's Ratio Tangent @50% UCS	Poisson's Ratio Secant @50% UCS	Linear Axial Strain at Failure mm/mm	Failure Code
Pa 1.1	366.1	219.8	36.6	37.7	0.28	0.20	0.006699	YA
Jd 1.1	259.3	382.5	110.0	114.0	0.30	0.29	0.003808	YA
C-Pd 1.1	76.7	53.8	13.6	23.9	0.16	0.27	0.004546	6B
Pp 1.1 (A)	243.2	363.4	58.4	53.1	0.15	0.13	0.006305	YA
Pp 1.1 (B)	45.0	67.8	34.4	36.3	0.17	0.15	0.002524	4B
Pw 1.1	226.8	157.6	40.8	33.8	0.28	0.17	0.004464	YA
Pp 2.1	295.2	204.9	38.0	39.6	0.20	0.18	0.005228	YA
Pw 2.1	24.7	38.1	4.8	5.1	0.24	0.18	0.007878	XA
Pw 3.1	84.5	87.5	12.1	14.2	0.23	0.15	0.006637	XA
Pp 3.1	-	-	-	-	-	-	-	-
C-Pd 2.1	122.8	124.9	33.9	29.5	0.23	0.12	0.003965	YA
Jd 2.1	372.2	377.5	94.7	96.0	0.31	0.27	0.004320	YA
Pko 1.1	204.4	208.5	40.0	43.2	0.33	0.25	0.005624	YA

To determine the porosity, water absorption and specific gravity in the laboratory, the following results were required from the surface samples for calculating the rock properties as shown in Table 33.

Table 33: Surface Samples - Dry-, saturated- and submerged masses of the twelve samples

Sample:		Sandstone (Pa 1.1)	Dolerite (Jd 1.1)	Tillite (C-Pd 1.1)	Shale (Pp 1.1)	Shale (Pw 1.1)	Shale (Pp 2.1)
Dry Mass (g)	Ms1:	69.98	101.86	157.01	102.29	143.29	137.34
	Ms2:	85.80	134.34	143.01	161.53	126.15	116.16
	Ms3:	87.76	105.80	156.19	139.56	142.33	122.59
	Ms Tot:	243.54	342.00	456.21	403.38	411.77	376.09
Saturated Mass (g)	Msat1:	71.23	102.17	157.33	103.21	144.83	138.16
	Msat2:	87.10	135.70	143.73	163.13	127.61	117.72
	Msat3:	89.26	106.38	157.24	141.57	143.76	123.33
	Msat Tot:	247.59	344.25	458.30	407.91	416.20	379.21
Submerged Mass (g)	Msub1:	43.91	67.88	99.53	64.66	90.60	85.95
	Msub2:	53.97	89.50	90.36	102.76	79.85	71.78
	Msub3:	55.13	70.44	98.41	89.22	89.99	75.37
	Msub Tot:	153.01	227.82	288.30	256.64	260.44	233.1
Sample:		**Shale** (Pw 2.1)	**Shale** (Pw 3.1)	**Shale** (Pp 3.1)	**Tillite** (C-Pd 2.1)	**Dolerite** (Jd 2.1)	**Sandstone** (Pko 1.1)
Dry Mass (g)	Ms1:	104.65	115.20	108.92	123.53	136.37	133.98
	Ms2:	77.33	136.58	128.99	134.90	94.38	90.32
	Ms3:	148.32	104.86	127.93	143.92	108.07	98.41
	Ms Tot:	330.30	356.64	365.84	402.35	338.82	322.71
Saturated Mass (g)	Msat1:	115.45	116.46	109.58	123.77	136.49	136.02
	Msat2:	84.98	137.72	129.23	135.21	94.52	91.62
	Msat3:	162.99	105.51	128.54	144.32	108.17	99.80
	Msat Tot:	363.42	359.69	367.35	403.30	339.18	327.44
Submerged Mass (g)	Msub1:	63.23	72.45	68.23	78.03	91.16	83.66
	Msub2:	46.52	86.21	80.69	85.15	63.31	56.43
	Msub3:	90.44	65.99	80.28	90.89	72.46	61.53
	Msub Tot:	200.19	224.65	229.20	254.07	226.93	201.62

The calculations as shown in Appendix A in Table 6A were also determined by using the dry -, saturated- and submerged mass of three specimens of each rock sample. The sample volume, pore volume, porosity, dry density, bulk specific gravity and water absorption of the surface samples were calculated by using equations (1-6) as previously indicated and the results shown in Table 34.

Table 34: Surface Samples - Porosity, dry density and water absorption of the twelve samples

Calculations		**Sandstone** (Pa 1.1)	**Dolerite** Jd 1.1	**Tillite** (C-Pd 1.1)	**Shale** (Pp 1.1)	**Shale** (Pw 1.1)	**Shale** (Pp 2.1)
Porosity (%)	**n Avg:**	**4.298**	**1.821**	**1.229**	**2.959**	**2.852**	**2.170**
Dry Density (g/cm^3)	**p_d Avg:**	**2.574**	**2.941**	**2.684**	**2.665**	**2.644**	**2.572**
Bulk Specific Gravity	**Sp. Gr. Avg:**	**2.574**	**2.941**	**2.684**	**2.665**	**2.644**	**2.572**
Absorption (%)	**Abs.Avg:**	**1.670**	**0.622**	**0.460**	**1.110**	**1.079**	**0.848**
Calculations		**Shale** (Pw 2.1)	**Shale** (Pw 3.1)	**Shale** (Pp 3.1)	**Tillite** (C-Pd 2.1)	**Dolerite** (Jd 2.1)	**Sandstone** (Pko 1.1)
Porosity (%)	**n Avg:**	**20.264**	**2.240**	**1.118**	**0.631**	**0.331**	**3.741**
Dry Density (g/cm^3)	**p_d Avg:**	**2.020**	**2.641**	**2.647**	**2.696**	**3.020**	**2.566**
Bulk Specific Gravity	**Sp. Gr. Avg:**	**2.020**	**2.641**	**2.647**	**2.696**	**3.020**	**2.566**
Absorption (%)	**Abs.Avg:**	**10.035**	**0.849**	**0.423**	**0.234**	**0.110**	**1.458**

For the Slake-Durability Index test on the surface samples, ten representative specimens of each of the twelve surface samples were tested by subjecting them to a two-standard cycle of wetting and drying. The results obtained by the tests are shown in Appendix A in Table 7A.

By using the equation (7) as previously indicated, the Slake-Durability Index can be calculated for the surface samples of the different rock types and lithologies, as shown in Table 35.

Table 35: Surface Samples - Slake-Durability Index of the samples

Sample:	**Sandstone** (Pa 1.1)	**Dolerite** (Jd 1.1)	**Tillite** (C-Pd 1.1)	**Shale** (Pp 1.1)	**Shale** (Pw 1.1)	**Shale** (Pp 2.1)
Slake-Durability Index (two-cycle) Id_2:	99.45	99.18	99.48	99.32	99.20	99.34
Sample:	**Shale** (Pw 2.1)	**Shale** (Pw 3.1)	**Shale** (Pp 3.1)	**Tillite** (C-Pd 2.1)	**Dolerite** (Jd 2.1)	**Sandstone** (Pko 1.1)
Slake-Durability Index (two-cycle) Id_2:	98.62	99.62	99.40	99.55	99.64	99.37

The XRD results indicating the amount of weight percentage of each mineral present in the twelve rock specimens of the surface samples retrieved, as shown in Table 36.

Table 36: Surface Samples - XRD results of the twelve rock specimens

Sandstone (Pa 1.1)		**Dolerite** (Jd 1.1)		**Tillite** (C-Pd 1.1)		**Shale** (Pp 1.1)	
	weight%		weight%		weight%		weight%
Chlorite	15.93	Actinolite	2.64	Chlorite	15.29	Chlorite	11.4
Muscovite	7.31	Augite	19.13	Muscovite	7.38	Muscovite	18.46
Orthoclase	10.15	Biotite	7.2	Orthoclase	9.08	Plagioclase	0.49
Plagioclase	34.71	Chlorite	1.87	Plagioclase	29.09	Quartz	69.64
Quartz	31.9	Enstatite	11.71	Quartz	39.16		
		Plagioclase	55.67				
		Quartz	1.81				
Shale (Pw 1.1)		**Shale** (Pp 2.1)		**Shale** (Pw 2.1)		**Shale** (Pw 3.1)	
	weight%		weight%		weight%		weight%
Calcite	2.21	Biotite	7.24	Jarosite	12.68	Chlorite	12.43
Chlorite	12.83	Calcite	1.57	Muscovite	24.33	Muscovite	13.04
Muscovite	17.9	Chlorite	5.08	Orthoclase	3.57	Orthoclase	4.9
Orthoclase	4.22	Muscovite	11.31	Plagioclase	18.58	Plagioclase	20.14
Plagioclase	19.07	Orthoclase	1.79	Quartz	40.84	Quartz	49.48
Quartz	43.76	Plagioclase	11.03				
		Quartz	61.98				
Shale (Pp 3.1)		**Tillite** (C-Pd 2.1)		**Dolerite** (Jd 2.1)		**Sandstone** (Pko 1.1)	
	weight%		weight%		weight%		weight%
Chlorite	4.7	Calcite	0.68	Actinolite	6.33	Chlorite	6.51
Muscovite	8.84	Chlorite	18.81	Augite	17.76	Laumontite	7.84
Plagioclase	2.42	Muscovite	5.69	Biotite	4.31	Muscovite	3.82
Quartz	84.05	Orthoclase	11.85	Chlorite	4.16	Orthoclase	8.03
		Plagioclase	24.07	Enstatite	8.67	Plagioclase	28.52
		Quartz	38.9	Muscovite	0.56	Quartz	42.65
				Plagioclase	52.89	Smectite	2.62
				Quartz	5.32		

The X-Ray Fluorescence Test (XRF) was done to determine the major elements in the twelve different rock specimens retrieved on the surface. The results obtained from the XRF Test are shown in Table 37.

Table 37: Surface Samples - XRF Major Element Analyses Results

% Major	Sample											
Elements	**C-P.d 1.1**	**C-Pd 2.1**	**Jd 1.1**	**Jd 2.1**	**Pa 1.1**	**Pko 1.1**	**Pp 1.1**	**Pp 2.1**	**Pp 3.1**	**Pw 1.1**	**Pw 2.1**	**Pw 3.1**
SiO_2	67.07	68.22	51.05	50.53	68.14	72.21	71.77	76.11	83.86	63.06	72.05	68.62
TiO_2	0.72	0.61	0.92	1.68	0.61	0.54	0.51	0.35	0.29	0.71	0.71	0.51
Al_2O_3	14.19	13.19	15.04	13.37	15.28	12.78	13.90	12.67	8.11	15.58	15.46	13.80
Fe_2O_3 (t)	5.51	5.61	11.40	15.55	4.32	3.13	5.99	2.45	3.09	4.96	1.39	6.24
MnO	0.083	0.108	0.177	0.222	0.067	0.050	0.070	0.042	0.024	0.084	0.006	0.044
MgO	1.92	2.47	7.11	5.08	1.62	0.97	0.92	0.68	0.39	1.54	1.26	1.37
CaO	1.80	1.25	11.08	9.77	1.34	1.67	0.17	0.37	0.06	3.19	0.18	0.49
Na_2O	2.83	2.76	2.19	2.45	4.05	3.75	0.14	1.82	0.24	1.94	1.56	1.99
K_2O	3.24	3.05	0.64	0.78	2.36	2.33	2.61	2.64	1.49	3.10	3.65	2.81
P_2O_5	0.208	0.169	0.162	0.262	0.178	0.173	0.099	0.111	0.063	0.217	0.069	0.159
Cr_2O_3	0.024	0.021	0.056	0.017	0.014	0.017	0.012	0.006	0.007	0.015	0.015	0.020
LOI	2.05	2.02	-0.22	-0.06	1.67	1.84	3.40	2.23	2.03	4.68	3.13	3.45
Total	**99.65**	**99.48**	**99.61**	**99.65**	**99.65**	**99.46**	**99.59**	**99.48**	**99.65**	**99.08**	**99.48**	**99.50**

The Ethylene Glycol Soaking Test done on each of the twelve surface samples indicated no signs of spalling, splitting, or disintegration of the rock samples and an extended submersing period of 40 days in total, still shown no signs of spalling, splitting, or disintegration.

6. Results

6.1.Results of borehole KWV-01

The results of each of the rock samples tested from the deep borehole KWV-01 drilled close to Willowvale are shown under the specific lithologies below. Careful selections of samples retrieved from the borehole were made to enable samples to be in an unweathered state.

6.1.1. Dolerite

The dolerite used for the variety of tests was in an unweathered state. From the Uniaxial Compressive Test and Seismic Wave Velocity Test, it showed that the dolerite is a hard, dense rock, which has a UCS of 299.9 MPa. The density of the dolerite was calculated both at Rocklab (Pty) Ltd. and the Analytical Laboratory in the Department of Geology at the University of Pretoria, to have a density between 2.99 g/cm^3 and 2.98 g/cm^3. Both the P-wave velocity and S-wave velocity are faster than any wave velocity in the other rock samples, which proves that the dolerite is the densest rock sample of the five rock samples tested in borehole KWV-01, as shown in Figure 30. In Figure 32, it is indicated that the porosity of the dolerite is the second highest of the five rock sample's porosity, but is still as low as only 0.719%. Both the dry density and the bulk specific gravity of the dolerite are the highest of the five rock samples, which both give a value of 2.978 g/cm^3. The absorption is as low as 0.242%, which results in the second highest porosity for the five rock samples. Dolerite has a high Slake-Durability Index, which is found to be 99.55 for a standard Two-cycle Test, as shown in Figure 36. From the XRD test results, it is indicated in Figure 38 that the dolerite has a very large amount of plagioclase 49.92% and a large amount of diopside 30.06%, where only minor amounts of clay minerals (kaolinite and muscovite) are present.

6.1.2. Sandstone

The Uniaxial Compressive Test done on the sandstone core sample indicated that the UCS of the sandstone is as high as 338.4 MPa. The density of the sandstone calculated at Rocklab is 2.76 g/cm^3 and 2.68 g/cm^3 at the University of Pretoria. The P-wave and S-wave velocities through the Sandstone are 5 567 m/s and 2 558 m/s, respectively. The porosity of the sandstone is the lowest of the rock samples in the borehole KWV-01, with a range of 0.056% – 0.058%, which indicates that the rock has the lowest pore volume. The sandstone has a dry density of 2.678 g/cm^3 and a bulk specific gravity of 2.767. The water absorption percentage of the sandstone is the lowest of all the five rock samples, with percentages as low as 0.021%. The Slake-Durability Index for the sandstone is also high and is found to be 99.78 for a standard two-cycle test. The XRD Test showed that a very large percentage of quartz and muscovite are present, where a large percentage of biotite and plagioclase have also been indicated.

6.1.3. Carbonaceous Shale

The carbonaceous shale has a UCS of only 74.1 MPa, which indicates that the carbonaceous shale is weaker than the massive shale tested in the borehole KWV-01. The carbonaceous shale is the weakest rock sample of the five lithologies tested, and the P-Wave and S-Wave velocities have the slowest travelling time through the sample. The density of the carbonaceous shale is 2.74 g/cm^3 and the dry density ranges from 2.67 - 2.72 g/cm^3. The carbonaceous shale has the highest porosity and pore volume of the five rock samples tested, where a porosity of 1.52% was calculated by using the buoyancy method. The bulk specific gravity of the carbonaceous shale is the lowest of the samples, whereas the water absorption is the highest of the five rock samples tested indicating a value of 0.559%. The Slake-Durability Index is also the lowest of the five rock samples, but is still as high as 99.40. From the XRD Test done on the carbonaceous shale, it showed that a very high percentage of quartz (43.6%) and muscovite (36.29%) are present with a large percentage of pyrrhotite (13.55%) and minor kaolinite (6.57%). From the Duncan or "Free" Swell Test done on the carbonaceous shale, it has been indicated that no swelling or a very low swelling potential is present in the sample.

6.1.4. Massive Shale

The massive shale is the second weakest rock of the five rock samples tested in borehole KWV-01, which has a UCS of only 169.8 MPa. The P-Wave and S-Wave velocities through the massive shale are the second slowest of all the five rock samples. The porosity of the massive shale is the second lowest of only 0.285% (buoyancy method). The dry density and the bulk specific gravity are the second highest of all the five core samples. The water absorption of the massive shale is 0.101%, which has the third-highest water absorption of all five core samples. The Slake-Durability Index for the massive shale is 99.71 for a standard two-cycle test. The massive shale consists of 43.47% quartz, 34.28% muscovite and 22.25% chlorite. No swelling or very low swelling potential is present in the massive shale, as indicated by the Duncan or "Free" Swell Test.

6.1.5. Tillite

Tillite has the second lowest dry density, according to the buoyancy method, which has a value of 2.731 g/cm^3. It has a very high compressive strength of 429.9 MPa, which is the highest UCS of the tested rock samples in borehole KWV-01. The tillite has the second lowest dry density of 2.731 g/cm^3, calculated with the buoyancy method. The porosity is as low as 0.305% and the water absorption is 0.112%. The Slake-Durability Index value of tillite is the highest value of all the samples tested, which was determined by a standard two-cycle test to be 99.80. From the XRD test done on the tillite, it has been determined that a very large amount of quartz is present (48.15%) and 27.47% consists of plagioclase, and the remaining 24.38% are made up of chlorite, muscovite and microcline.

6.2. Results of borehole KZF-01

The results of each of the rock samples tested from the deep borehole KZF-01 drilled close to Ceres are shown under the rock type's heading below. Dolerite was not encountered in the borehole KZF-01, where testing was only done on the lithologies namely fine sandstone, carbonaceous shale, shale and diamictite. The samples from the borehole were careful selected to enable the retrieved samples to be in an unweathered state.

6.2.1. Fine Sandstone

The fine sandstone of the borehole KZF-01 has a uniaxial compressive strength of 140.4 MPa. The density of the fine sandstone as tested at Rocklab is indicated as 2.65 g/cm^3, where the density of the fine sandstone tested at the University of Pretoria is nearly the same, with a value of 2.63 g/cm^3. The P-wave and S-wave velocities through the fine sandstone are 2 861 and 1 606 m/s, respectively. The average porosity is 2.431% with the highest porosity of the fine sandstone is no higher than 2.539%. The average dry density and bulk specific gravity of the fine sandstone is 2.63 g/cm^3. The water absorption has a percentage of 0.924, which is the second lowest water absorption of the four core samples tested from borehole KZF-01 as indicated in Figure 34. The standard two-cycle Slake-Durability Test determined that the fine sandstone has a value of 99.72. Based on the

XRD results it is indicated that a very large percentage of quartz is present, with a large percentage of plagioclase, muscovite and chlorite.

6.2.2. Carbonaceous Shale

The carbonaceous shale tested has a uniaxial compressive strength (UCS) of 99.9 MPa, which has the second lowest UCS of the four core samples tested in borehole KZF-01. The P-wave and S-wave velocity of the carbonaceous shale is 2 643 m/s and 1 648 m/s, respectively. The density of the carbonaceous shale tested at Rocklab is 2.64 g/cm^3, where the dry density tested at the University of Pretoria is indicated as 2.563 g/$cm^{3;}$ which are the lowest average dry densities of the four core samples tested. The average porosity of the carbonaceous shale is 4.181%, which is the highest percentage porosity of the core samples of borehole KZF-01. The water absorption is also then the highest with a percentage of 1.631%. The bulk specific gravity is also 2.563, which is the same as the dry density of the carbonaceous shale. The Slake-Durability Index (two-cycle) has a value of 99.23, indicating the second lowest value of the four core samples. Quartz and muscovite are present in very large percentages, where plagioclase and chlorite are present in large quantities in the carbonaceous shale, based on the XRD results. Using the Duncan or "Free Swell" Test, it is shown that no swelling displacement has occurred on the samples during the required submerging time, according to the standards. Based on the Ethylene Glycol Soaking Test, no reaction or disintegration were visible after the 21 days, where, after 40 days of prolonged soaking, there were still no reaction or disintegration of the sample.

6.2.3. Shale

The shale is the weakest rock of the four samples tested in borehole KZF-01, with a uniaxial compressive strength of only 70.6 MPa. The P-wave and S-wave velocities through the shale are also the slowest, with values of 2 511 m/s and 1 490 m/s, respectively. The average porosity of the shale is the second highest of the four samples tested, with a percentage of 3.975%. Water absorption of the shale is also classified as the second highest, with an average absorption of 1.542%. The dry density and bulk specific gravity have a value of 2.588 g/cm^3 indicating the second lowest dry density of the four samples. The shale has the lowest Slake-Durability Index of the samples tested with a value of 98.70. A very large weight percentage of quartz and muscovite are present, with percentages of 34.01% and 33.03%, respectively, where large percentages of plagioclase and pyrite are also indicated from the XRD test results. Based on the Duncan or "Free" Swell Tests, it is determined that the shale has not shown any swelling displacement after the testing required period of 60 days. Samples submersed in the Ethylene Glycol resulted in no disintegration or fracturing, which indicates that no reaction occurred during the test.

6.2.4. Diamictite

The Uniaxial Compressive Strength Test showed that the diamictite is the strongest of the four samples tested with a strength value of 202.3 MPa. The density tested at Rocklab indicated that the diamictite is also the most dense core sample in borehole KZF-01, with a value of 2.71 g/cm^3. The P-wave and S-wave velocity through the diamictite are also the fastest, with velocities of 5 657 m/s and 3 101 m/s, respectively. The porosity and water absorption of the diamictite are the lowest of the four core samples of the borehole KZF-01, which has values of 0.339% and 0.125%, respectively. The dry density and bulk specific gravity were indicated as the highest, at 2.720 g/cm^3. The Slake-Durability Index is determined as 99.57. Based on the XRD results, the diamictite is shown to contain a very large percentage of quartz, and large percentages of plagioclase and muscovite, with percentages of 23.99% and 13.37%, respectively.

6.3. Results of surface samples

The results obtained from the variety of tests done on surface samples are summarised and explained under the specific rock types below. The twelve samples are further divided into their specific lithologies below to summarise results. Due to the samples that were retrieved on surface, some surface samples were unweathered to moderately weathered, which could affect the engineering or mechanical properties of the samples.

6.3.1. Surface Dolerite

The two dolerite samples that were tested as shown in Figure 27 had a uniaxial compressive strength of 382.5 and 377.5 MPa, respectively. Both of the dolerite densities determined by Rocklab had a value of 3.00 g/cm^3. The P-wave velocities of the two dolerites were 6509 m/s and 6324 m/s, with S-wave velocities of 3401 m/s and 3367 m/s, respectively. The porosity and water absorption of the two dolerites differed in value, where one sample had a porosity of 1.821% and the other sample a much lower porosity of 0.331% as indicated in Figure 33. The same resulted in the water absorption value, with a higher 0.622% and a low 0.11% as shown in Figure 35. The dry densities and bulk specific gravity of the dolerite are the highest of the surface samples tested with values of 2.941 g/cm^3 and 3.02 g/cm^3. The Slake-Durability Index test determined that the samples had a value of 99.18 and 99.64, respectively. The XRD results show that the dolerite has a very high percentage of plagioclase (>50%) and high percentage of augite (>15%), with percentages of minerals from the two samples nearly the same, as indicated in Figure 40.

6.3.2. Surface Sandstone

Two sandstone samples were tested and they had a uniaxial compressive strength of 219.8 MPa and 208.5MPa. The densities of the sandstone samples as determined by Rocklab varied from a value of 2.50 g/cm^3 and of 2.59 g/cm^3. The sandstone has P-wave velocities of 4292 m/s and 4539 m/s, with S-wave velocities of 1980 m/s and 2588 m/s, respectively. Porosity of the one sample had a percentage of 4.298%, where the other sample had a percentage of 3.741%. The water absorption of the two sandstone samples was 1.67% and 1.46%, respectively. According to a dry density test, the one sandstone had a value of 2.574 g/cm^3, and the other an almost identical value of 2.566 g/cm$^{3.}$ From the Slake-Durability Index Test, it is determined that the sandstone had values of 99.45 and 99.37, respectively. High percentage of plagioclase (>25%) and quartz (>30%) is present in both the sandstone samples as determined by the XRD tests.

6.3.3. Surface Carbonaceous Shale

A total of three samples of carbonaceous shale were retrieved from the Whitehill and Waterford Formations. One sample from the Whitehill Formation (namely, Pw 2.1) was moderately weathered, a state that causes the lowering of strength or engineering properties. The uniaxial compressive strength of these carbonaceous shales ranges from 38.1 MPa to 157.6 MPa. The densities determined at Rocklab, determined that it ranges from 2.12 g/cm^3 to 2.63 g/cm^3. The carbonaceous shale samples have P-wave velocities that range from 1898 to 3670 m/s. S-wave velocities of the carbonaceous shale samples range from 936 m/s to 1956 m/s. Porosity of the sample Pw 2.1 was as high as 20.264%, with high water absorption of 10.035%. The porosities of the other samples (namely, Pw 1.1 and Pw 3.1) were 2.852% and 2.240%, where their water absorption percentages were 1.079% and 0.849%, respectively. Dry densities of the samples ranged from 2.02 g/cm^3 to 2.647 g/cm^3. The slake durability index of the moderately weathered shale was 98.62, where the slake durability index of the other samples ranged from 99.20 to 99.62. The XRD results indicate that all carbonaceous samples have a very high amount percentage quartz (>40%) present, with high amounts percentage of plagioclase (>15%) and muscovite (>10%).

6.3.4. Surface Massive Shale

The surface massive shale samples were retrieved from the Prince Albert Formation. There was one of the samples that could not undergo uniaxial compressive strength or sonic wave velocity tests, due to a fracture on the sample which will result in an incorrect strength result. The uniaxial compressive strength values of the other samples ranges from a low 67.8 MPa to a high 363.4 MPa. Densities determined from Rocklab ranges from 2.63 g/cm^3 to 2.71 g/cm^3. The P-wave velocities ranges from 4538 m/s to 4744 m/s, where the S-wave velocities are determined to be 2510 m/s to 2687 m/s. The porosities of the massive shale samples range from 1.118% to a higher 2.959%. Water absorption ranges from a low 0.423% to a higher 1.11%. The dry density and/or bulk specific gravity value range from 2.647 g/cm^3 to 2.665 g/cm^3. Slake durability index of the three massive shale samples range from 99.32 to a slightly higher 99.40. A very high amount of percentage quartz (>60%) is present in samples with moderately amounts of microcline (>8%).

6.3.5. Surface Tillite

Two tillite surface samples were retrieved from the Dwyka Group, where the uniaxial compressive strength varies from a low 53.8 MPa to a higher 124.9 MPa. The densities determined from Rocklab have nearly the same values of 2.68 g/cm^3 and 2.70 g/cm^3. The P-wave velocities for the two samples were 2041 m/s and 3852 m/s, where the S-Wave velocities were 1268 m/s and 2079 m/s, respectively. Porosity for the two tillite samples ranged from 0.631% to 1.229%, with water absorption from 0.234% to 0.460%. The dry densities of the tillite were 2.684 g/cm^3 and 2.696 g/cm^{3,} respectively. The slake durability for the tillite ranged from 99.48 to 99.55. Both the tillite samples contained very large amounts quartz (>35%), where large amounts of plagioclase (>20%) and chlorite (>15%) are also present.

7. Summary of Results

The results of the lithologies' different engineering properties and mineralogy are shown below in graphs to summarise and correlate the results with each other. The graphs in Figure 27 to 43 respectively show the lithologies' engineering and chemical properties, namely: uniaxial compressive strength, Poisson's ratio, density, porosity, water absorption, slake durability index, XRD and XRF results. The colour legend on the graph is an indicator of which lithology or mineral is shown.

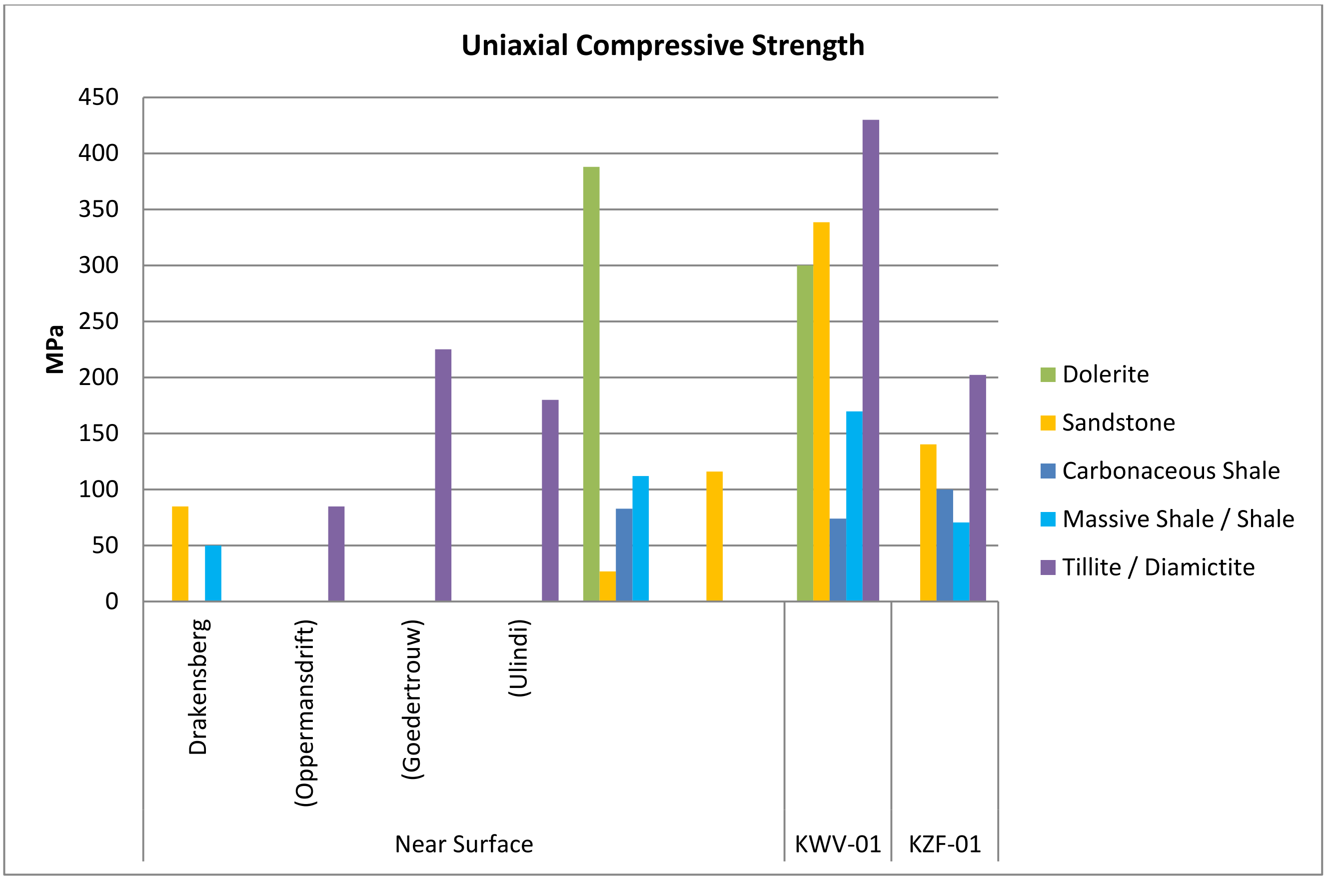


Figure 27: Uniaxial Compressive Strength of previously determined near surface samples and borehole KWV-01 and KZF-01 samples.

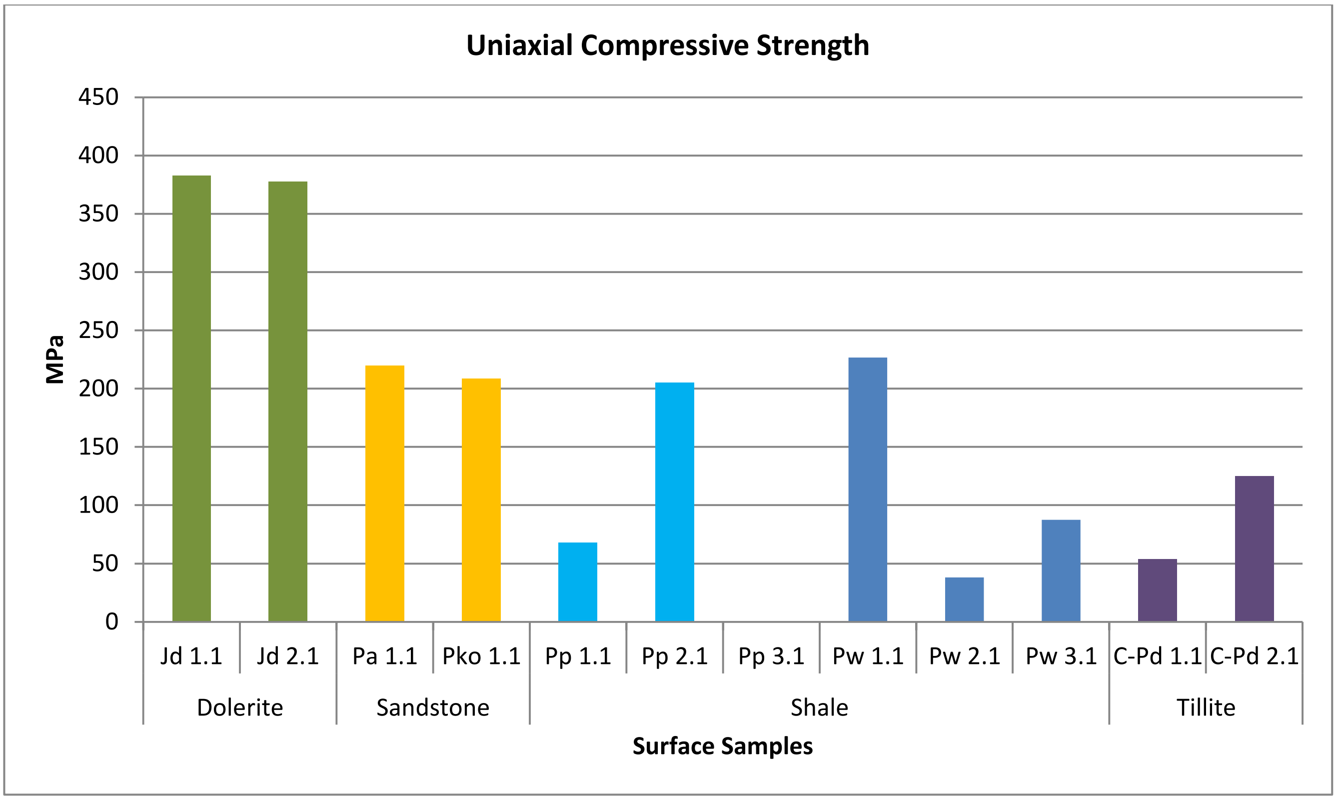


Figure 28: Uniaxial Compressive Strength of surface samples

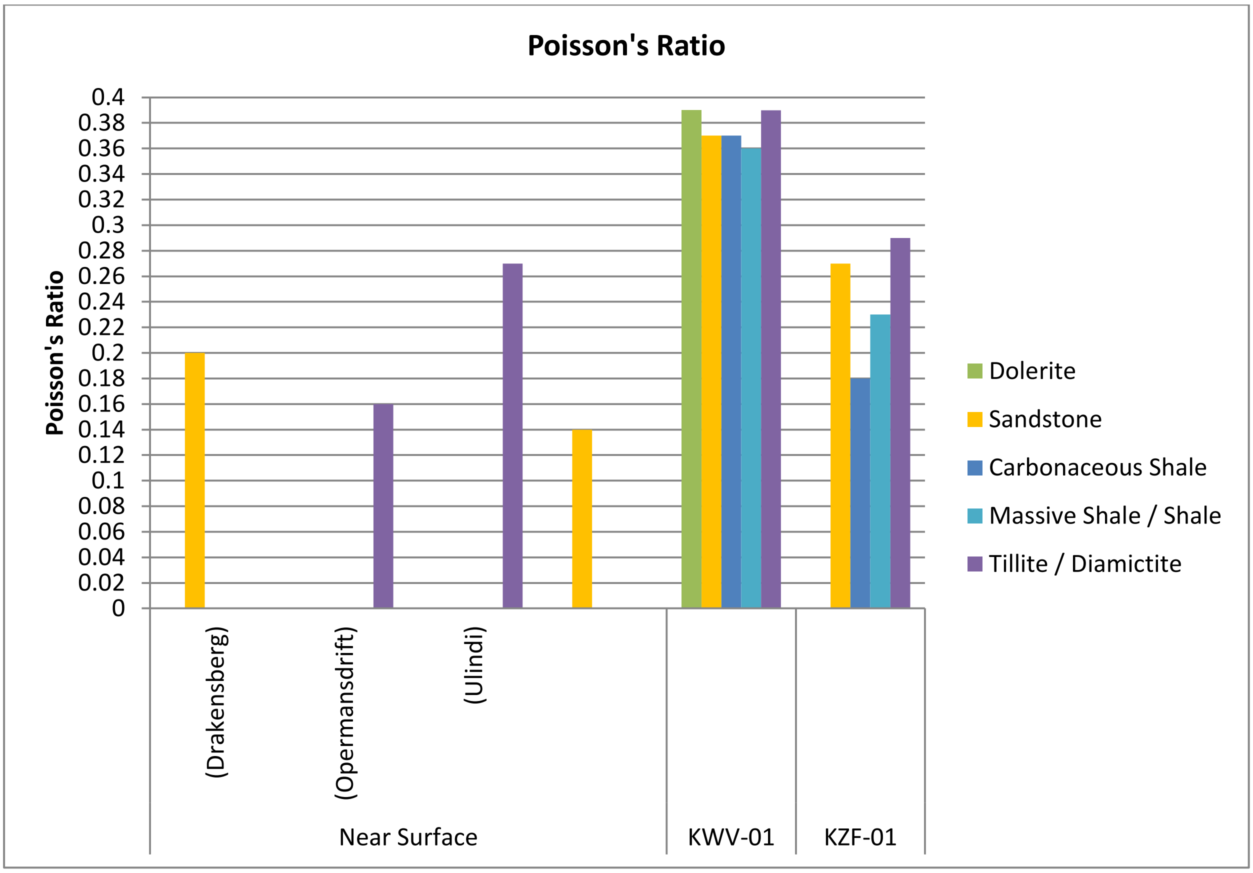


Figure 29: Poisson's Ratio of previously determined near surface samples and borehole KWV-01 and KZF-01 samples.

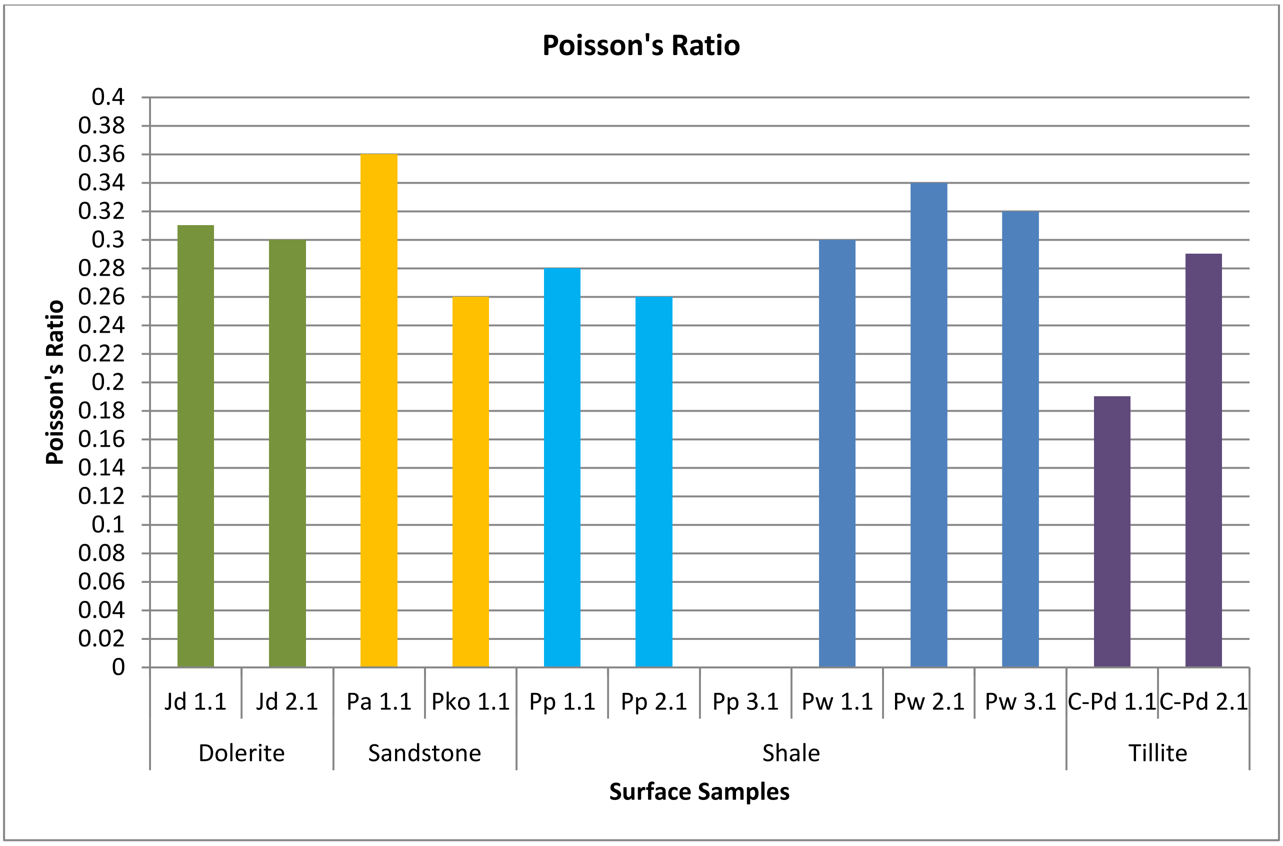


Figure 30: Poisson's Ratio of surface samples

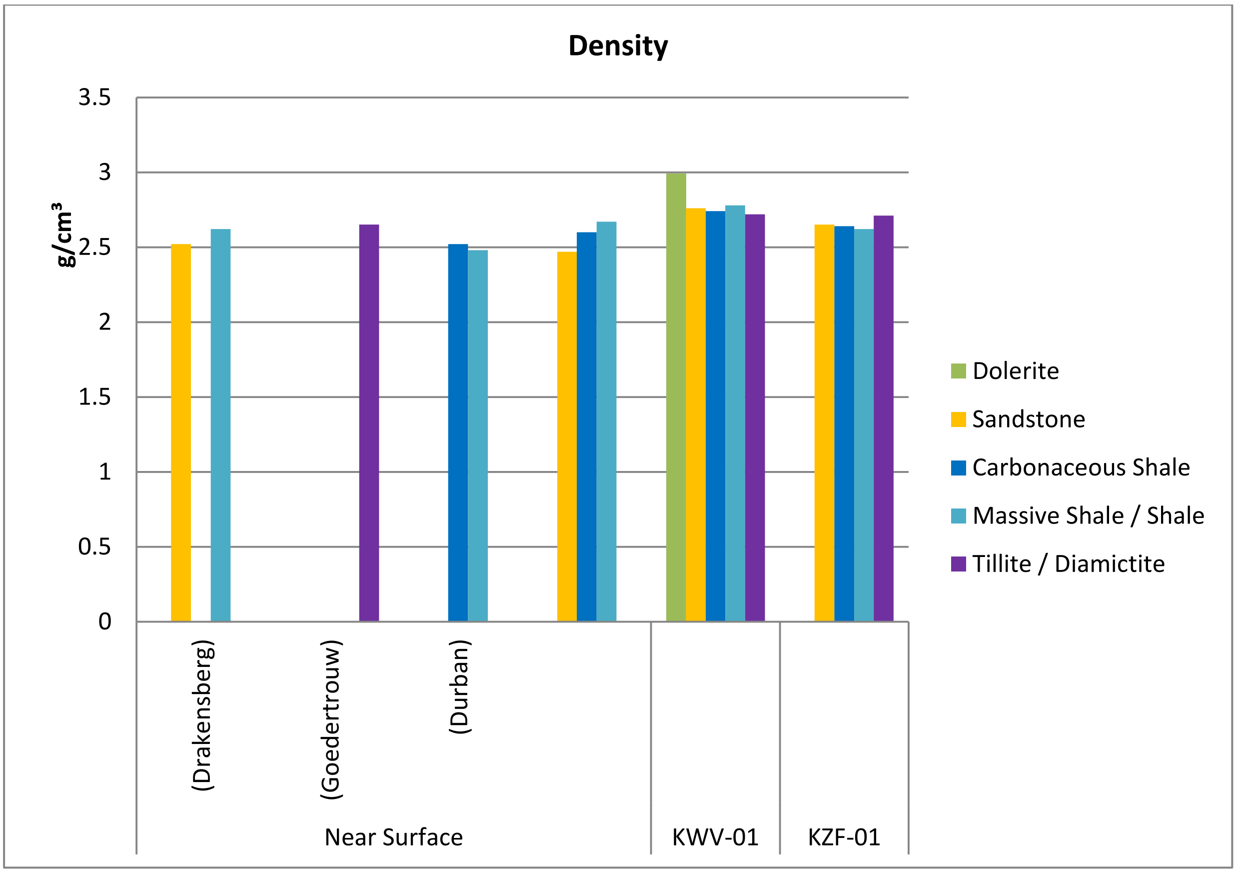


Figure 31: Density of previously determined near surface samples and borehole KWV-01 and KZF-01 samples.

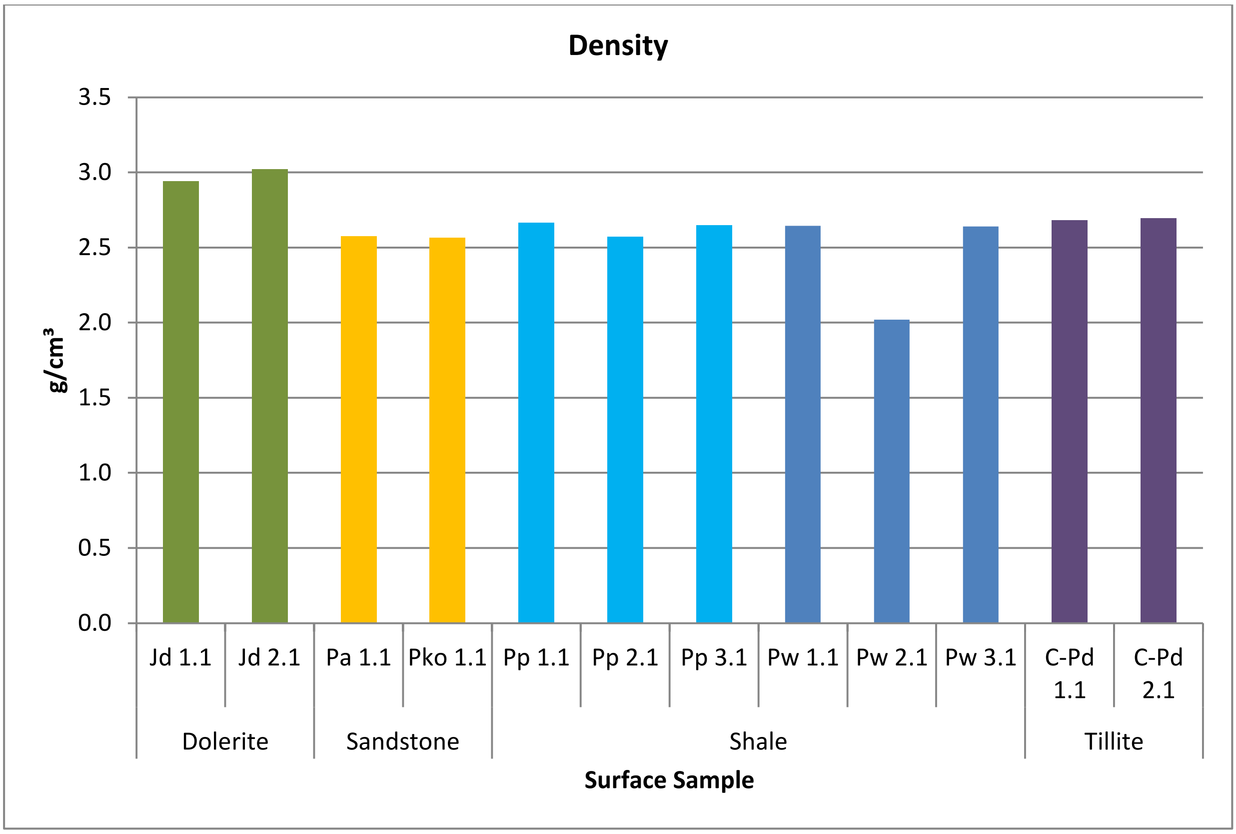


Figure 32: Density of surface samples.

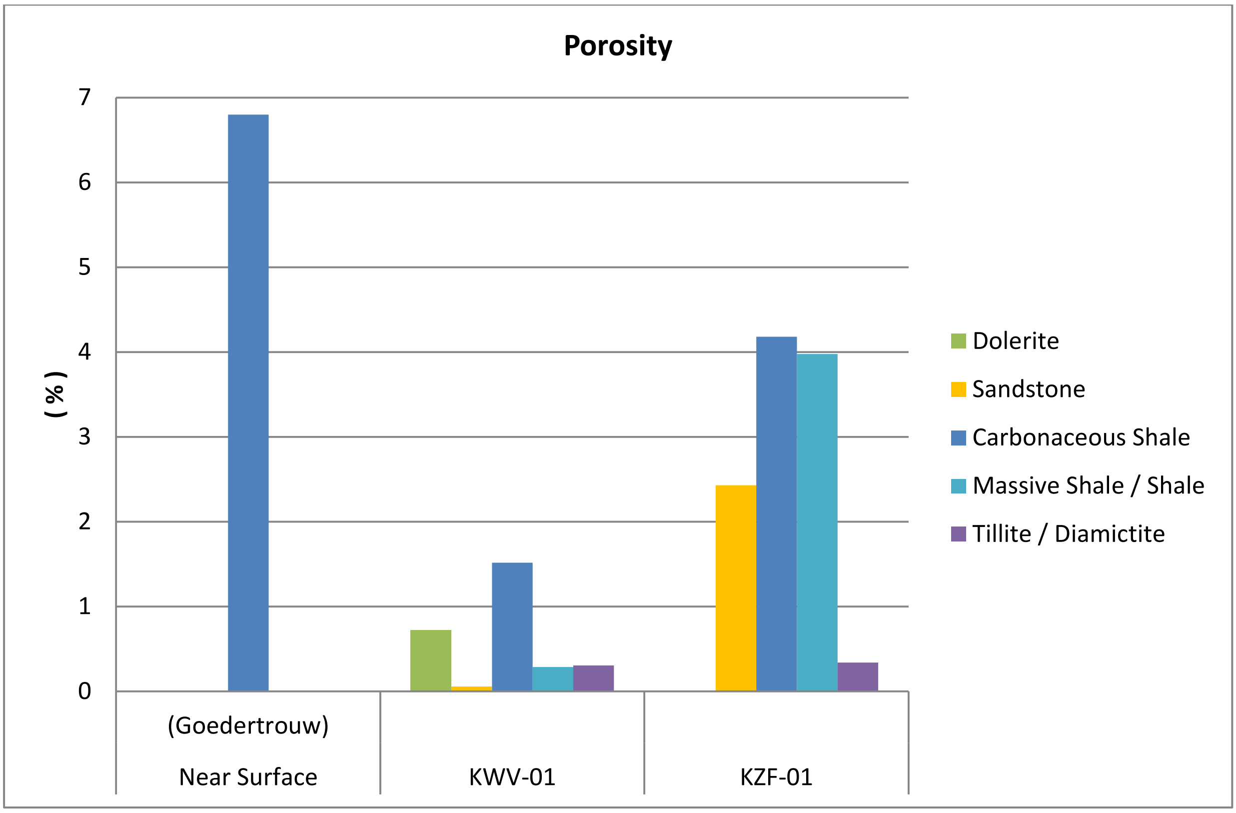


Figure 33: Porosity of previously determined near surface samples and borehole KWV-01 and KZF-01 samples.

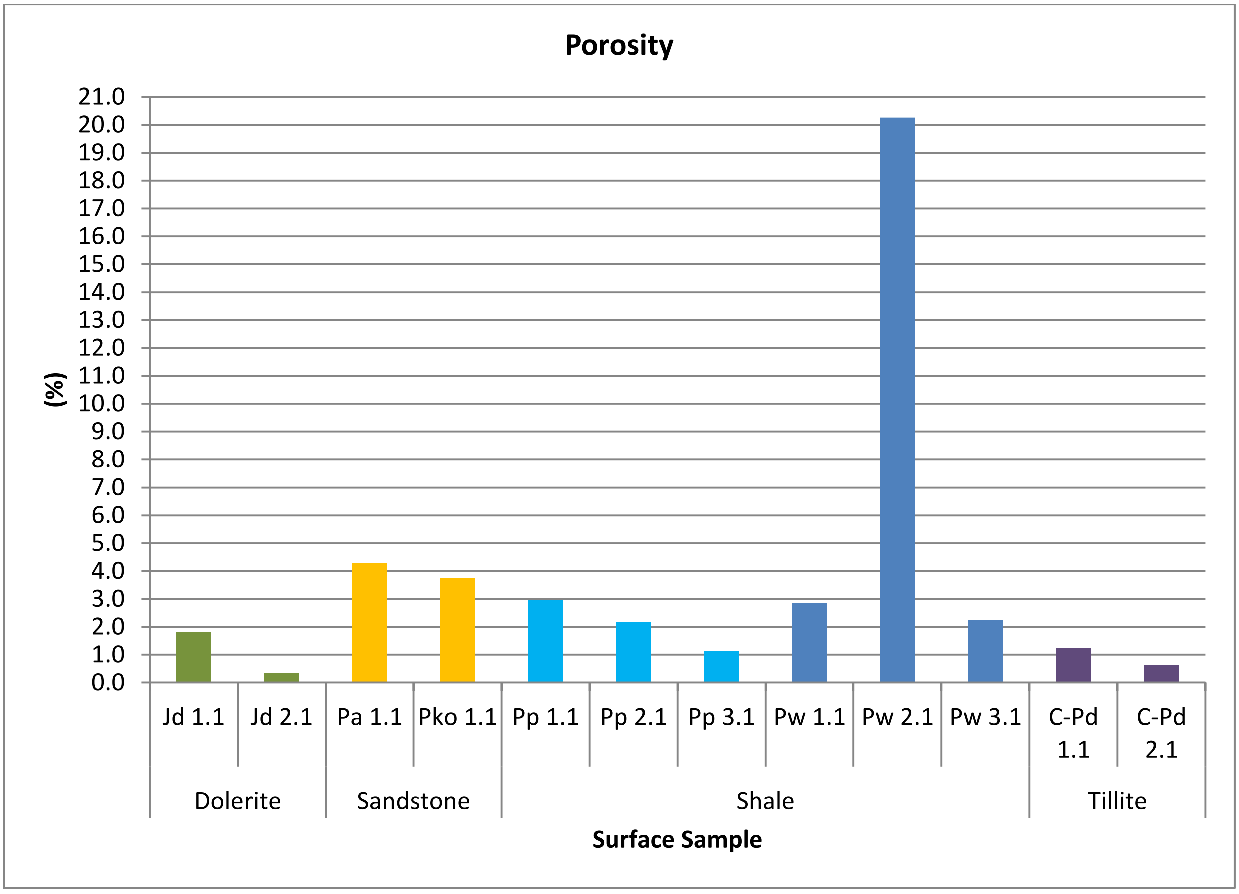


Figure 34: Porosity of surface samples

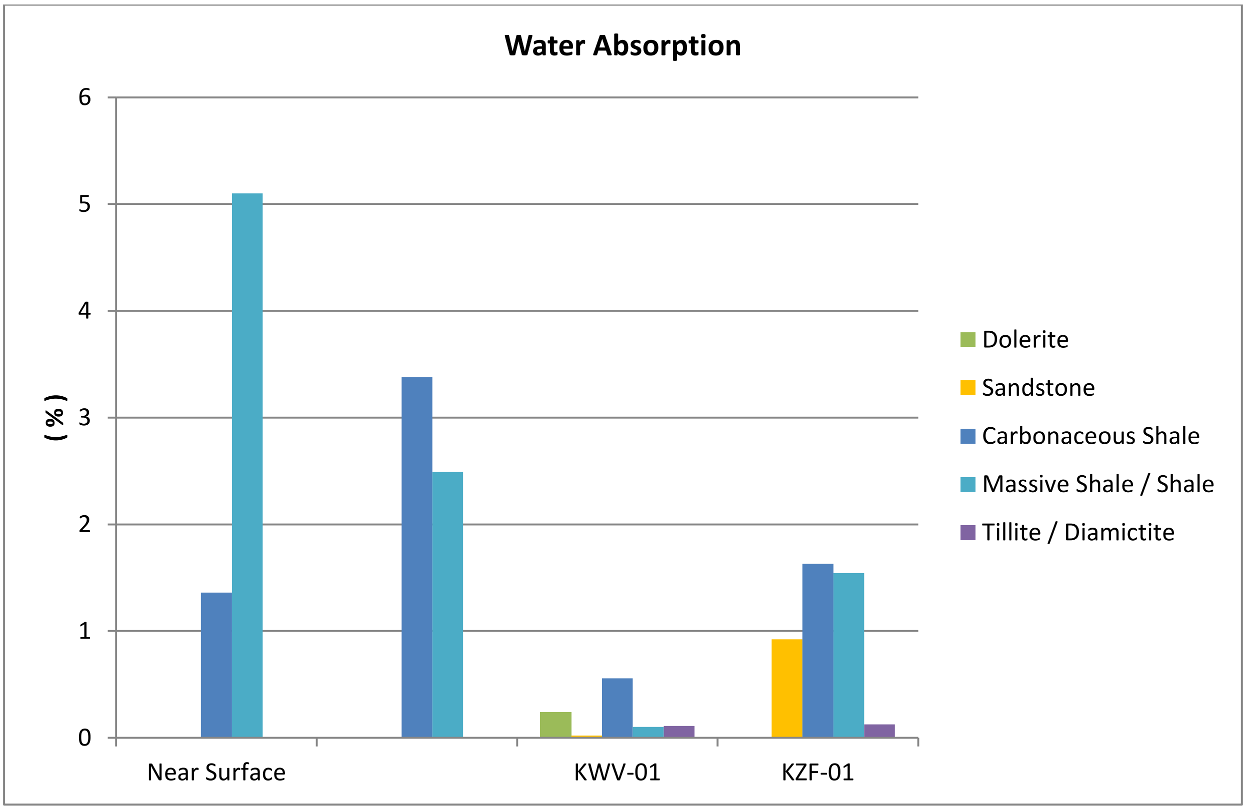


Figure 35: Water absorption of previously determined near surface samples and borehole KWV-01 and KZF-01 samples.

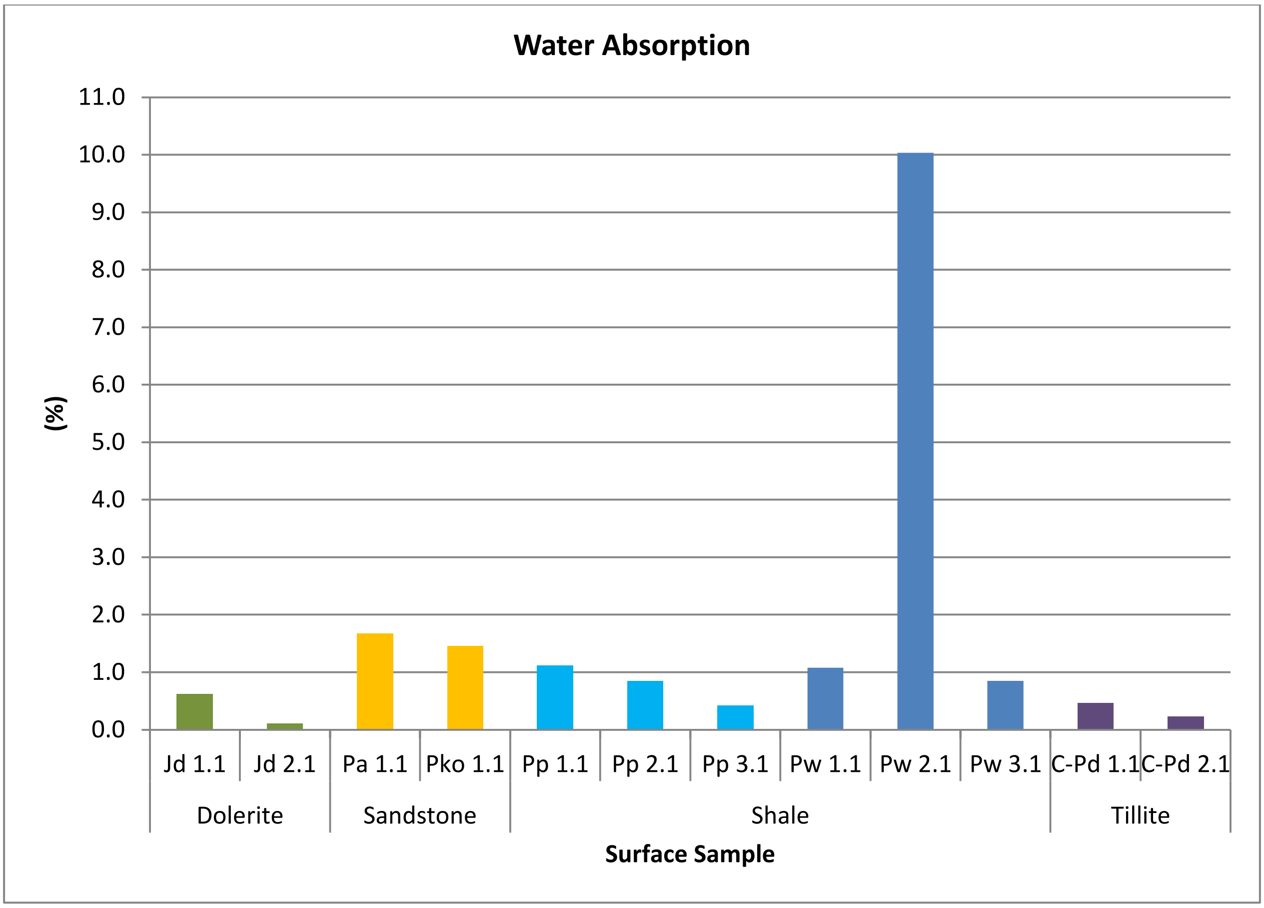


Figure 36: Water absorption of surface samples

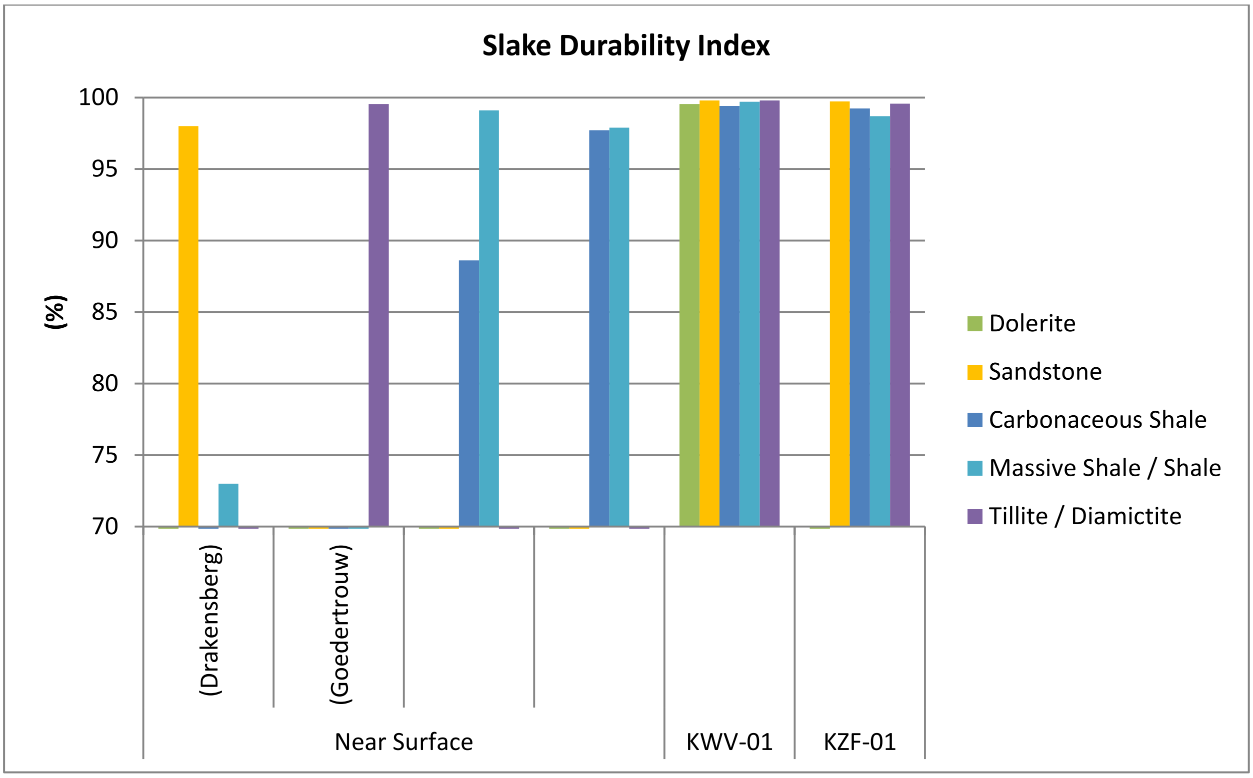


Figure 37: Slake Durability Index of previously determined near surface samples and borehole KWV-01 and KZF-01 samples.

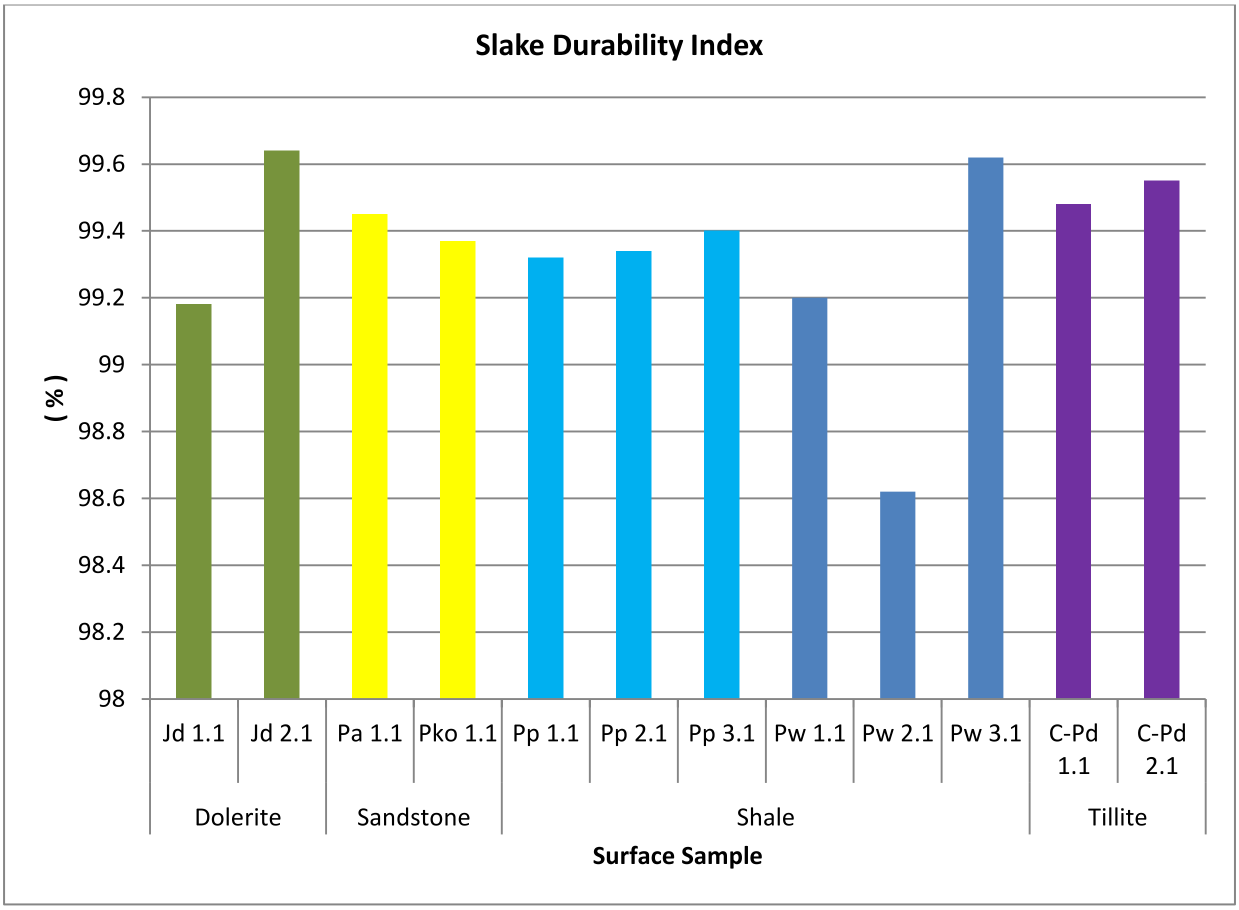
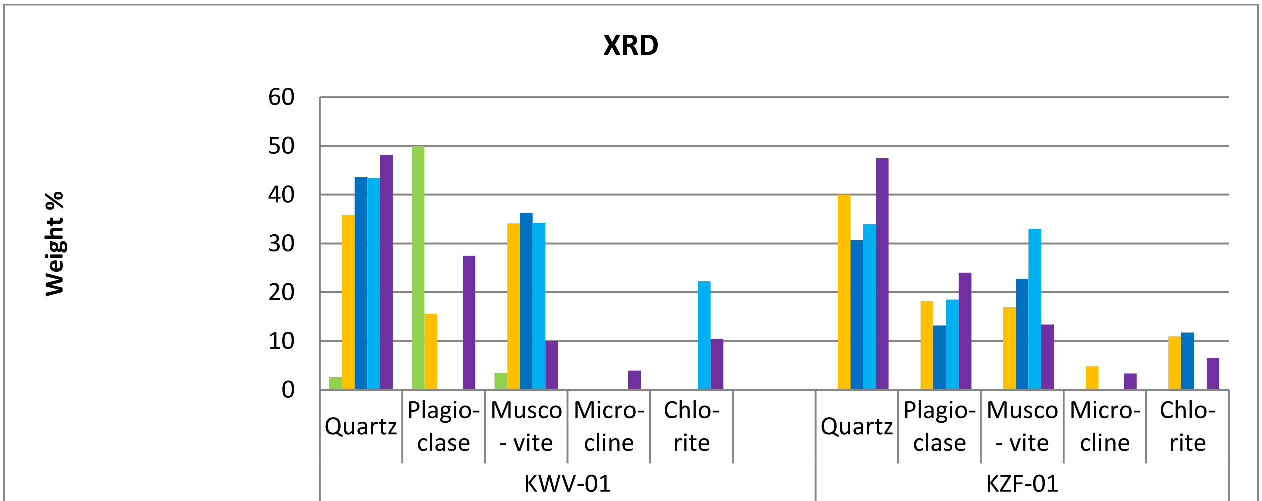
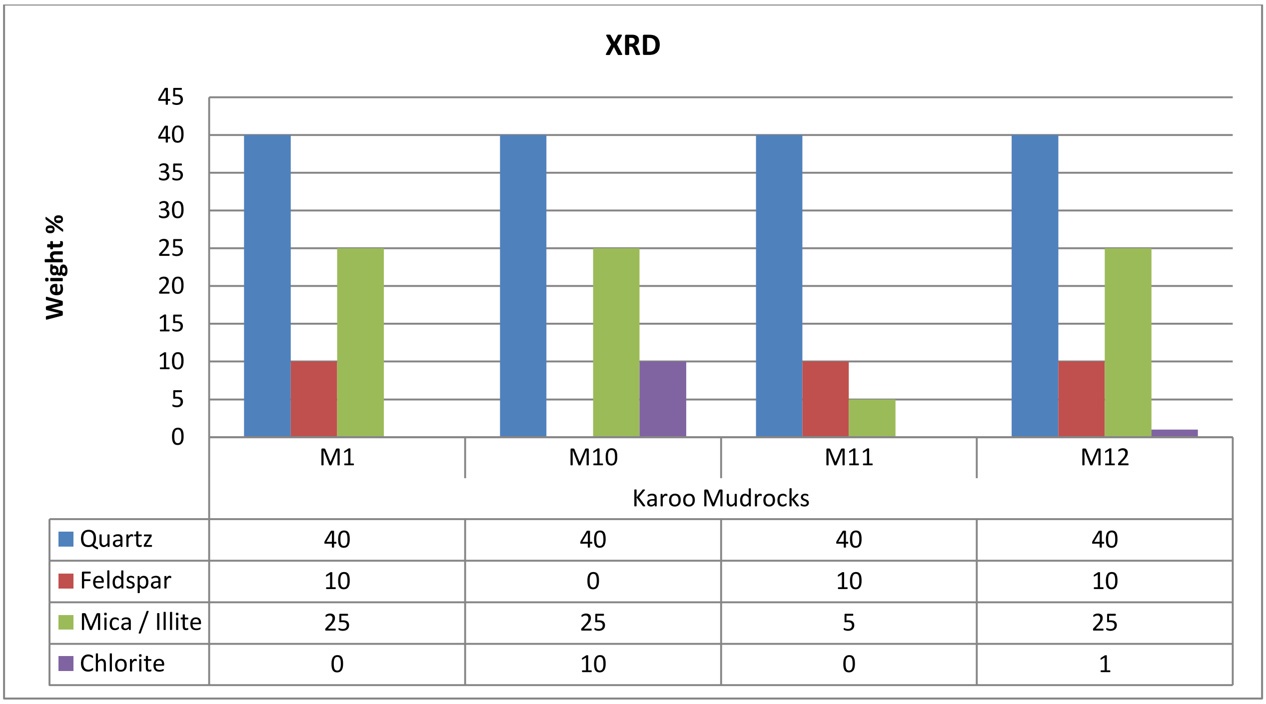


Figure 38: Slake-Durability Index of surface samples.



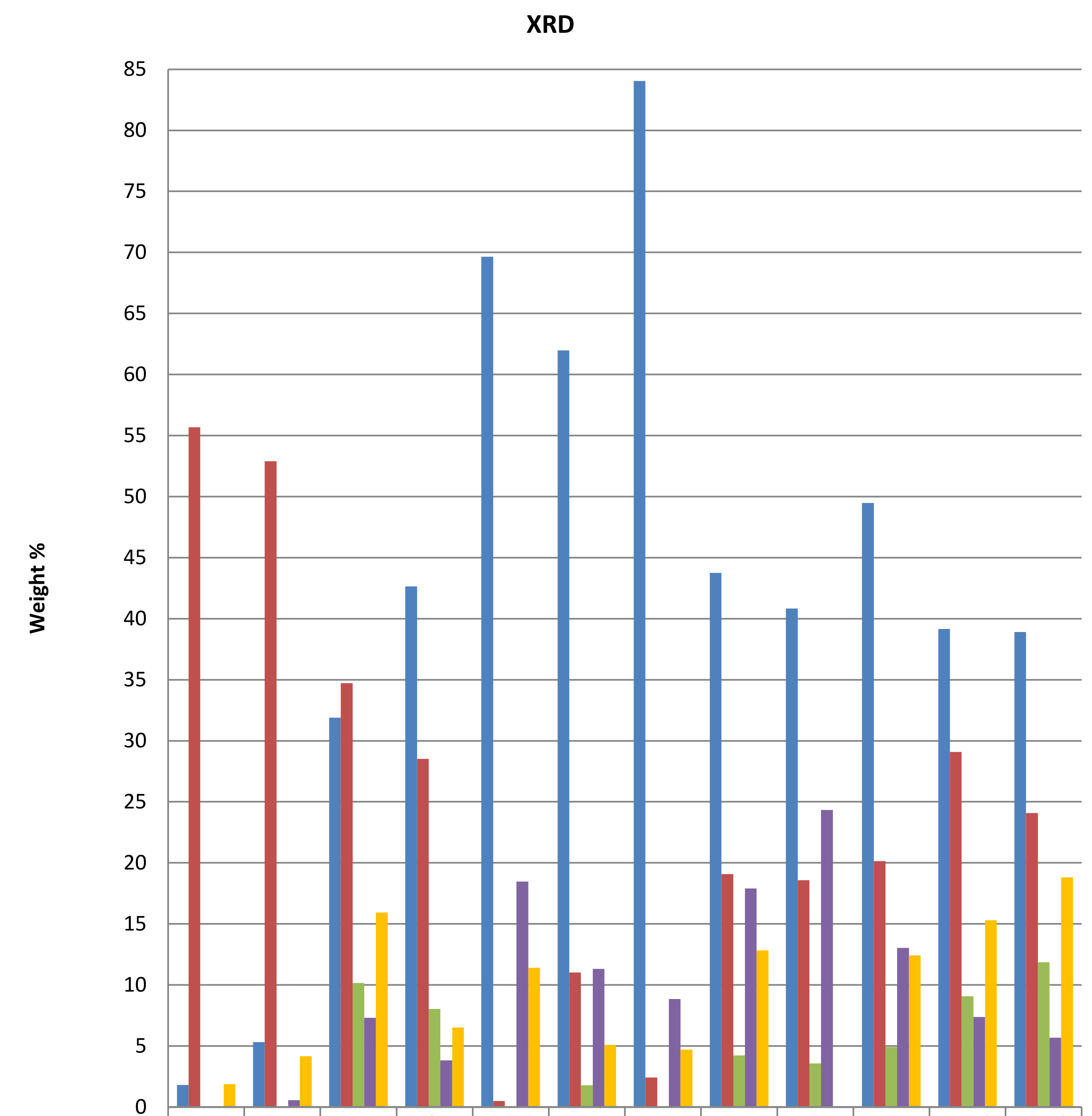
	KWV-01 Quartz	KWV-01 Plagio-clase	KWV-01 Musco-vite	KWV-01 Micro-cline	KWV-01 Chlo-rite		KZF-01 Quartz	KZF-01 Plagio-clase	KZF-01 Musco-vite	KZF-01 Micro-cline	KZF-01 Chlo-rite
Dolerite	2.63	49.92	3.46	0	0		0	0	0	0	0
Sandstone	35.82	15.64	34.11	0	0		40.05	18.19	16.92	4.89	10.98
Carbonaceous Shale	43.6	0	36.29	0	0		30.72	13.16	22.79	0	11.72
Massive Shale / Shale	43.47	0	34.28	0	22.25		34.01	18.51	33.03	0	0
Tillite / Diamictite	48.15	27.47	10	3.95	10.43		47.54	23.99	13.37	3.37	6.58

Figure 39: XRD Results of borehole KWV-01 and KZF-01 samples.



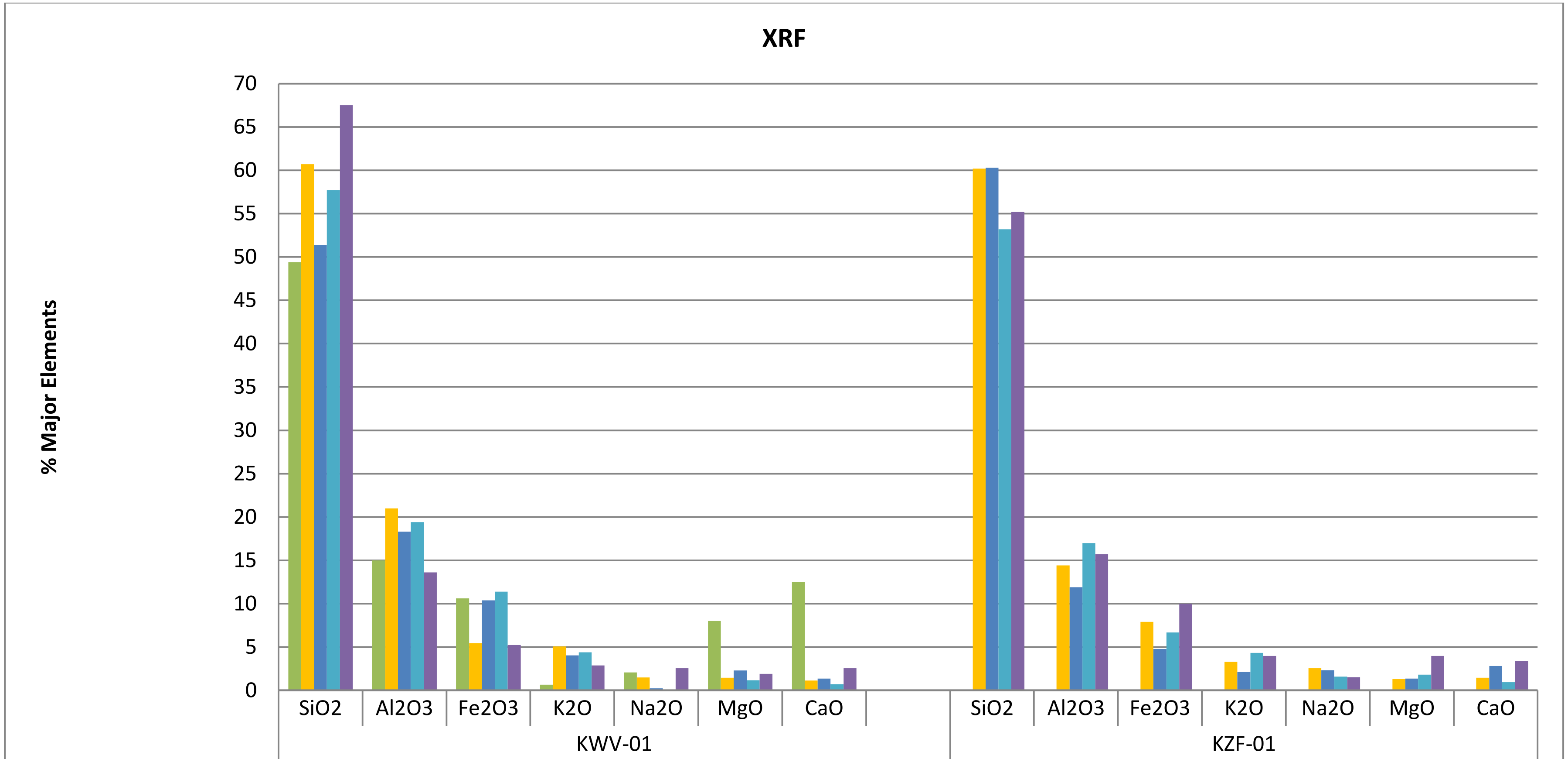
	M1	M10	M11	M12
Quartz	40	40	40	40
Feldspar	10	0	10	10
Mica / Illite	25	25	5	25
Chlorite	0	10	0	1

Figure 40: XRD Results of previously determined surface samples



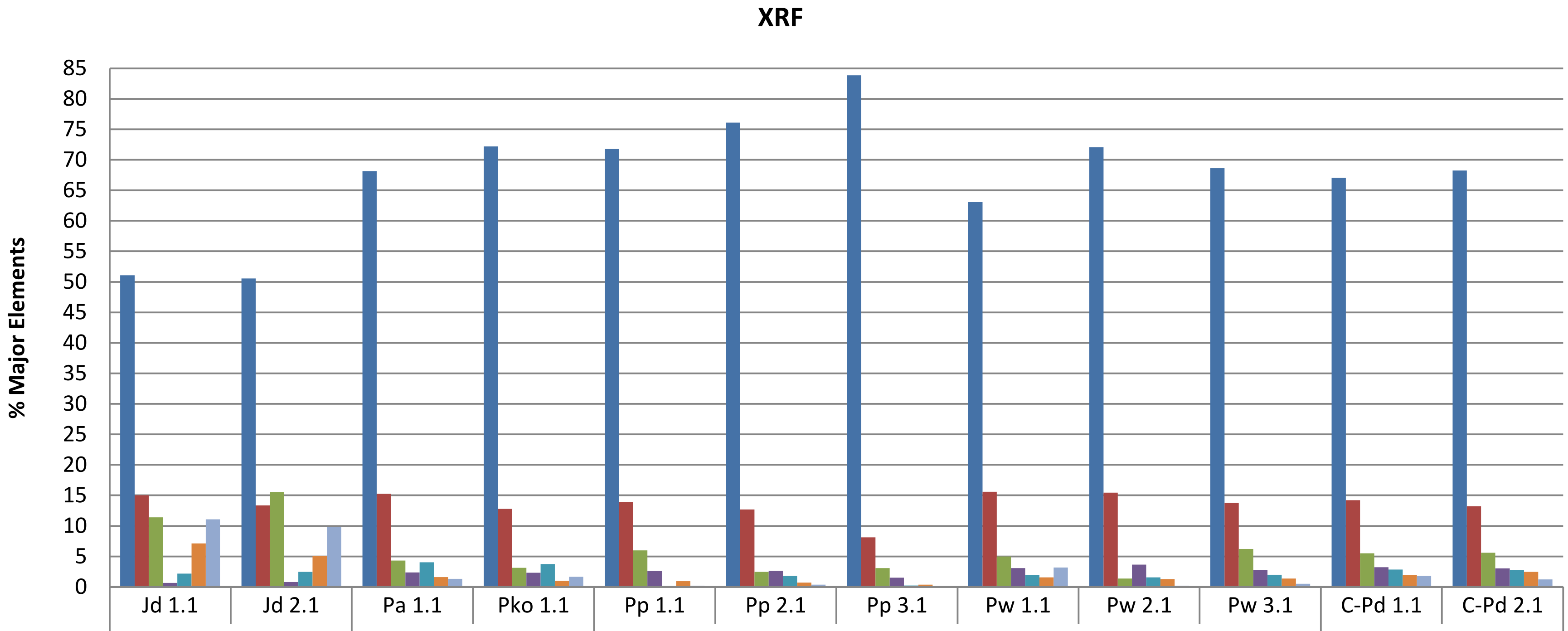
	Jd 1.1	Jd 2.1	Pa 1.1	Pko 1.1	Pp 1.1	Pp 2.1	Pp 3.1	Pw 1.1	Pw 2.1	Pw 3.1	C-Pd 1.1	C-Pd 2.1
	Dolerite		Sandstone		Shale						Tillite	
Quartz	1.81	5.32	31.9	42.65	69.64	61.98	84.05	43.76	40.84	49.48	39.16	38.9
Plagioclase	55.67	52.89	34.71	28.52	0.49	11.03	2.42	19.07	18.58	20.14	29.09	24.07
Orthoclase	0	0	10.15	8.03	0	1.79	0	4.22	3.57	4.9	9.08	11.85
Muscovite	0	0.56	7.31	3.82	18.46	11.31	8.84	17.9	24.33	13.04	7.38	5.69
Chlorite	1.87	4.16	15.93	6.51	11.4	5.08	4.7	12.83	0	12.43	15.29	18.81

Figure 41: XRD Results of surface samples.



	KWV-01 SiO2	KWV-01 Al2O3	KWV-01 Fe2O3	KWV-01 K2O	KWV-01 Na2O	KWV-01 MgO	KWV-01 CaO		KZF-01 SiO2	KZF-01 Al2O3	KZF-01 Fe2O3	KZF-01 K2O	KZF-01 Na2O	KZF-01 MgO	KZF-01 CaO
Dolerite	49.4	15	10.6	0.66	2.08	7.99	12.5		0	0	0	0	0	0	0
Sandstone	60.7	21	5.47	5.06	1.5	1.45	1.15		60.2	14.4	7.89	3.3	2.54	1.29	1.47
Carbonaceous Shale	51.4	18.3	10.4	4.04	0.22	2.31	1.37		60.3	11.9	4.79	2.12	2.34	1.37	2.8
Massive shale / Shale	57.7	19.4	11.4	4.38	0.01	1.17	0.72		53.2	17	6.69	4.34	1.58	1.82	0.95
Tillite / Diamictite	67.5	13.6	5.24	2.89	2.55	1.91	2.55		55.2	15.7	10	3.96	1.53	3.98	3.39

Figure 42: XRF Results of borehole KWV-01 and KZF-01 samples



	Jd 1.1	Jd 2.1	Pa 1.1	Pko 1.1	Pp 1.1	Pp 2.1	Pp 3.1	Pw 1.1	Pw 2.1	Pw 3.1	C-Pd 1.1	C-Pd 2.1
	Dolerite		Sandstone		Shale						Tillite	
SiO2	51.05	50.53	68.14	72.21	71.77	76.11	83.86	63.06	72.05	68.62	67.07	68.22
Al2O3	15.04	13.37	15.28	12.78	13.9	12.67	8.11	15.58	15.46	13.8	14.19	13.19
Fe2O3	11.40	15.55	4.32	3.13	5.99	2.45	3.09	4.96	1.39	6.24	5.51	5.61
K2O	0.64	0.78	2.36	2.33	2.61	2.64	1.49	3.1	3.65	2.81	3.24	3.05
Na2O	2.19	2.45	4.05	3.75	0.14	1.82	0.24	1.94	1.56	1.99	2.83	2.76
MgO	7.11	5.08	1.62	0.97	0.92	0.68	0.39	1.54	1.26	1.37	1.92	2.47
CaO	11.08	9.77	1.34	1.67	0.17	0.37	0.06	3.19	0.18	0.49	1.80	1.25

Figure 43: XRF Results of surface sample

8. Findings and Conclusion

The engineering properties and strength characteristics of the different rock types that have been determined by various amounts of case studies and self-testing on the surface rocks are correlated to the engineering properties and strength characteristics of the rocks from the deep boreholes (KWV-01 & KZF-01). Each rock type's engineering and chemical properties whether shallow or deep of the same lithology are correlated with each other below under the specific headings.

8.1. Karoo Dolerite

The engineering properties and strength characteristics of shallow unweathered dolerite have no single value, but in fact, a range of values are determined for each engineering property of the dolerite. To narrow down the large range of values for properties of the dolerite, the mean can be used for a single value to correlate the properties of the deep rock samples tested.

It has been noted (Anon, 1979) that when an igneous rock has a dry density of over 2.75 g/cm^3, it is described to have a 'very high' dry density and when it has a porosity less than 1%, where the porosity is described as 'very low' (Bell, 2007). From the laboratory tests done on surface samples and core samples in the current study, it has been indicated that the dolerite has a very high dry density and a very low porosity. This indicates that the higher the dry density of the rock is the lower the porosity will be, however when the rock is in an unaltered.

The unconfined compressive strength, also known as uniaxial compressive strength of the Karoo dolerite, consists of a range of values. The compressive strength tests done on fresh unweathered dolerite at different sites on or near the surface have mean UCS values between 201 MPa and 472 MPa, where the strength of the surface samples that were tested also situated in this range. The UCS of the dolerite tested from the deep borehole is 299.9 MPa, which indicates that the strength is within the range of the shallow Karoo dolerites. According to the ISRM (Anon, 1981), rocks with a UCS of over 200 MPa are classified to have a 'very high' strength by using the grades of unconfined compressive strength (Bell, 2007), which indicates that the tested dolerite in the deep borehole and surface samples in the current study exhibit a very high strength. This indicates that the stronger the dolerite, by having a higher UCS, a higher density, the lower the porosity will be.

The strength characteristics of the shallow Karoo dolerites are practically the same as the strength characteristics of the deep dolerite sill at a depth of 2 073.55 m in borehole KWV-01. It could however then not be ruled out that the deep dolerite found at borehole KWV-01 has different engineering properties and strength characteristics than the shallow dolerite at or near surface.

8.2. Karoo Sandstone

According to previous results, the sandstone near surface from the Vryheid Formation has a mean unconfined compressive strength of 27 MPa, where the sandstone of the Estcourt Formation has a higher mean UCS of 116 MPa. The surface samples tested were stronger, with an uniaxial compressive strength of up to 219.8 MPa. This indicates that the sandstone with the highest UCS tested in these formations is up to 271 MPa based from previous results. The sandstone of the Pluto's Member from the deep borehole KWV-01 is stronger than the sandstone found near surface, however the sandstone tested from borehole KZF-01 has a uniaxial compressive strength of only 140.4 MPa. The unconfined compressive strength of the sandstone found at a depth of 2259.06 m in the Pluto's Vale Member is 338.4 MPa, which is higher than any Karoo sandstone tested at the surface. The deep sandstone is thus not necessarily stronger than the shallow near surface sandstone, due to the strength properties of the sandstone from the borehole KZF-01 found at a depth of 240.46 m. The reason for the lower UCS as expected could be evidence for discontinuity features in the samples that suggest that the sample was in an altered state.

The highest Tangent Elastic Modulus at 50% UCS of the surface sandstone from the Ecca Group is only 40.0 GPa at its highest, where the deep sandstone of the Pluto's Vale Member is 63.3 GPa. The highest Poisson's ratio (ν) for the shallow near surface sandstone of the Ecca Group is 0.36, where the highest Poisson's ratio of the deep sandstones of the Ecca Group is 0.37. The highest density of the deep sandstone is 2.76 g/cm^3, which is higher than the highest density value of the shallow sandstone of 2.66 g/cm^3. This proves that the deep sandstone has a lower porosity than the shallow sandstone, as well as that the deep sandstone can resists a higher strength and has a higher deformation ability before failure would occur.

The unconfined compressive strength, tangent elastic modulus, Poisson's ratio and density of the deep sandstone in borehole KWV-01 proved to be higher than the shallow sandstone situated near the surface. It cannot, however, be interpreted that the deep sandstone is stronger and more durable than the shallow sandstone, due to some of the lower engineering properties of the sandstone tested in borehole KZF-01 which tends to be weaker. Some degree of localised metamorphism to the deep sandstone may result in these engineering properties. Metamorphic reactions in the Karoo Group is possible, due to the changing conditions of temperature and/or pressure in the pre-existing rock type. The masses of overburden material of the Main Karoo Basin could cause pre-existing rocks to be pressurised which eventually could lead to some degree of metamorphism..

8.3. Karoo Mudrocks

Previous results determined that the Ecca clay-shale and Ecca shale at or near the surface have a UCS range of 57 MPa to 83 MPa and 112 MPa, respectively. The shale surface samples retrieved from the southern boundary of the Karoo Basin have uniaxial compressive strength values that range from 38.1 MPa to 363.4 MPa, which indicates a wide range of values. The carbonaceous shale of the Whitehill Formation from borehole KWV-01 found at a depth of 2 303.7 m has a UCS of 74.1 MPa. The massive shale of the Prince Albert Formation from the same borehole found at a greater depth of 2 326.29m has a UCS of 169.8 MPa, which is also in the strength value range of the near-surface shale. From borehole KZF-01 the carbonaceous- and massive shale have a UCS of 99.9 and 70.6 MPa respectively, which also situates in the range of the surface shale. This then indicates that the deeper shales are not stronger than the shallow near-surface shale. The UCS of the carbonaceous shale is, in some cases, stronger than the massive shale, where in other cases the opposite occurred. No interpretations could be made with the present data that the deeper shales are stronger than the near surface shale.

The Slake-Durability Index of the carbonaceous shale in borehole KWV-01 is 99.40, where the massive shale's index is 99.71 from the same borehole. From borehole KZF-01 the carbonaceous shale has a Slake-Durability Index of 99.23, and the massive shale a value of 98.70. As shown in the literature review under mudrocks, the Ecca clay-shale has a slake-durability index that ranges from 99.1 to 97.7, and the index value for the shallow Ecca shale is 97.9. The Slake-Durability Index of the shale tested on surface ranges from 98.62 to 99.62. This indicates that the Slake-Durability Index of the deep shales in both boreholes KWV-01 and KZF-01 is usually higher than the shallow shale found on or close to surface, which makes the deeper shale more durable. It also determines that the degree to which extent of weathering occurred plays a big role to the Slake-Durability Index. Thus means that the shallow or near surface shale prone to more weathering than deeper shale are more likely to have a lower durability. However, the shale is the least durable than all the different lithologies tested, it is still classified as to have an extremely high durability according to (Bell, 2007).

The literature review shows that the bulk density of the Ecca clay-shale and the Ecca shale found on or close to the surface have been found to have densities of 2.67 g/cm^3, 2.52 g/cm^3 and 2.48 g/cm^3, respectively. From the surface samples tested the densities ranges from 2.572 g/cm^3 to 2.665 g/cm^3, excluding shale sample Pw 2.1 affected by the degree of weathering. At a depth of 2 303.27 m in borehole KWV-01, the carbonaceous shale has a density of 2.74 g/cm^3 which is higher than the shallow mudrock. In borehole KZF-01, the carbonaceous shale and massive shale have densities of 2.563 g/cm^3 and 2.588 g/cm^3, respectively, which is within the shallow shales' densities range. The massive shale found at borehole KWV-01 has a higher density of 2.78 g/cm^3, which indicates more dense shale than the shallow mudrock. However, this is not true for all the deep shale, where borehole KZF-01 indicates that the shale has a lower density.

From the literature review, it is indicated that the water absorption of the shallow Ecca clay-shale ranges from 1.36 to 3.38 per cent. The surface shale samples tested have a water absorption range of 0.848 to 1.110 %, excluding shale sample Pw 2.1, where the results are influenced by its fractures. The water absorption of the deep carbonaceous shale in borehole KWV-01 is 0.559% and that of the massive shale is 0.101%, which is lower than the shallow mudrock. Carbonaceous shale from borehole KZF-01 has a water absorption value of 1.631% and a lower value of 1.542% for the massive shale. In borehole KWV-01 the deep mudrocks has a lower water absorption characteristics which indicates that less water will be absorbed by the mudrocks when water is applied to those deep environment. In borehole KZF-01, the deeper shale has also higher water absorption ability, as for the shallow near-surface shale. However, the majority of the deeper shale has a lower water absorption percentage than that of the near surface shale.

Previous XRD analyses results from the literature review show that three mudrock samples (M1, M10 and M12) found near surface, determine the mineralogy of the Ecca clay-shale and Ecca shale. The surface mudrocks indicates that the shale samples contain a large percentage of illite and medium amounts of feldspar. The surface shale tested indicates that the majority of samples contained large amounts of muscovite and plagioclase. Mineralogy determined by XRD tests for the deep carbonaceous shale of borehole KWV-01, indicating that over 30% of muscovite was present, and that only a small amount of kaolinite (6.57%) was found. From borehole KZF-01 a smaller amount, below 25%, of muscovite was found. The large percentage of muscovite and illite present in the shallow mudrocks can cause excessive expansion when saturated, and undergo further shrinkage when dried again. The XRD test done on the deep massive shale indicates medium amount of chlorite present, but no kaolinite is indicated.

By using the information gained by uniaxial compressive strength tests, slake-durability tests, and calculating the density and water absorption of the shale samples, it can be interpreted that the deep carbonaceous shale and the massive shale are more likely to be stronger and more durable than the shallow Ecca shale. However this may also be related to the degree of weathering, due to shallower shale exposed to more weathering. The deep massive shale is stronger and more durable than the deep carbonaceous shale, but as a result the carbonaceous shale is still stronger than the near-surface unweathered shale in borehole KWV-01. In borehole KZF-01 there is no clear indication that this is also the same hypothesis, where the majority of samples have these properties, and there are some samples that do not support the data. From the XRD analyses done on the mudrock and the Duncan or "Free" Swell tests, more expansive minerals are indicated to be present in the near surface shale, where little to no amounts of these minerals are present in the deep shale.

8.4. Karoo Tillite

As previously shown in the literature review of the Karoo tillite, the unconfined compressive strength of the tillite has a large variance of values. The tillite tested at Goedertrouw Dam has UCS values that range from 122 to 298 MPa. In the railway tunnel near Ulindi, some compressive strength tests were also done, with UCS values ranging from 142 to 194 MPa. The surface tillite tested from the Dwyka Group on the southern boundary of the Main Karoo Basin has a lower UCS value of 53.8 MPa, while another sample recorded a value of 124.9 MPa. The deep Dwyka tillite in borehole KWV-01 found at a depth of 2326.29 m underwent an unconfined compressive strength test, recording a UCS of 429.9 MPa. The other deep tillite at a depth of 661.5 m had a UCS value of 202.3 MPa. This proved that the deep Dwyka tillite in the borehole KWV-01 is stronger than the shallow tillite, however the deep tillite in borehole KZF-01 has a strength property which is in the range of the surface tillites' strength properties.

The density of the deep tillite found in the borehole KWV-01 and borehole KZF-01 is higher than the densities of the shallow tillite that are near or on the surface. Densities of shallow tillite range from 2.51 g/cm^3 to 2.696 g/cm^3, where the deep tillites have a density of 2.73 g/cm^3 and 2.72 g/cm^3, respectively. The higher densities that are found from the deep tillite indicate that the porosity of the deep tillite is lower than the porosities of the shallow near surface tillite. However the composition and dropstone sizes of the tillite will result in a variable which affects the density characteristics.

The maximum Tangent Elastic Modulus and Secant Elastic Modulus for the tillite in the railway tunnel are 70 and 68 GPa, respectively. The maximum Tangent Elastic Modulus and Secant Elastic Modulus for the surface tillite tested are 33.9 and 29.5 GPa, respectively. The Tangent Elastic Modulus and Secant Elastic Modulus of the deep tillite in borehole KWV-01 have a value of 80.5 and 82.5 GPa respectively, which is also higher than the Secant and Tangent Elastic Modulus of shallow tillite. Tillite from the KZF-01 also has a higher Tangent- and Secant Elastic Modulus than the near-surface tillites. The Poisson's ratio can then be determined when the Secant and Tangent Elastic Modulus of the tillite are known.

Poisson's ratio for the deep tillite in borehole KWV-01 at a depth of 2 326.29 m is 0.39 and the Poisson's ratio of the tillite in borehole KZF-01 is 0.29, where the shallow tillite in the railway tunnel has a Poisson's ratio range between 0.22 and 0.33. This proves that the Poisson's ratio of the deep tillite in borehole KWV-01 is higher than shallow near surface tillites. The tillite in borehole KZF-01 has a high Poisson's ratio, but is within the range of values for the surface tillite. A rock with a higher Poisson's ratio has a higher susceptibility for deformation before failure would occur, thus indicating that the deeper tillite can withstand a higher force than the shallow near surface tillite before failure would occur.

To determine the rock durability for all the lithologies, a Geodurability Classification System can be used as previously indicated in the Orange-Fish tunnel case study. The dolerite, sandstone and tillite tested have strength values that are classified as very high strength, according to the Geodurability Classification. The massive shale and the carbonaceous shale are classified as high strength and medium strength, respectively. The sample reflects little to no Duncan or "Free" Swelling Coefficient, and this indicates that all lithologies namely, dolerite, sandstone, carbonaceous shale, massive shale and tillite are classified to have 'excellent' rock durability. This proves that all samples are situated in the 'A-Zone' (Olivier, 1979).

The densities and strength characteristics of the different lithologies are proven to increase as deeper samples are tested in most cases. This indicates that there is a possibility that the deeper unweathered rocks are stronger and more durable than the same type of unweathered rocks close to surface. Deeper rocks have a lower porosity than the shallow rocks of the same lithology, which also indicates a lower water absorption percentage for deeper rocks, however, some samples' engineering properties didn't follow the same statement due to possible weathering defects. It should also be remembered that the lithologies of the same formations were deposited at the same time, indicating that they are the same age. When a lithology was deposited from the start of their existence they were the same depth, where the convergence and subduction of the plates first caused the uplifting and exposure of the lithologies from the Karoo Supergroup. It is also revealed that rock density is not directly proportional to its compressive strength. According to the data from the tests done, the tillite had the highest UCS, but the density of the tillite was the lowest of the five lithologies tested.

From the results obtained by the different tests done, the engineering properties and strength characteristics could be compared with the deep and shallow rocks. It has been concluded that:

- The dolerite located near surface has nearly the same properties than the deep dolerite located in borehole KWV-01.
- The sandstone, shale and tillite proved to have a stronger UCS, more durable, lower expansiveness, and higher density properties when moving deeper from surface conditions.
- The deep carbonaceous shale is weaker and less durable than the deep massive shale, but the carbonaceous shale is still stronger and more durable than the shale located near surface. This indicates that the massive shales are stronger than the carbonaceous shale and that shales of similar composition from a deeper location will be stronger than the shallow located shales.
- The slake durability index of almost all the samples, whether it is shale, sandstone, tillite or dolerite are above 98. This means that the samples are not easily susceptible to slaking in the Karoo, since the humidity is generally low there.
- Some results does not support the hypothesis, because some samples' engineering properties are affected by discontinuities and weathering which indicates that the sample is not in an unaltered state.

- All five lithologies, whether found to be shallow or deep, are classified to have an ‘excellent durability’ according to the Geodurability Classification.
- The reason for the rock properties and outcomes could be a certain degree of metamorphism, which occurred on these deeply laid rocks. If a rock was exposed to a certain degree of metamorphism, the engineering and mechanical properties of the pre-existing rock will change.
- For the way forward, further prospecting, deep drilling and testing of deep cores are recommended, so as to determine whether the engineering and chemical properties of deep rocks constitute the case for the entire Main Karoo Basin.
- Two selective deep boreholes may not give representative engineering and chemical properties of the lithologies from the entire Main Karoo Basin, however, the more deep boreholes that could be drilled for prospecting and testing the representative value will have a smaller variance.

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Appendix A

Table 1A: KWV-01 Porosity, dry density and water absorption for the five core samples

Calculations		**1- Dolerite**	**2- Sandstone**		**3- Carbonaceous Shale**		**4- Massive Shale**		**5- Tillite**
Volume calculation method		*Buoy-ancy Method*	*Caliper Method*	*Buoy-ancy Method*	*Caliper Method*	*Buoy-ancy Method*	*Caliper Method*	*Buoy-ancy Method*	*Buoy-ancy Method*
Volume (cm^3)	V1:	32.88	37.39	36.65	40.55	39.93	28.51	27.18	37.74
	V2:	29.94	40.67	39.01	44.73	43.75	33.47	31.84	36.29
	V3:	26.12	47.6	45.88	43.17	42.59	29.88	28.74	37.53
	V Tot:	88.94	125.66	121.54	128.45	126.27	91.86	87.76	111.56
Pore Volume (cm^3)	Vv Tot:	0.64	0.07	-	1.92	-	0.25	-	0.34
	Vv1:	0.26	0.02	-	0.58	-	0.09	-	0.17
	Vv2:	0.18	0.03	-	0.75	-	0.1	-	0.14
	Vv3:	0.2	0.02	-	0.59	-	0.06	-	0.03
	Vv Avg:	0.213	0.023	-	0.640	-	0.083	-	0.113
Porosity (%)	n Tot:	0.720	0.056	0.058	1.495	1.521	0.272	0.285	0.305
	n1:	0.791	0.053	0.055	1.430	1.453	0.316	0.331	0.450
	n2:	0.601	0.074	0.077	1.677	1.714	0.299	0.314	0.386
	n3:	0.766	0.042	0.044	1.367	1.385	0.201	0.209	0.080
	n Avg:	**0.719**	**0.056**	**0.058**	**1.491**	**1.518**	**0.272**	**0.285**	**0.305**
Dry Density (g/cm^3)	ρ_d Tot:	2.979	2.677	2.768	2.670	2.716	2.687	2.812	2.731
	ρ_d1:	2.996	2.712	2.767	2.679	2.720	2.687	2.818	2.739
	ρ_d2:	2.981	2.652	2.764	2.651	2.710	2.667	2.803	2.740
	ρ_d3:	2.956	2.671	2.771	2.682	2.718	2.710	2.817	2.713
	ρ_d Avg:	**2.978**	**2.678**	**2.767**	**2.670**	**2.716**	**2.688**	**2.813**	**2.731**
Bulk Specific Gravity	Sp. Gr. Tot:	2.979	2.768	-	2.716	-	2.812	-	2.731
	Sp. Gr.1:	2.996	2.767	-	2.720	-	2.818	-	2.739
	Sp. Gr.2:	2.981	2.764	-	2.710	-	2.803	-	2.740
	Sp. Gr.3:	2.956	2.771	-	2.718	-	2.817	-	2.713
	Sp.Gr. Avg:	**2.978**	**2.767**	**-**	**2.716**	**-**	**2.813**	**-**	**2.731**
Absorp-tion (%)	Abs. Tot:	0.242	0.021	-	0.560	-	0.101	-	0.112
	Abs.1:	0.264	0.020	-	0.534	-	0.117	-	0.164
	Abs.2:	0.202	0.028	-	0.633	-	0.112	-	0.141
	Abs.3:	0.259	0.016	-	0.510	-	0.074	-	0.029
	Abs. Avg:	**0.242**	**0.021**	**-**	**0.559**	**-**	**0.101**	**-**	**0.112**

Table 2A: KWV-01 Mass of samples during and after Slake-Durability Index Test

Sample:		1- Dolerite	2- Sandstone	3- Carbonaceous Shale	4- Massive Shale	5- Tillite
Oven Dry Sample Mass (g)	Ms1:	98.5	101.41	108.77	76.61	103.36
	Ms2:	89.22	107.84	118.71	89.26	99.44
	Ms3:	77.18	127.12	115.9	80.96	101.79
	Ms4:	149.19	103.15	124.89	102.32	64.31
	Ms5:	132.5	76.59	91.9	89.97	83.73
	Ms Tot:	546.6	516.12	560.18	439.12	452.63
Drum Mass A/B (without lid) (g)		940.46	940.55	925.06	940.43	924.99
Mass A (g)		**1487.06**	**1456.67**	**1485.24**	**1379.55**	**1377.62**
Cycle 1 Sample Mass (g)	Ms1:	98.25	101.32	108.39	76.42	103.22
	Ms2:	88.71	107.71	118.31	89.12	99.33
	Ms3:	76.6	127.03	115.44	80.87	101.7
	Ms4:	149.01	102.82	124.43	101.67	64.22
	Ms5:	132.33	76.42	91.42	89.87	83.65
	Ms Tot:	544.91	515.36	558	437.96	452.13
Drum Mass A/B (without lid) (g)		940.48	940.69	925.17	940.87	924.99
Mass B (g)		**1485.39**	**1456.05**	**1483.17**	**1378.83**	**1377.12**
Cycle 2 Sample Mass (g)	Ms1:	98.12	101.25	108.15	76.32	103.14
	Ms2:	88.57	107.6	118.13	89.01	99.23
	Ms3:	76.21	126.96	115.08	80.79	101.55
	Ms4:	148.89	102.74	124.19	101.59	64.16
	Ms5:	132.23	76.31	91.22	89.77	83.6
	Ms Tot:	544.03	514.87	556.77	437.49	451.68
Drum Mass A/B (without lid) (g)		940.59	940.67	925.13	940.8	925.05
Mass C (g)		**1484.62**	**1455.54**	**1481.9**	**1378.29**	**1376.73**
Clean Drum Mass D (g)		**940.36**	**940.47**	**925.03**	**940.44**	**924.95**

Table 3A: KZF-01 Dry-, saturated- and submerged masses of the four core samples

Sample:		C1- Fine Sandstone	C2- Carbonaceous Shale	C3- Shale	C4- Diamictite
Dry Mass (g)	Ms1:	149.20	135.31	126.08	125.46
	Ms2:	133.21	134.59	129.04	89.80
	Ms3:	106.07	134.16	92.46	77.94
	Ms Tot:	388.48	404.06	347.58	293.2
Saturated Mass (g)	Msat1:	150.64	137.41	127.41	125.6
	Msat2:	134.46	136.76	130.83	89.92
	Msat3:	106.99	136.48	94.48	78.04
	Msat Tot:	392.09	410.65	352.72	293.56
Submerged Mass (g)	Msub1:	93.92	85.08	79.38	79.47
	Msub2:	83.79	83.36	81.09	56.90
	Msub3:	66.75	84.53	58.14	49.39
	Msub Tot:	244.46	252.97	218.61	185.76

Table 4A: KZF-01 Porosity, dry density, and water absorption for the four core samples

Calculations		C1- Fine Sandstone	C2- Carbonaceous Shale	C3- Shale	C4- Diamictite
Volume (cm^3)	V1:	56.72	52.33	48.03	46.13
	V2:	50.67	53.4	49.74	33.02
Buoyancy method	V3:	40.24	51.95	36.34	28.65
	V Tot:	147.63	157.68	134.11	107.8
Pore Volume (cm^3)	Vv Tot:	3.61	6.59	5.14	0.36
	Vv1:	1.44	2.1	1.33	0.14
	Vv2:	1.25	2.17	1.79	0.12
	Vv3:	0.92	2.32	2.02	0.1
	Vv Avg:	1.203	2.197	1.713	0.120
Porosity (%)	n Tot:	2.445	4.179	3.833	0.334
	n1:	2.539	4.013	2.769	0.303
	n2:	2.467	4.064	3.599	0.363
	n3:	2.286	4.466	5.559	0.349
	n Avg:	**2.431**	**4.181**	**3.975**	**0.339**
Dry Density (g/cm^3)	p_d Tot:	2.631	2.563	2.592	2.720
	p_d1:	2.630	2.586	2.625	2.720
	p_d2:	2.629	2.520	2.594	2.720
	p_d3:	2.636	2.582	2.544	2.720
	p_d Avg:	**2.632**	**2.563**	**2.588**	**2.720**
Bulk Specific Gravity	Sp. Gr. Tot:	2.631	2.563	2.592	2.720
	Sp. Gr.1:	2.630	2.586	2.625	2.720
	Sp. Gr.2:	2.629	2.520	2.594	2.720
	Sp. Gr.3:	2.636	2.582	2.544	2.720
	Sp. Gr. Avg:	**2.632**	**2.563**	**2.588**	**2.720**
Absorption (%)	Abs. Tot:	0.929	1.631	1.479	0.123
	Abs.1:	0.965	1.552	1.055	0.112
	Abs.2:	0.938	1.612	1.387	0.134
	Abs.3:	0.867	1.729	2.185	0.128
	Abs.Avg:	**0.924**	**1.631**	**1.542**	**0.125**

Table 5A: KZF-01 Mass of samples during and after slake-durability index test

Sample:		**C1- Fine Sandstone**	**C2- Carbonaceous Shale**	**C3- Shale**	**C4- Diamictite**
Oven Dry Sample Mass (g)	Ms Tot:	496.20	524.14	534.71	577.26
Drum Mass A/B (without lid) (g)		939.84	924.47	939.73	924.35
Mass A (g)		**1436.04**	**1448.61**	**1474.44**	**1501.61**
Cycle 1 Sample Mass (g)	Ms Tot:	493.39	511.94	526.47	574.28
Drum Mass A/B (without lid) (g)		941.02	933.93	944.93	925.70
Mass B (g)		**1434.41**	**1445.87**	**1471.40**	**1499.98**
Cycle 2 Sample Mass (g)	Ms Tot:	493.22	508.74	504.33	573.36
Drum Mass A/B (without lid) (g)		941.42	935.86	963.18	925.77
Mass C (g)		**1434.64**	**1444.60**	**1467.51**	**1499.13**
Clean Drum Mass D (g)		**939.93**	**924.57**	**939.88**	**924.50**

Table 6A: Surface Samples - Porosity, dry density and water absorption of the twelve samples

Calculations		**Sandstone** (Pa 1.1)	**Dolerite** Jd 1.1	**Tillite** (C-Pd 1.1)	**Shale** (Pp 1.1)	**Shale** (Pw 1.1)	**Shale** (Pp 2.1)
Volume (cm^3) *Buoyancy method*	V1:	27.32	34.29	57.80	38.55	54.23	52.21
	V2:	33.13	46.20	53.37	60.37	47.76	45.94
	V3:	34.13	35.94	58.83	52.35	53.77	47.96
	V Tot:	94.58	116.43	170.00	151.27	155.76	146.11
Pore Volume (cm^3)	Vv Tot:	4.05	2.25	2.09	4.53	4.43	3.12
	Vv1:	1.25	0.31	0.32	0.92	1.54	0.82
	Vv2:	1.30	1.36	0.72	1.60	1.46	1.56
	Vv3:	1.50	0.58	1.05	2.01	1.43	0.74
	Vv Avg:	1.350	0.750	0.697	1.510	1.477	1.04
Porosity (%)	n Tot:	4.282	1.932	1.229	2.995	2.844	2.135
	n1:	4.575	0.904	0.554	2.387	2.840	1.571
	n2:	3.924	2.944	1.349	2.650	3.057	3.396
	n3:	4.395	1.614	1.785	3.840	2.659	1.543
	n Avg:	**4.298**	**1.821**	**1.229**	**2.959**	**2.852**	**2.170**
Dry Density (g/cm^3)	p_d Tot:	2.575	2.937	2.684	2.667	2.644	2.574
	p_d1:	2.561	2.971	2.716	2.653	2.642	2.631
	p_d2:	2.590	2.908	2.680	2.676	2.641	2.529
	p_d3:	2.571	2.944	2.655	2.666	2.647	2.556
	p_d Avg:	**2.574**	**2.941**	**2.684**	**2.665**	**2.644**	**2.572**
Bulk Specific Gravity	Sp. Gr. Tot:	2.575	2.937	2.684	2.667	2.644	2.574
	Sp. Gr.1:	2.561	2.971	2.716	2.653	2.642	2.631
	Sp. Gr.2:	2.590	2.908	2.680	2.676	2.641	2.529
	Sp. Gr.3:	2.571	2.944	2.655	2.666	2.647	2.556
	Sp. Gr. Avg:	**2.574**	**2.941**	**2.684**	**2.665**	**2.644**	**2.572**
Absorption (%)	Abs. Tot:	1.663	0.658	0.458	1.123	1.076	0.830
	Abs.1:	1.786	0.304	0.204	0.899	1.075	0.597
	Abs.2:	1.515	1.012	0.503	0.991	1.157	1.343
	Abs.3:	1.709	0.548	0.672	1.440	1.005	0.604
	Abs.Avg:	**1.670**	**0.622**	**0.460**	**1.110**	**1.079**	**0.848**

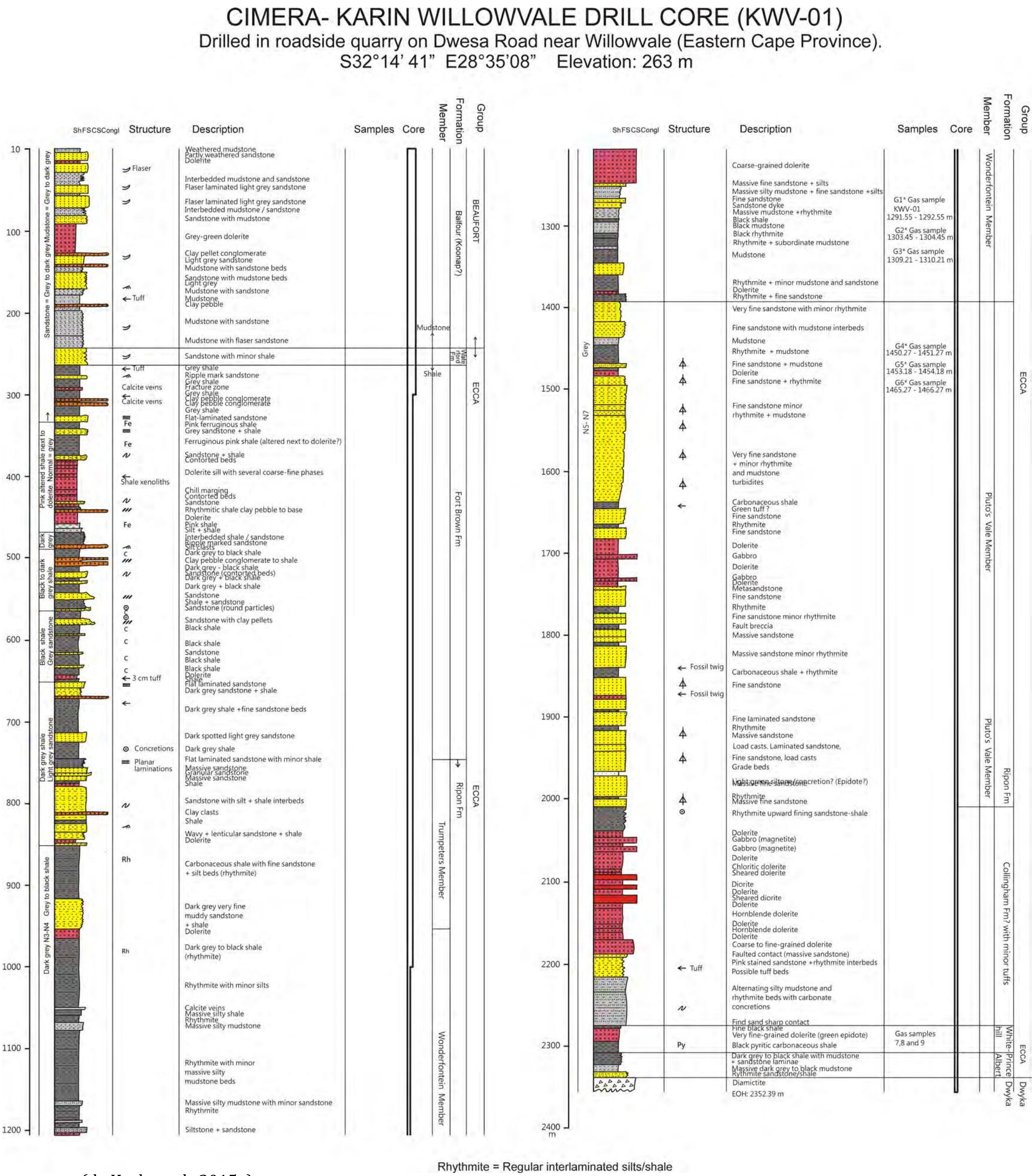
**See next page for continuous calculations*

*Calculations		Shale (Pw 2.1)	Shale (Pw 3.1)	Shale (Pp 3.1)	Tillite (C-Pd 2.1)	Dolerite (Jd 2.1)	Sandstone (Pko 1.1)
Volume (cm^3) *Buoyancy method*	V1:	52.22	44.01	41.35	45.74	45.33	52.36
	V2:	38.46	51.51	48.54	50.06	31.21	35.19
	V3:	72.55	39.52	48.26	53.43	35.71	38.27
	V Tot:	163.23	135.04	138.15	149.23	112.25	125.82
Pore Volume (cm^3)	Vv Tot:	33.12	3.05	1.51	0.95	0.36	4.73
	Vv1:	10.80	1.26	0.66	0.24	0.12	2.04
	Vv2:	7.65	1.14	0.24	0.31	0.14	1.30
	Vv3:	14.67	0.65	0.61	0.40	0.10	1.39
	Vv Avg:	11.04	1.02	0.50	0.32	0.12	1.58
Porosity (%)	n Tot:	20.290	2.259	1.093	0.637	0.321	3.759
	n1:	20.682	2.863	1.596	0.525	0.265	3.896
	n2:	19.891	2.213	0.494	0.619	0.449	3.694
	n3:	20.221	1.645	1.264	0.749	0.280	3.632
	n Avg:	**20.264**	**2.240**	**1.118**	**0.631**	**0.331**	**3.741**
Dry Density (g/cm^3)	p_d Tot:	2.024	2.641	2.648	2.696	3.018	2.565
	p_d1:	2.004	2.618	2.634	2.701	3.008	2.559
	p_d2:	2.011	2.652	2.657	2.695	3.024	2.567
	p_d3:	2.044	2.653	2.651	2.694	3.026	2.571
	p_d Avg:	**2.020**	**2.641**	**2.647**	**2.696**	**3.020**	**2.566**
Bulk Specific Gravity	Sp. Gr. Tot:	2.024	2.641	2.648	2.696	3.018	2.565
	Sp. Gr.1:	2.004	2.618	2.634	2.701	3.008	2.559
	Sp. Gr.2:	2.011	2.652	2.657	2.695	3.024	2.567
	Sp. Gr.3:	2.044	2.653	2.651	2.694	3.026	2.571
	Sp. Gr. Avg:	**2.020**	**2.641**	**2.647**	**2.696**	**3.020**	**2.566**
Absorption (%)	Abs. Tot:	10.027	0.855	0.413	0.236	0.106	1.466
	Abs.1:	10.320	1.094	0.606	0.194	0.088	1.523
	Abs.2:	9.893	0.835	0.186	0.230	0.148	1.439
	Abs.3:	9.891	0.620	0.477	0.278	0.093	1.412
	Abs.Avg:	**10.035**	**0.849**	**0.423**	**0.234**	**0.110**	**1.458**

Table 7A: Surface Samples - Mass of samples during and after slake-durability index test

Sample:		Sandstone (Pa 1.1)	Dolerite (Jd 1.1)	Tillite (C-Pd 1.1)	Shale (Pp 1.1)	Shale (Pw 1.1)	Shale (Pp 2.1)
Oven Dry Sample Mass (g)	Ms. Tot:	501.11	529.42	510.45	500.47	529.88	555.48
Drum Mass A/B (without lid) (g)		940.37	925.00	940.32	924.94	940.24	924.86
Mass A (g)		**1441.48**	**1454.41**	**1450.77**	**1425.41**	**1470.12**	**1480.34**
Cycle 1 Sample Mass (g)	Ms. Tot:	498.69	526.19	508.49	498.29	527.77	552.06
Drum Mass A/B (without lid) (g)		940.35	925.01	940.56	925.01	940.25	926.16
Mass B (g)		**1439.03**	**1451.20**	**1449.05**	**1423.30**	**1468.02**	**1478.22**
Cycle 2 Sample Mass (g)	Ms. Tot:	498.37	524.91	507.58	496.83	522.28	549.05
Drum Mass A/B (without lid) (g)		940.35	925.18	940.52	925.17	943.61	927.61
Mass C (g)		**1438.72**	**1450.09**	**1448.10**	**1422.00**	**1465.89**	**1476.66**
Clean Drum Mass D (g)		**940.35**	**924.96**	**940.27**	**924.92**	**940.11**	**924.85**
Sample:		**Shale** (Pw 2.1)	**Shale** (Pw 3.1)	**Shale** (Pp 3.1)	**Tillite** (C-Pd 2.1)	**Dolerite** (Jd 2.1)	**Sandstone** (Pko 1.1)
Oven Dry Sample Mass (g)	Ms. Tot:	526.85	501.33	511.10	530.36	526.41	561.00
Drum Mass A/B (without lid) (g)		940.21	924.93	940.41	924.89	924.82	940.10
Mass A (g)		**1467.05**	**1426.26**	**1451.52**	**1455.25**	**1451.23**	**1501.10**
Cycle 1 Sample Mass (g)	Ms. Tot:	522.29	500.15	509.02	528.78	525.10	558.22
Drum Mass A/B (without lid) (g)		940.58	924.94	940.44	924.92	924.96	940.67
Mass B (g)		**1462.87**	**1425.09**	**1449.46**	**1453.70**	**1450.06**	**1498.89**
Cycle 2 Sample Mass (g)	Ms. Tot:	519.32	499.30	508.00	527.96	524.35	556.92
Drum Mass A/B (without lid) (g)		940.48	925.04	940.44	924.88	924.96	940.65
Mass C (g)		**1459.79**	**1424.34**	**1448.44**	**1452.84**	**1449.31**	**1497.56**
Clean Drum Mass D (g)		**940.14**	**924.87**	**940.12**	**924.85**	**924.80**	**940.07**

Appendix B

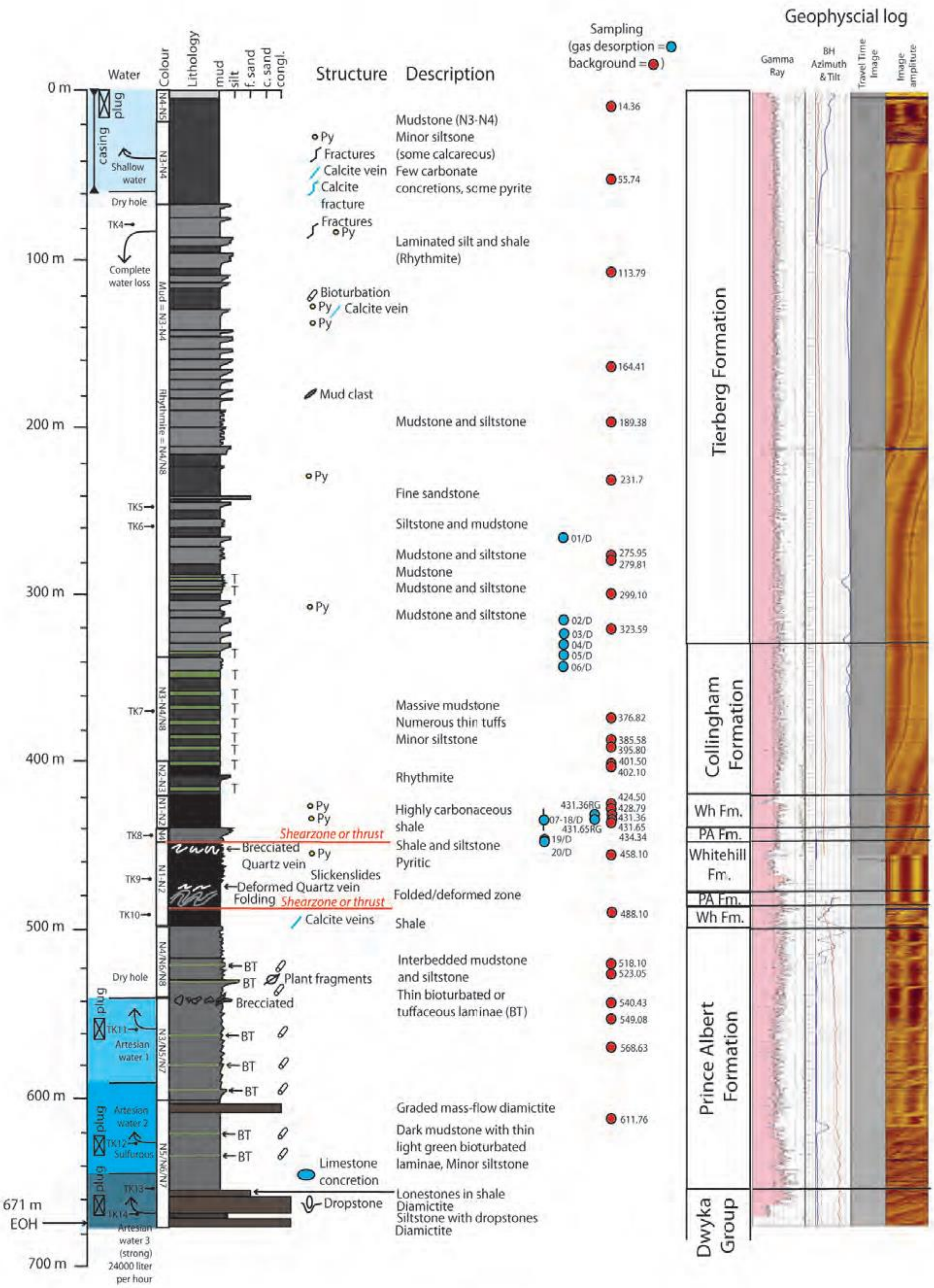


(de Kock, et al., 2015a)

KARIN–TheKarooResearchInitiative **Borehole KZF-01**

Zandfontein, Witzenberg (Ceres) District

S32°50'30.43"/E019°44'33.02"



(de Kock, et al., 2015b)