Consideration of the Criteria Required for the Selection of Potential Underground Coal Gasification Sites in South Africa

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Declaration

I, Buyisiwe Carol Dzimba, hereby declare that the research report with the title:

“Consideration of criteria required for the selection of potential underground coal gasification sites in South Africa”

is my own work and has not been submitted at any other university.

Signed at Johannesburg on the day of …..…………….……….April 2011

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B.C Dzimba

Abstract

Underground coal gasification (UCG) is believed to be one of the cleaner coal exploiting technologies for energy generation. In this study UCG is assessed as a technology for unlocking coal seams that are too deeply buried underground for extraction and those which are enclosed by complex geological settings making it impossible to extract using conventional mining methods. The assessment of the UCG technique was based on a desktop study from previous UCG trials globally. The objective of this study was mainly focused on considering factors which could be useful in the selection of potential UCG sites in South Africa. It was noted that the coal geology, coal properties, geological and geotechnical condition are crucial parameters to consider when selecting a UCG site. Three boreholes from the Highveld coalfield were used for the subsurface evaluation by means of geophysical wireline logging. Five coal samples from these borehole cores were studied using different characterisation techniques to understand the nature of coal and determine the coal properties suitable for UCG. The information acquired by wireline logging gave an insight into the geological and geotechnical condition of the area, and the properties of coal determined show some degree of suitability for UCG process in terms of their physical and chemical composition.

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Symbol	Description	Units
Å	Angstrom	10^{-10} m
DENB	Bed resolution (15cm) Density tool	gmcc
DEPO	Porosity from density log	%
GRDE	Gamma-ray from density tool	api
RoVmr	Mean random reflectance	%
SHER	Shear wave transit time	us/m
SPOR	Porosity from sonic log	%
VAMP	Vertical amplitude	cps
VL6F	60 cm velocity (R1 –R4)	m/s
δ	Standard deviation	-

Nomenclature

Abbreviation	Description
AMPM	Amplitude image (hardness)
API	American Petroleum Institute
BET	Brunauer-Emmett-Teller
BH1	Borehole 1
BH2	Borehole 2
BH3	Borehole 3
C	Coal layer
CCT	Clean coal technology
CCS	Carbon capture and storage
CSH	Carbonaceous shale
DEPO	Density porosity
DO	Dolerite
GTL	Gas to liquid
GRW	Greywacke
ISO	International standard
SLT	Siltstone
SST	Sandstone
SPO	Sonic porosity
UCG	Underground coal gasification
UCS	Uniaxial compressive strength
XRD	X-ray diffraction

Chapter 1

General Introduction

1.1 Study Background

Fossil fuels such as petroleum, natural gas and coal have been used as a major source of energy in the world for past years and will continue to play important role in the supply of energy for the next decades (Juntgen, 1987; Li and Fan, 2008). Coal, as the most abundant fossil fuel, dominates the world's energy sector. Coal is a natural combustible carbonaceous sedimentary rock. Due to its combustible nature and relative abundance coal is used as a primary source of energy in many parts of the world.

Compared to other fossil fuels coal offers superior economic efficiency mostly in developing countries such as India, China and South Africa since it is the least expensive source of energy. According to the study done by Powell and Morreale (2008) there will be an increase in the world reliance on coal as a source of energy for the next decades due to the global economic growth resulting in an increase of the world energy requirements.

In South Africa coal is the most abundant fossil fuel resource which plays an important role in the country's energy sector. Coal supplies about 74.1% of the country's total commercial energy requirements, with most of the coal used specifically for the production of electricity and petrochemical products (Engelbrech *et al,* 2008; van Dyk *et a*l, 2006). South Africa and other countries will for many years to come rely on their abundant coal resources for energy and the production of chemicals until alternative (renewable) energy sources are fully developed (Li and Fan, 2008; van Dyk *et al*, 2006). However coal faces significant environmental challenges, associated with both its mining and conversion to energy.

1.1.1 Coal Conversion and Impacts

Coal conversion is the process of converting coal from its solid form into other forms of energy (Steynberg and Nel, 2004). Combustion and gasification are the major coal conversion processes used in South Africa and elsewhere in the world. Combustion is the generation of thermal energy through oxidation of solid coal while gasification is the conversion of solid coal into combustible gases through a series of oxidation-reduction reactions. Coal is naturally made-up of organic and inorganic material, and is regarded as the dirtiest form of fossil fuels (Li and Fan, 2008). During coal utilisation, via conversion processes, waste material and toxic (greenhouse) gases are released into the environment and atmosphere (Powell and Morreale, 2008). Coal combustion releases large quantities of environmentally hazardous pollutants. Gasification is a slightly cleaner process. The concern regarding coal usage worldwide based on the emission of greenhouse gases and other pollutants resulting from these coal conversion processes.

1.1.2 Clean Coal Technology

The growing demand for energy together with the depletion of better quality coal seams led the world to consider environmentally friendly methods for coal extraction and exploitation, referred to as clean coal technology (CCT). CCT's are used to effectively remove the pollutants generated during coal conversion prior its utilisation. Coal gasification is by far the most effective method of converting coal into usable energy forms with multipollutant emission control technologies as compared to combustion (Li and Fan, 2008; Powell and Morreale, 2008).

According to King (1981) there are number of advanced gasification processes which are under development worldwide with the aim of increasing conversion efficiency and improving the reduction of pollutants. Underground coal gasification (UCG) is one of the selected conversion techniques presently being researched worldwide. UCG is amongst the oldest method in gasification process and CCT's but has not reached the stage of large scale commercialisation. The UCG technique enables access to coal seams which are too deeply buried or uneconomic to be exploited by conventional mining methods (Shackley *et al*, 2006).

This technique converts coal into combustible gases underground with minimal emission of greenhouse gases and other air pollutants, but if is not carefully monitored it can be problematic in terms of hydrology and the environment (Sateesh *et al.,*2010).

1.2 Motivation

For the past decades South Africa has been utilising its low-cost coal resource to meet the country's energy requirements. South Africa's dependency on coal as a source of energy is projected to increase as the energy demand increases due to population and economic growth. Though South Africa contains a vast amount of coal resources, it has a limited amount of exploitable coal reserves due to limited accessible coal deposits. In order to secure a long term energy supply for the country, it is necessary to develop alternative techniques which are capable of extracting energy present in those coal resources which are considered to be unminable by means of conventional mining methods.

UCG is regarded as one of the technologies that are capable of exploiting unminable coal resources effectively. UCG converts solid coal into combustible gases underground without actually mining the coal. During the past years, UCG has been studied extensively in many parts of the world and has been viewed as a viable option for utilising unminable coal seams economically.

In South Africa, interest on UCG was shown by Eskom (the South African electricity giant). As a result a single pilot scale trial is currently under investigation in the Majuba coal deposit. This leaves room for further research and development of this technique in the country. The current investigation is based on determining factors which can be used as selection criteria for potential UCG sites in South Africa. This investigation also includes the evaluation of the feasibility of wireline logging as a site evaluation technique. It is anticipated that the outcomes of this study will add to the research and development of UCG technology in South Africa.

1.3 Research Questions

According to Blinderman *et al* (2008) and Ufton and Thomson (2006) the understanding of the geology and geotechnical properties of the coal seam and its associate rocks is important for UCG site evaluation. Hence the following research questions are proposed:

- Can a literature study of past global UCG exploration and operations be useful in developing coalfield parameters that can be used as selection criteria for potential UCG sites in South African coalfields?
- Would the use of geophysical wireline logging techniques in UCG exploration produce sufficient information for site evaluation?
- What are the specific coal properties that would be suitable for a successful UCG process?

1.4 Aim and Objectives of the study

Aim

The main aim of the study is to address the selection criteria for potential UCG sites in South Africa, with a specific focus on geological and geotechnical aspects.

Objectives:

1. Undertake a detailed literature review in order to understand worldwide successes and non-successes of previous UCG projects.
2. Assess the application of borehole geophysical (wireline) logging technique in enhancing the understanding of the geology of a potential UCG sites and predicting its suitability as a UCG site consideration tool.
3. Undertake coal characterisation analysis for the assessment of coal properties suitable for UCG process.
4. Combine information from 1, 2 and 3 to work towards determining the required rock and coal properties for an ideal UCG potential site.

1.5 Project Scope

Essentially the project is composed of three phases which will later be pulled together in determining the requirements for a potential UCG sites. Each phase has its own aims and sub objectives. The division is as follows:

- **Phase One / Chapter Two:** Aim to determine the selection criteria for potential UCG sites. This aim will be achieved by undertaking a detailed literature review to understand the worldwide success and non-success of UCG research projects. A table incorporating general characteristics required for selection of potential UCG sites will be created.

- **Phase Two / Chapter Three:** Includes the application of downhole geophysical (wireline) logging techniques in the evaluation of potential UCG sites. This phase aim to determine the feasibility of downhole geophysical (wireline) logging to acquire the required properties or characteristics for potential UCG sites. Geophysical data obtained by different wireline logging tools will be evaluated for its potential to acquire the required site properties.

- **Phase Three / Chapter Four:** The overall aim of this phase is to determine the required coal characteristics for UCG processes. Different analytical techniques will be used to serve this purpose. Analytical techniques involved in coal characterisation include thermogravimetric analysis (TGA), BET, X-ray diffraction (XRD) and petrography.

The summary and conclusions of this study as well as the future research recommendations will be outlined in Chapter five.

Chapter 2

Underground Coal Gasification: UCG

In this chapter the development and trials pertaining to UCG are discussed, with a specific focus on the selection criteria for potential UCG sites. Information was gathered by literature review, internet searches and through attendance of conferences, workshops and discussions with specialists in the various relevant disciplines. The information obtained from previous UCG operations/research are used to understand the successes and non-successes of those investigations. The primary aim of this chapter is to enhance the understanding of UCG technique and determining factors that could be used to characterise potential UCG sites in South Africa.

2.1 Introduction

Recently there has been renewed interest in UCG around the world due to the growing concerns over inadequate energy sources and reduction of carbon footprints (Kostur and Blistanova, 2009; Thompson, 1978). The growing interest in UCG is based on the fact that UCG has a potential to increase the world's coal reserves as UCG can successfully exploit coal resources which are either uneconomic to work by conventional mining process or not accessible due to depth and complex geology (Aghalayam, 2009). UCG technology is currently under investigation in South Africa and else where in the world.

UCG is regarded as one of the cleaner and cheaper methods of converting energy present in solid coal into other forms of energy (Shu-qin *et al*, 2009). The syngas produced by UCG processes is cleaned using the same cleaning process used in conventional gasification methods, and can be used to produce electric power or as a chemicals/liquid fuels feedstock. With the addition of carbon capture and storage (CCS), UCG is expected to be a zero emission method for coal exploitation in the near future (Shu-qin *et al*, 2009).

2.2 Principles of UCG

The UCG process involves drilling a series of adjacent boreholes into the coal seam *in situ* and then linking the boreholes within the seam using specialised techniques such as fracturing or directional drilling. Thereafter injection of highly pressured oxidants (air/ steam or oxygen) into the coal seam through the injection wells and the collection of product gas through the production wells to the surface occur (Kavalvo and Chapman, 2007). On the Earth's surface the product gas (synthetic natural gas) is cleaned and then distributed via pipes to its final destination for various applications. The basic process of UCG is shown in Figure 1.

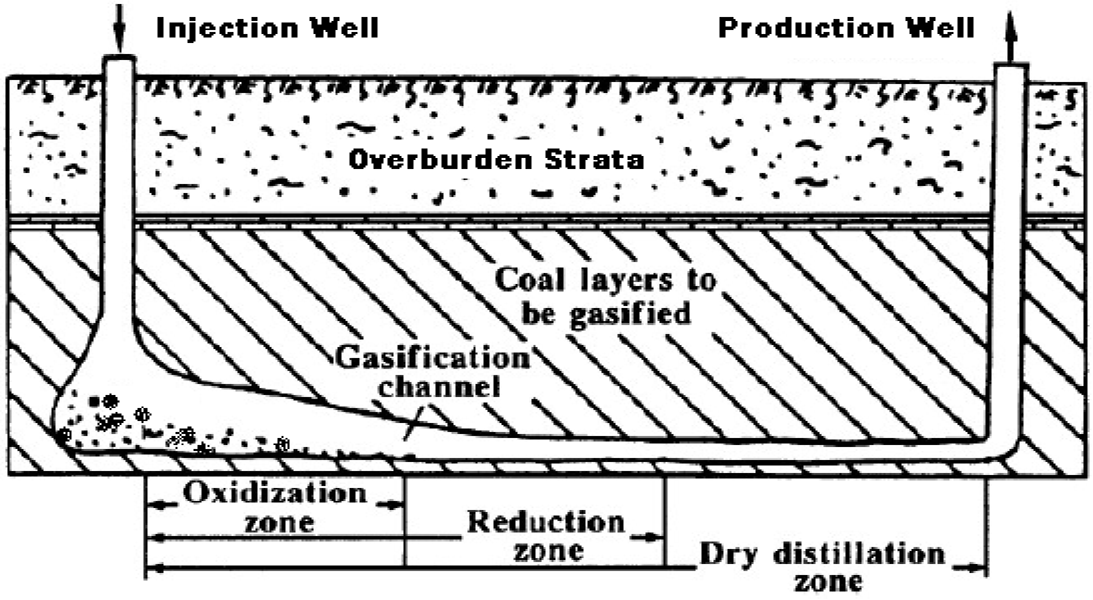

Figure 1: The basic process of UCG. Modified from (Yang *et al.*, 2003)

The production of the product gas is due to the occurrence of various reactions between the gases and solid coal. The reaction that occurs between the solid coal and injected gases underground includes the following:

$C + O_2 \longrightarrow CO_2$ (+ heat)

$C + CO_2$ (+ heat) $\longrightarrow 2CO$

$C + H_2O$ (+ heat) $\longrightarrow H_2 + CO$

$C + 2H_2 \longrightarrow CH_4$ (+ heat)

Generally the UCG product gas is primarily composed of H_2, CO_2, CO, CH_4 and steam (Khadse *et al*, 2007; Yang *et al.*, 2003).

2.3 UCG History

The idea of gasifying coal underground was brought out by the Siemens brothers in the late 1800's. This idea came as a suggestion to exploiting coal waste left after underground mining was completed (Hurley 2008; Kostur and Blistanova, 2009). Twenty years later a Russian chemist, Dmitry Mendeleev, developed a detailed design and operational concept for UCG (Burton et al., 2009; Kostur and Blistanova, 2009; Hurley, 2008). The first underground gasification patent was awarded to Betts in Britain in 1901 (Hurley, 2008).

The first practical implementation of the UCG concept was initiated and planed by William Ramsay in the UK in 1912; however the experiment was not conducted due to the onset of the First World War and the unfortunate death of Ramsey (Burton *et al.*, 2009; Hurley, 2008). In May 1913 the Russian evolutionary, Vladimir Lenin, while in exile, published the first article on UCG based on Ramsay's work, declaring huge potential benefits of UCG to the Mine Society because it could eliminate hard mining labour (Burton et al., 2009). The article laid a good foundation for UCG development in the world (Burton *et al.*, 2009; Hurley, 2008; Bond, 2007; Walker, 2007).

The first UCG experiment was finally conducted in 1920 in the United Kingdom (UK) followed by trials in 1928 which lasted for approximately fifty years and resulted in the operational development of the UCG technique (Hurley, 2008; Bond, 2007). Further work on UCG was carried out in the United State (USA) during their energy crisis in 1970. A great deal of money was invested in developing the UCG technique for power generation and as a result more than thirty pilot tests were conducted (Hurley, 2008). USA progress was cut down by the decreasing natural gas price in 1990, and thereafter UCG work was not resumed due to the lack of experienced personnel.

The USSR interest in UCG was based on the same interest that Ramsay and Lenin had on UCG, and the first UCG experiments were conducted in 1933. Most of the UCG research and development work was done by the USSR (Shafirovich and Varma, 2009). The major UCG experience of USSR in different locations is presented in Table 1.

Table 1: Summary of the Major USSR UCG Trials (Couch, 2009)

Location	Year	Coal type	Ash (%)	Seam thickness (m)	Seam depth	Seam dip
Lisichansk (Ukraine)	1934 - 63	Bituminous	6 - 16	0.4 - 1.5	400	Steeply dipping
Gorlovka (Ukraine)	1937 -39	-	-	1.9	40	Steeply dipping
Podmoskova (Russia)	1940 - 62	Lignite	27 - 60	2 - 4	40 - 60	Horizontal
Yuzhno-abinsk (Siberia)	1955 - 89	Bituminous	4 - 10	2 - 9	-	Steeply dipping
Angren (Uzbekistan)	1962 - 89	Lignite	11	4 - 24	110 - 250	5 -15˚

In Europe the interest on UCG grew due to the shortage of energy during 1944 – 59. As a result several UCG tests were conducted. These include the trials in Italy, France and Poland. The interest on UCG ceased because of the availability of oil at lower price during the early 1960's. The work was resumed again around the 1980's, this time lead by the European Commission. Research and development trials were carried out in different places that include Belgium, France, Spain and UK. The main target coal resources were those of high rank coals which are deeply buried underground, because much work was already done using low rank permeable seams (Couch, 2009). Table 2 show the summary of UCG past experience in Europe.

Table 2: Summary of the past experience with UCG in the Europe (Couch, 2009)

Location	Year	Coal type	Seam thickness (m)	Seam depth (m)	Oxidant
Bois-la-Dame (Belgium)	1948	Anthracite	1	400	air
Newman Spinney (UK)	1949 – 59	Sub-bituminous	1	75	air
Bruary-en-Artois (France)	1981	Anthracite	1.2	1200	air
Thulin (Belgium)	1982 – 84	Semi-anthracite	6	860	air
Haute-Deule (France)	1985-86	Anthracite	2	880	air
Thulin (Belgium)	1986-87	Semi-anthracite	6	860	air

In Australia UCG received attention during the early 1980's. This interest was due to the increase of oil price in the 1970's. The Chinchilla UCG project in Australia has been the largest and most successful UCG pilot test in the Western world to date. However the Chinchilla UCG plant did not run for a long period due to the lack of finances to commercialise the project (Burton *et al*., 2009; Walker, 2007).

The remarkable successes of the Chinchilla UCG trial lead to the development of new UCG trials in developing countries such as China and South Africa. In China, the first UCG trials were conducted in the late 1980s, about sixteen trials were carried out (Burton *et al*., 2009; Walker, 2007). The main target for UCG trials in China was in abandoned coal mines.

Eskom was the first to initiate the investigation of UCG in South Africa. Eskom's interest on UCG became visible in 2001 when the first UCG trial was initiated. The practical operation of that trial occurred in January 2007 in the Majuba coal deposit which was complex to mine using conventional mining methods (Friedmann, 2009; Couch, 2009). Eskom uses the Canadian Technology for their trial known as ɛUCG technology. During the same period Sasol also decided to start with the second UCG trial in South Africa that was set for 2009. Sasol's interest on UCG was based on the use of synthetic gas produce by UCG to the GTL process. Unfortunately the trial was withdrawn for reasons mostly likely related to the economic downturn (Kostur and Blistanova, 2009; Walker, 2007). Table 3 show the some of the world successful UCG trials.

Table 3: Summary of successful UCG field trials with coal type, thickness and depth (Khadse *et al*., 2007; Couch, 2009)

Location	Coal Type	Thickness (m)	Depth (m)	Year	Gas Produced ($m^3 \times 10^6$)	Comment
Lisichanakaya	Bituminous	0.44 - 2	60 - 250	1948 - 1965	220	Discontinued due to thin seam
Yuzhno-Abinskaya	Bituminous	2.2 - 9	50 - 300	199 - current	290	Used for heating
Angrensikaya	Lignite	2 - 22	120 - 250	1957 - current	860	Used for power generation
Podmoskovnaya	Lignite	2.5	30 - 80	1946 - 1953	-	Coal exhausted in 1953
Shatskaya	Lignite	2.6 - 4	30 - 60	1963 - 1965	-	Abandoned due to technical problems
Sinelnikovsky	Lignite	3.6 - 6	80	-	0	-
Chinchilla (Australia)	-	8 - 10	130	1999 - 2004	155000 Nm/h	UCG - IGCC and multiple wells (8)
Tremedal (Spain)	Sub-bituminous, lignite	2 -5	530 - 580	1989 - 1998	-	-
France	Anthracite	-	1200	1981 - 1986	-	Well link by combustion and hydrofracture were unsuccessful
Belgium	Anthracite	-	860	1979 - 1987	-	Difficulties in completing gasifying circuit
Newman Spinney(UK)	Sub-bituminous	0.75	75	1959	-	Four boreholes of 140 m and diameter 0.3m
USA (Hanna 2)	Sub-bituminous	6.8	90 - 120	1973 - 1974	4800 - 10 200 Kmol/day	The best instrumented UCG test
USA (Hoe Creek)	Sub-bituminous	7.6	38	1976 - 1979	0	Explosive charges were used to create linkage path
Majuba (South Africa)	Bituminous	1.8 – 4.5	250 - 380	2007 - current	3 - 5000m^3/h	Trial successful with no signs of environmental problems

2.4 UCG Environmental Concerns

Many of the world’s current environmental problems are associated with utilisation of fossil fuel mostly coal. UCG is considered an environmentally friendly method for coal exploitation as compared to conventional mining process (Khadse *et al.,* 2007). UCG presents several environmental advantages over conventional coal mining since it does not require the following:

- Coal mining
- Coal transportation and storage
- Surface conversion
- Ash disposal

The effects of UCG the process on the environment are minimal and less severe than those of conventional mining. However UCG could also have significant environmental consequence if not properly implemented. The well known environmental concerns associated with the UCG process include groundwater contamination of aquifers close to the UCG operation, and surface subsidence (Humenick and Mattox, 1977). Unlike conventional mining processes the environmental problems posed by UCG can be managed through utilisation of proper site selection (Friedmann *et al.*, 2009).

2.5 UCG Site Selection

The determination of selection criteria for a potential UCG sites is one of the most challenging factors for UCG technology in different locations of the world. UCG requires special understanding of various aspects of the site under consideration. Coal deposits of different regions around the world differ remarkably in their geological setting and other natural coal properties. Hence UCG sites are likely to be unique from place to place. According to Bialecka (2008), ‘’natural factors play a decisive role among the criteria of seam selection for a successful UCG process’’. These factors include coal seam geology, physical and chemical properties of coal, nature of the surrounding rocks and geo-hydrological condition of area under consideration.

2.5.1 Coal Seam Geology

Coal deposits and their geological settings vary from seam to seam and coalfield to coalfield globally. Coal seam properties and their geological setting which determines the potential for UCG operation are important. Coal properties for UCG can be deduced from the following: coal seam depth, seam thickness, seam inclination and Coal rank and other properties (quality).

2.5.1.1 Coal Seam Depth

Coal seam(s) occurs in various depths in the world, with some being shallow while others lying deep within the earth. Coal seam depth is one of the important parameter in UCG. Coal seams at shallow depth (depth of up to 300m) are generally easy to ignite (Bialecka, 2008), and in most cases are associated with aquifer. Coal seam suitable for a successful UCG process must be in a vertical separation of more than 100m from the major aquifer (Khadse *et al*., 2007). Hence it is more preferable to conduct UCG process at greater depth than at shallow depth to avoid problems like groundwater pollution and land subsidence.

2.5.1.2 Coal Seam Thickness

Many authors in literature have suggested different coal seam thicknesses suitable for UCG process, according Bialecka (2008) seam thickness of more than 1m is preferred while Khadse (2007) records seam thickness used in the United Kingdom to be greater than 2 m. εUCG technology (Ergo exergy, 2009) prefers seam thickness of between 0.5 and 30m. Thinner coal seams (anything less than 0.5m) in UCG are problematic in the fact that there is possibility for heat loss to the surrounding formation. Hence moderate seam thickness (more than 1m) is required and preferred for UCG process, though UCG has potential to utilise thin coal seams.

2.5.1.3 Coal Seam Inclination (Dip)

Coal seam inclination is one of the criterions considered in the selection of potential UCG site but have less influence on the process. According to Bialecka (2008) and Ghose and Paul (2007), dipping (greater than 70 degrees) coal seams are easy to sustain and ignites very easy compared to horizontal seams. In general dipping coal seams are associated with complex geology which makes them more suitable targets for UCG technology.

2.5.2 Coal Rank and Properties

Based on the literature analysis coal rank and properties are important and have a large influence on the gasification of coal underground. The rank and physicochemical properties of coal are discussed below.

2.5.2.1 Coal Rank

Almost any coal rank type can be extracted and exploited and by means of UCG process. The literature emphases that low rank (lignite and sub-bituminous) and non swelling coals are mostly preferred for UCG process (Bialecka, 2008; Ghose and Paul, 2007). Low rank coals shrink upon heating making the connection between the injections well and production well even greater. Coal rank also affects coal permeability and its reactivity. Naturally low rank coals are more permeable compared to high rank coals (Shafirovich *et al*., 2008).

2.5.2.2 Coal Seam Properties (Quality)

The physicochemical properties of coal seams also play an important role in UCG. Coal properties which have the most effect on UCG process are discussed in section 2.5.2.2 (a) this include permeability and porosity. Chemical properties are discussed in section 2.5.2.2 (b)

2.5.2.2 (a) Permeability and Porosity

The structural nature of coal can also affect the gasification behaviour of coal. Successful UCG processes depend on the porosity and permeability of the coal seam. Coal porosity is natural pores formed during coal formation. Permeability is the ability of pores or cracks present in coal to transport fluids. In general high rank coals and those deeper have low permeability. Permeability is important in UCG; better cleated and more permeable coal seams have ability to transport gases during gasification process (Ghose and Paul, 2007). Permeable coal seams are preferred for UCG process (Shafirovich and Varma, 2009). Low rank coal are characterised by having porous and permeable structure.

2.5.2.2 (b) Chemical Properties

The chemical composition of coal influences the gasification reaction. Literature analysis confirms that volatile matter, moisture and ash content have the primary effect on gasification reaction (Bialecka, 2008; Couch, 2009; Khadse *et al*., 2007; Juntgen, 1987).

2.5.3 Geological and Hydrological Condition

2.5.3.1 Geology and Geotechnical Condition

The coal layers (seams) underground are enclosed by rock material which are generally referred to as overburden (strata lying above the seam) and underburden (strata below the seam). The geological and geotechnical condition of overburden and underburden strata as well as the coal seams will have a direct influence on the UCG process. Hence high strength yield impermeable strata with low porosity and stable geological structures are the most favourable to be overlying and underlying a coal deposit suitable for UCG processes because they provide a seal between the coal seam(s) and the surrounding rocks which in turn limit the amount of subsidence (Shafirovich *et al*., 2008).

2.5.3.2 Hydrological Condition

The hydrology of a potential UCG prospecting site is very important. Water is needed for the UCG process because it plays an important part in the gasification reaction. Water ingress in the reaction chamber is limited to the need of gasification reaction. If the inflow is too high it reduces the gasification efficiency or can even stop the gasification process altogether. However, if there is a presence of a fresh water aquifer a few meters above the target coal seam in the prospect site, that particular site must be abandoned in order to avoid groundwater pollution. Coal layers to be gasified need to be in a vertical separation of about 100m from the major aquifers. The hydrology is an important criterion for the screening of potential UCG site (Khadse *et al*., 2006; Shafirovich *et al*., 2008).

2.6 Exploration Requirements for UCG

Exploration is essential for UCG; it is a principal stage of site selection. Exploration is conducted to reveal the nature of the coal deposit, geology and geohydrological condition of the area under consideration. The data obtained from exploration can be used to make a decision on whether that particular site is suitable for UCG process or not. Different exploration techniques are used to evaluate the subsurface condition of the target area for UCG. These may include geophysical wireline logging, where a borehole is drilled and wireline probes are sent through the borehole into the underground to determine the physical properties of the subsurface formation. Such properties may include the lithological boundaries, rock type and rock strength. The cost of exploration in UCG is determined by the quality and quantity of data as well as the complexity of the geology.

2.7 South African Coal Reserves and Resources

South Africa has over 70% of Africa's coal resources (Snyman and Botha, 1993; Wagner and Hlathwayo, 2005). Coal resources in South Africa are divided into nineteen coalfields only nine of which are currently productive (Wagner and Hlathwayo, 2005). According to Jeffrey (2005) and Schmidt (undated) the Waterburg, Witbank and Highveld coalfields contain about 70% of the country's coal reserves. South Africa consists of about 121 billion tons of in situ coal resources of which only 55 billion tons are considered to be economically minable reserves (Snyman and Botha, 1993). Figure 2 shows the difference between coal resources, reserves and proven coal reserves.

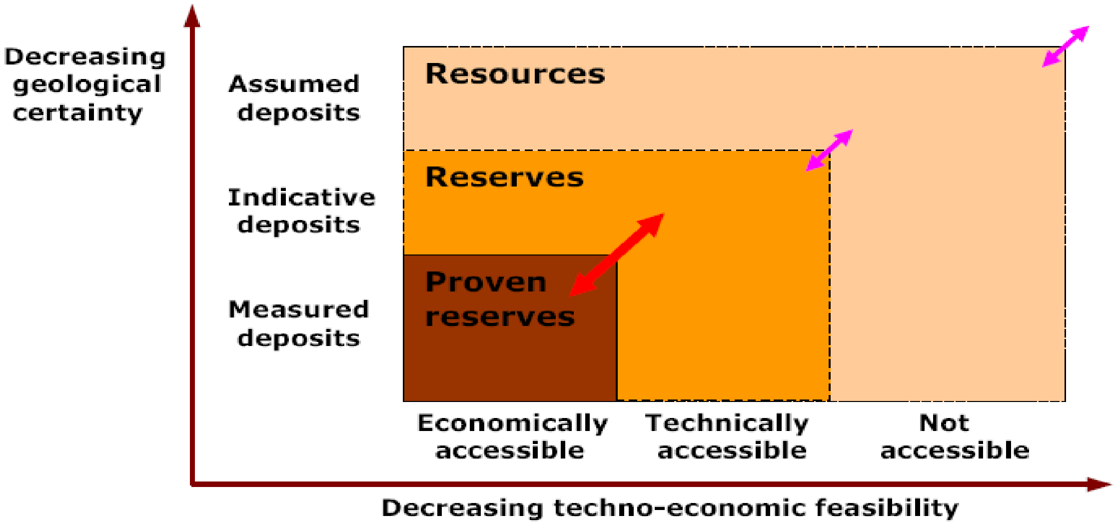

Figure 2: Estimation of resources, reserves and proven reserves (Kavalov and Peteves, 2007)

UCG can increase the amount of recoverable reserves. If employed instead of the normal conventional mining, UCG has potential to exploit coal resources that are considered uneconomic due to geological and mining constrains. Table 4a shows the South African coal reserves and the annual production of coal.

Table 4a: South African Coal Reserves and Production (CMM Global Overview, 2009)

Indicator	**Anthracite& Bituminous (Million Tonnes)**	**Sub-bituminous & Lignite (Million Tonnes)**	**Total (Million Tonnes)**	**Global Rank (%)**
Estimated Proved Coal Reserves (2005)	4875	0	4875	6(5.6%)
Annual Coal Production (2005)	245	0	245	6(4.46%)

Coal in South Africa is generically similar to that of Permian Gondwana coals (Australia, India) but different from the Carboniferous coals of the northern hemisphere (Falcon and Ham, 1988). The coals are assigned to the Early Permian Vryheid Formation, which forms part of the Ecca Group that belongs to the Karoo Supergroup. The strata primarily consist of sandstone, carbonaceous siltstone, shale, minor conglomerate and several coal seams (Cairncross, 2001; Snyman and Botha, 1993).

2.7.1 Properties of South African Coalfields

The nature and quality of South African coals is that of low grade high inertinite content as compared to their counterpart coals of northern hemisphere which are vitrinite rich (Falcon and Ham, 1988). South African coals are predominately bituminous and generally composed of high proportions of inert and semi-reactive inertinite maceral group. The depths of these Permian seams are relatively shallow, with most of the coal seams lying less than 200m below earth surface. The coal seams properties of South African coals from different coal fields are presented in Table 4b. The main focus of using UCG is based on utilising the country's coal resources which are enclosed by complex geology making it difficult to be extracted by conventional method.

Table 4b: Properties of coal seams of South African coalfields (Zieleniewski, 2008)

Coalfield	Seam	Depth (m)	Thickness (m)	Ash (%)
Highveld	No 2	30 - 240	4.75 -10	22 -29
	No 3	170 - 185	0.5 - 1	22 - 25
	No 4	15 - 300	1.2 - 4.5	18 - 42
Witbank West	Seam 2	95 - 105	5 - 7	20 - 25
Utrecht	Dundas	260 -265	0.7 - 2.6	
	Gus	250 - 260	1 - 3.3	
	Alfred (Moss)	225 - 230	1.9 - 3.8	15 - 22
	Cokina	275 - 285	0.3 - 1.5	
Klip River	No 3	94 - 105	Up to 1.3	23 - 25
Limpopo	Main	245 - 255	10 - 11	20 - 27
Waterberg	No 1	300 - 305	0.7 - 1	20 - 24
	No 2	290 - 295	3.5 - 4	
	No 3	280 - 292	8 - 9	
	No 4	265 - 270	0.7 - 0.8	

2.8 Feasibility of UCG in South Africa

South Africa, as well as other countries in the world, has developed interest on UCG technology in order to utilise its vast reserves of unminable coal. As mentioned in Section 2.3, UCG interest in South Africa was first taken-up by Eskom in 2001. This interest was based on utilising the unminable coal of Majuba which is found to be within complex geology (Blistanova and Kostur, 2009). The Majuba coal deposit is typically bituminous coal with thickness range of 1.8 to 4.5 m and lies at depth of between 250 and 380 m deep (Couch, 2009). After the feasibility study which was conducted in 2003 and site characterisation studies in 2005, it was concluded that Majuba was suitable for UCG process. A UCG pilot plant (trial) in Majuba started in January 2007 using the Canadian technology known as έUCG and is still operating currently. The plant has resulted in the production of 3 - 5000m^3/h of syngas which in turn used to produce 100kWh electricity (Couch, 2009). Sasol had also decided on investigation UCG for their GTL process in Secunda. The trial was set to be conducted in 2009; unfortunately the work was on hold for unknown reasons. The current study is being conducted to develop further understanding of UCG site selection based on the previous non successful and successful UCG trials.

2.8.1 Comparisons of South African Coals Properties with UCG Trial Coals

Unsuccessful UCG trials were documented in European Union where a number of tests were conducted at greater depth (600 to 1200m). An example of unsuccessful UCG trial is that of Bruay in France that was conducted in 1980-1981 using coal seam thickness of 1.2 m at depth of 1170m. The failure of this trial was due to poor connection of the wells (Shafirovich and Varma, 2009).

Successful UCG trials conducted at shallow depth include that of Chinchilla in Australia and Yuzhno-Abinskaya in Russia. South African coals are generally shallow of depth and predominantly low grade bituminous coals. The coal properties of Chinchilla UCG trial are shown in Table 5, and the coal properties of the South African Highveld coalfield (seam 2, 4 and 5) in Table 6.

Table 5: Properties of coal utilised for Chinchilla and Yuzhno-Abinskaya UCG trials Australia (Khadse et al., 2007).

Location	Seam Depth (m)	Seam Thickness (m)	H2O (%)	Ash (%)	VM (%)	CV (MJ/Kg)
Chinchilla (Australia)	130	8 – 10	6.8	19.3	40	33.9
Yuzhno – Abinskaya (Russia)	50 - 300	2.2 - 9	2.5 – 8	2.3 – 5.2	27 - 32	-

Table 6: Highveld coal properties, deduced from typical analyses of raw coals (Cairncross, 2001; Jeffrey, 2005).

Coalfield	Depth (m)	Seam (No)	Seam thickness (m)	H_2O (%)	Ash (%)	VM (%)	CV(MJ/Kg)
Highveld Coalfield (South Africa)	0 – 300 m	2	1.5 – 4 m	3.8	22 - 35	19.9	20 – 27
		4	1 – 12 m	2.5	20 - 40	20.2	15 – 25
		5	1 – 2 m	3.2	17 - 19	19 - 32.7	> 25.9

The coal properties of previous successful UCG trials (Chinchilla and Yuzhno – Abinskaya) are compared with the Highveld coal (seam 2). These properties include moisture (H_2O), ash, volatile matter (VM) and calorific value (CV) as well as seam depth and thickness. Figure 3 shows the coal properties of Chinchilla and Highveld. The Chinchilla coal has much higher moisture, volatile matter and calorific value compared to the Highveld coal. Highveld coal contains high ash content compared to Chinchilla coals. In Figure 4 the Yuzhno–Abinskaya coal show to have higher ash and volatile matter as compared to Highveld coal which have higher moisture content. The thickness and depth of coals used for trial are compared with the Highveld coal. In Figure 5 the seam depth of Highveld is comparable to that of Yuzhno–Abinskaya and the seam thickness fall within the range of UCG coal trails.

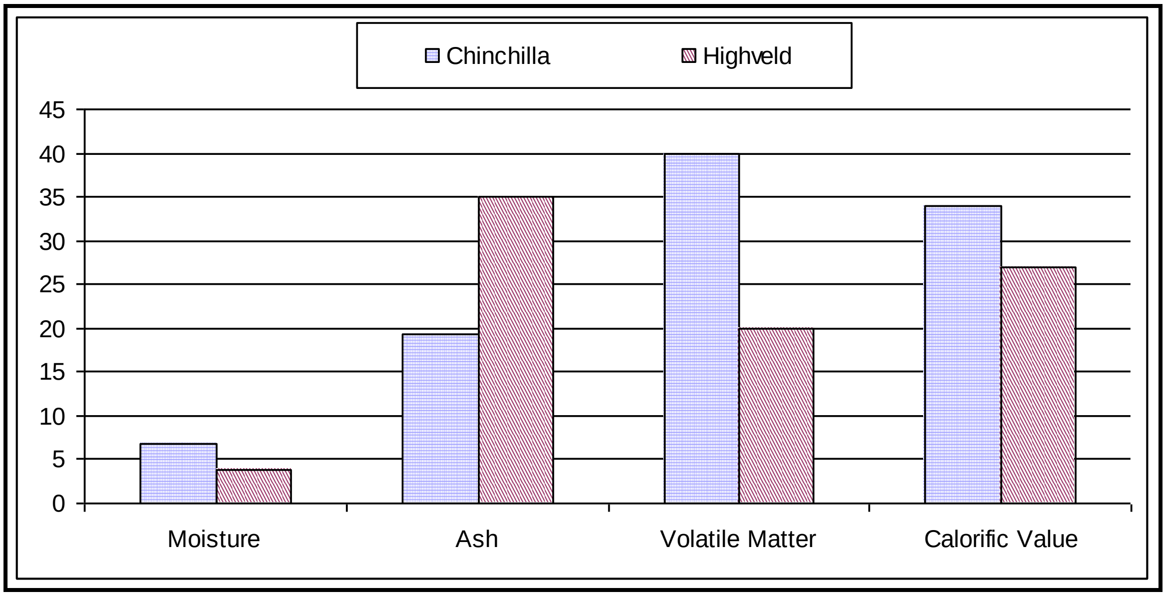

Figure 3: Coal properties comparison between Chinchilla coal and the Highveld seam 2 coal

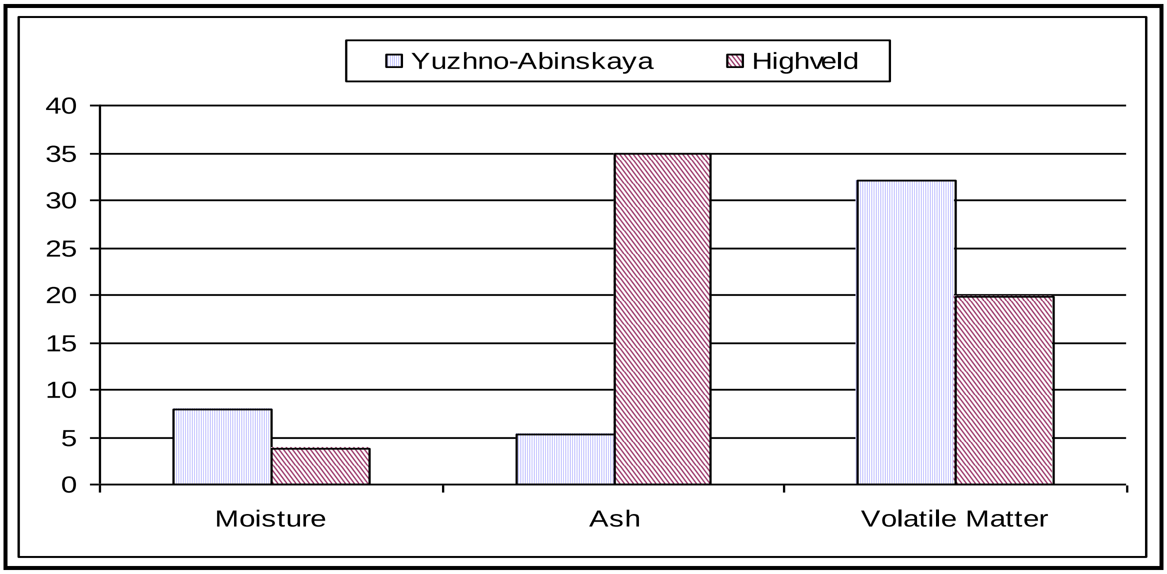

Figure 4: Coal properties comparison between Yuzhno–Abinskaya coal and the Highveld seam 2 coal

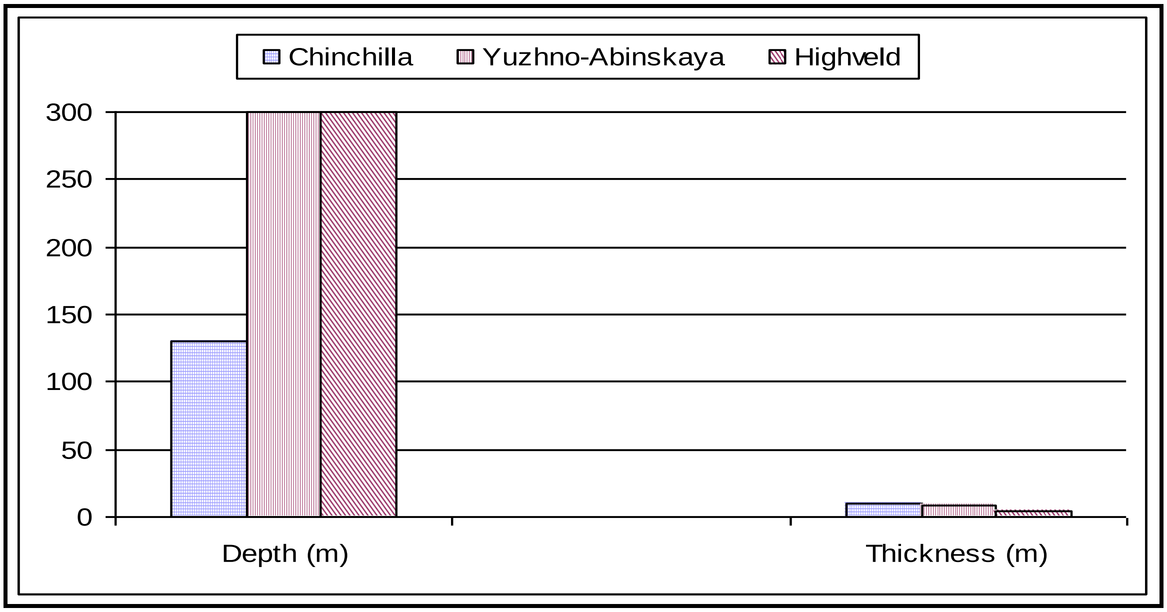

Figure 5: Coal seam depth and thickness comparison between Chinchilla , Yuzhno–Abinskaya and the Highveld seam 2 coal

2.8.2 Consideration of Criteria for UCG Site Selection in South Africa

The site identification criteria for UCG in South Africa will be based on the same natural factors as those of the previous successful trials. These factors include coal geology, coal properties, and geohydrological and geotechnical properties of the floor and roof strata. List of factors to consider when screening a potential UCG sites in South Africa are presented in Table 7.

Table 7: Factors to consider when selecting a potential UCG sites (Bialecka, 2008; Couch, 2009; Ergo exergy, 2009; Khadse, *et al*., 2007; Shafirovich and Varma, 2009; Thomas, 2002; Zieleniewski, 2008)

Underground Coal Gasification (UCG) Site Identification Factors	
Parameters	**Standard Requirements for UCG Site**
1. Coal Seam Geology	
(i) Depth	Depth of greater than 100m is preferred
(ii) Thickness	Coal Seam of greater 1 metres thick
(iii) Dip	Both flat and dipping seam (dipping coal seam easier to sustain)
2. Coal Properties (Coal Quality)	
(i) Rank	All coal type: preferable low rank, free swelling-index should be low
(ii) Chemical composition	Ash content of less than 60%
	Volatile matter of greater than 10%
	Moisture – preferred moisture content 7- 35%,
(iii) Permeability	More permeable, greater than 20%
(vi) Porosity	Porous coal seam with porosity of greater than 30%
3. Geo-hydrological and Geotechnical Properties of Floor and Roof Strata	
(i) Geology	
- Lithology	Competent Lithology (High UCS, non porous and impermeable strata)
(ii) Hydrology	Non aquifer strata is preferred
- Porosity	Non porous strata (non aquifer) < 30%
- Permeability	Impermeable (< 5%)
- Water ingress	Moderate (not quantified)
(iii) Geotechnical Strata properties	
- Rock strength (Shear Wave)	Low shear wave is required (Not quantified)
- Uniaxial Compressive Stress (UCS)	UCS range (50 to > 250 MPa)
- Sonic Velocity (m/s)	Slow velocity preferred (not quantified)
- Density	Density of greater 2 g/cm^3

Note: Structural condition of coal and associated rocks not included in these criteria

2.9 Summary

In this chapter (Phase one) UCG technology was investigated using information available in literature. UCG is seen as a technology which can utilise vast amounts of coal deposits which are regarded unminable by means of conventional methods. Such deposits include those coal seams which are within complex geology or occurring at great depth. The aim of this chapter was to determine criteria which can be used in the selection of potential UCG sites in South Africa. This was achieved by comparing information obtained from previous successful UCG trials to that of South African coal deposit. The recommended factors are listed Table 7 Section 2.8.2. Some components in Table 7 can be determined by geophysical logging (phase two) and some components are related to coal characterization in phase three. In the next chapter geophysical wireline logging methods are investigated for their feasibility in well evaluation for UCG exploration.

Chapter 3

Geophysical Survey Technique:

(Borehole Wireline Logging)

The primary aim of this chapter is to discuss the effectiveness of applying geophysical wireline logging techniques to the evaluation of potential UCG sites. This chapter also gives an overview of geophysical techniques with an emphasis placed on borehole wireline logging. The last part of the chapter summarises the importance of borehole wireline logging in the exploration for potential UCG sites.

3.1 Introduction

Most countries in the world have gained interest in UCG in the past years with the aim of utilising their vast reserves of unminable coal. UCG is particularly employed in order to utilise the low grade, thin coal seams economically. The criteria used for the selection of UCG sites in South Africa are almost the same criteria used for the same purpose internationally (Chapter 2). Since coal in UCG is gasified *in situ*, the geological, hydrological and geotechnical properties of coal and its surrounding rocks are the major parameters to be considered in the selection of potential UCG sites.

Although coal properties such as the coal seam thickness, depth, chemical and petrographical composition are significant for UCG, the geophysical properties of the roof and the floor strata requires special attention for proper selection of potential UCG sites. Geophysical (wireline) log analysis is conducted in order to determine the geological and geotechnical properties of coal and its associated rock formations (Wonik and Olea, 2009). A basic log suit is run in a cored borehole with the aim of determining rock properties such as rock strength, porosity, density, formation composition, depth and thickness of rock formation (Couch, 2009). At present there is no log that can directly measure permeability.

3.2 Geophysical Techniques

Geophysical exploration technique is a surveying method that uses the principle and application of physics to search for natural resources and to obtain information about the subsurface structures and condition of a target area. According to Zong (1993) applications of this method in exploration began in the early 1600’s when it was first used to search for solid mineralisation (iron ore). Different geophysical exploration methods were applied with varying degrees of success during the early years of its application. Due to the advancement of technology the same methods are currently used with greater accuracy and sensitivity (Zong, 1993).

Geophysical exploration techniques are regarded as the most effective methods used in exploration of hydrocarbons (oil and natural gas) and mineral deposits. Geophysical exploration techniques have long been applied in exploration for petroleum and gas industry and have most recently been useful in the exploration of coal and other minerals (Thomas, 2002). Table 8 presents a summary of geophysical exploration methods that are used in the exploration and exploitation for hydrocarbon and mineral resources.

Table 8: Major geophysical exploration methods (Kearey and Brooks, 1991)

Method	**Measured Parameter**	**Physical Properties**
Seismic	Travel times of reflected/ refracted seismic waves	Density and elastic module, which determines the propagation velocity of seismic waves
Gravity	Spatial variation in the strength of the gravitational field of the earth	Density
Magnetic	Spatial variation in the strength of the geomagnetic field	Magnetic susceptibility and ramanence
Electrical		
Resistivity	Earth resistance	Electrical conductivity
Induce polarization	Polarization voltage or frequence-dependent ground resistance	Electrical capacitance
Self potentials	Electrical potential	Electrical conductivity
Electromagnetic	Response to electromagnetic radiation	Electrical conductivity and inductance
Radar	Travel times of reflected radar pulses	Dielectric constant

3.2.1 Borehole Wireline Logging

Borehole wireline logging is a geophysical surveying technique. This technique is used to examine the borehole walls condition by lowering different wireline probes into the borehole, which then measures properties of the rock masses around the borehole (Chopra *at el*., 2002). Borehole wireline logging technique records detailed continuous information about the composition, variability and physical properties of the rock formation encountered in the boreholes (Reid *at el.*, 1989). Wireline logging is used in exploration as a tool for evaluating the geological and geotechnical parameters of the site under investigation (Elkington *at el*., 1983). In coal exploration the primary interest of borehole wireline logging lies in determination of geological, geohydrological and geotechnical properties of the deposit and the surrounding rock sequence. Borehole information is recorded with depth using a combination of different wireline probes to enable data acquisition for detailed and accurate formation evaluation.

3.2.2 Borehole Wireline Logs

There are several different logging tools (sondes) that are used in borehole wireline logging technique. The most commonly used logging tools are discussed below, namely radiation logs, electric logs, sonic log and other logs that are used in well evaluation including caliper log, dipmeter log, and fluid temperature log.

3.2.2.1 Radiation Logs

Radiation logs are those logs that make use of natural radioactive elements (Thomas 2002). Currently available radiation logs include the following: gamma–ray, density log and neutron log. These logs measure the nuclear radiation emitted from naturally occurring sources within geological formations or sources carried in the logging tool. In coal exploration, radioactive logs are generally used for the identification of coal beds (Kearey and Brooks, 1991; Thomas, 2002).

(a) Natural gamma ray log

Natural gamma-ray logs measure the variation in natural radioactivity of the rock formation encountered in the borehole (Thomas, 2002). Natural radioactivity in rock formation is due to the presence of radioactive elements such as uranium, thorium and potassium (Bird, 2006). The natural gamma radiation measurements are made in a cased well and the measuring scale of the log is in API (American Petroleum Institute) units. Natural gamma ray log is used in conjunction with other logs (i.e. density log) to distinguish geological formations encountered in the boreholes. In coal bearing sequences, radioactive elements are predominantly found in clay rich siltstone and mudstone while good quality coal and clean sandstone may have very low levels of radioactive elements (Hatherly, et al, 2005; Kearey and Brooks, 1991)

(b) Gamma ray Density log

Gamma ray density log is sometimes referred to as density log. It uses two detectors to measure gamma rays passed into the formations from the source and reflected to the detector by scattering. Its primary application is based on determining the formation's bulk density, porosity and indicating different types of geological units encountered in the borehole. In coal exploration density logs are generally used to identify coal beds since coal has the lowest density as compared to other lithologies (Chatfield, 2009; Thomas, 2002).

(c) Neutron - gamma ray log

Neutron log is one of the radiation logs. It emits fast neutrons which in turn lose their energy to the surrounding media through collision with the hydrogen proton nucleus (Chopra et al., 2002). Neutron log is used to determine the porosity of rock formation based on its sensitivity to the presence of hydrogen ions. It is also known as a porosity log (Timur and Toksoz, 1985).

Figure 6 shows the Schematic diagram of radiation logs (gamma ray and Neutron log) and the summary of radioactive logs are presented in Table 9.

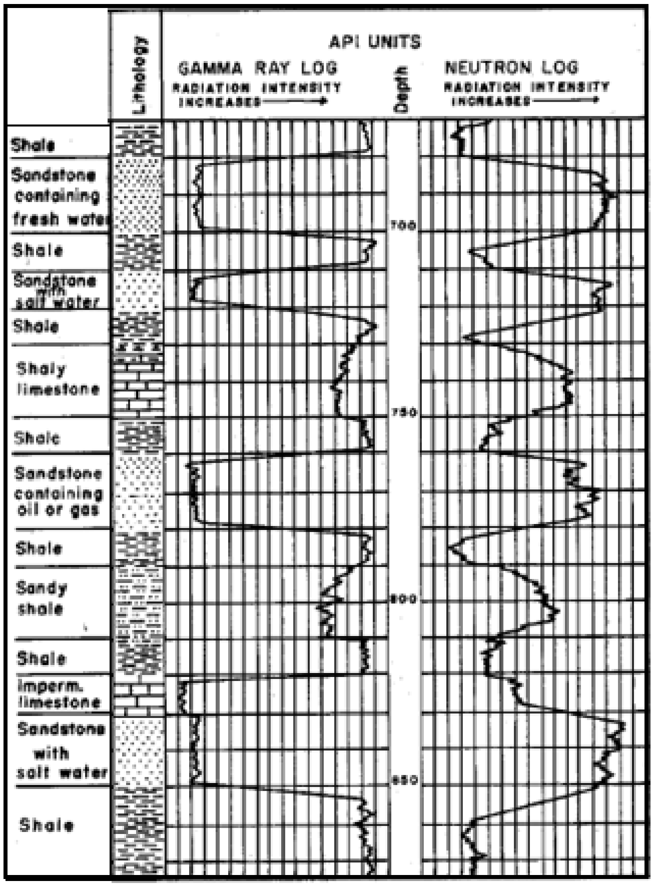

Figure 6: Schematic log showing radiation logs (gamma ray and Neutron log)
(Modified from Timur and Toksoz, 1985)

Table 9: Summary of radiation logs (modified from Fricke and Schon, 1999)

Method	Principle	Log	Measured parameter (Derived parameter)
Radioactivity Logging Methods			
a) "Passive " Gamma measurement	Measurements of the natural gamma radiation -sum –spectral	gamma-ray log, Spectral gamma-ray log	Counting rate (cps, API-units) [Th, U, K concentration (%, ppm)]
b) Active gamma-gamma measurements	Measurements of the gamma radiation using the Compton effect	Gamma-gamma log, density log	[Density (gm^{-3})]
Neutron measurements	Measurements of the neutron radiation on collision with an atom; measurements of the radiation resulting from neutron capture	Neutron-neutron log	[Neutron porosity (%)]

3.2.2.2 Electrical log

Electrical logs can only be measured within water or drilling fluid filled boreholes. They are used in open holes to determine the electrical resistivity of the rock, which together with other physical parameters can be used to derive a lithological log for the borehole (Thomas, 2002). Some electrical well logging tools measure the self-potential; others measure the resistivity using one of several electrode configurations (Timur and Toksoz, 1985).

3.2.2.2 (a) Self-Potential SP log

Self-potential (SP) log is amongst the first generation of well logs used for rock characterisations. SP log measures the natural potentials of the surrounding rock materials in the borehole. The SP log is generally used in the determination of bed thickness, and separating non-porous from porous rocks (Chopra *et al.,* 2002). It is run only in open (uncased) boreholes that are filled with a conducting fluid, such as mud or water.

3.2.2.2 (b) Resistivity log

Resistivity log records formation electric resistance, in ohms. A potential difference between the electrodes is measured in volts, and then converted to resistance using Ohm's law because a constant current is maintained. Resistivity log is primarily used to determine rock formation permeability.

Table 10: Summary of electrical logs (modified from Fricke and Schon, 1999)

Method	**Principle**	**Log**	**Measured parameter (Derived parameter)**
Electrical Methods			
Self potential	Measurements of the self-potential	Self-potential log	Potential (mV)
Resistivity	Measurements of the electrical resistivity	Conventional resistivity measurement	Electrical resistivity (Ωm)
		Focused electric log	Electrical resistivity (Ωm)
		Dipmeter	Electrical resistivity (Ωm)

3.2.2.3 Sonic log

Generally sonic logs are used in the determination of rock strength of different formation along the borehole. Different sonic logs that are used for estimation of rock strength include uniaxial compressive strength (UCS), sonic velocity and shear wave from full wave sonic logs. Sonic log is also used to determine the formation porosity just like density and neutron log (Hagan and Gibson, 1983; McNally, 1987).

3.2.2.3 (a) Acoustic Televiewer (ATV) log

Acoustic televiewer (ATV) log is a downhole imaging device. It generally provides an orientated image of the borehole. ATV can also be used to determine rock strength and identifies fractures along the borehole. ATV produces magnetic photographic images of the intensity of acoustic reflection of the borehole wall. Acoustic borehole televiewer log is the most expensive logging tool as compared to other wireline logging tools (Hagan and Gibson, 1983).

3.2.2.4 Other Logs

Other wireline logs used in well evaluation other than the radioactive and electrical logs include the following: Caliper log, Dipmeter and temperature log.

(a) Caliper Log

The caliper log can either be part of a density logging tool where it is a single arm or as an individual tool with three arms or four arms known as 3-arms/4-arms caliper. Caliper log generally records continuously the borehole diameter variation, which can influence the response of other logs (Elkington *et al*., 1982; Hagan and Gibson, 1983). It measures the borehole temperature and identifies water producing and receiving zones. Calliper log is also used to identify fractures along the borehole (Bird, 2006; Conger, 1997). Measurement is done as the arms are moved along the borehole wall.

(b) Dipmeter Log

The dipmeter log measures the magnitude and direction of formation inclination. It is primarily used to determine structural attitudes as well as sedimentation features in the borehole surrounding (Keys and MacCary, 1971; Miller 1979).

(c) Temperature Log

Temperature log measures the temperature gradients of the borehole, using a thermometer as a sensing element. Temperature log gives a continuous record of the temperature of the borehole surrounding. It is primarily used to provide information on the source and movement of water and the thermal conductivity of rocks (Keys and MacCary, 1971)

Figure 7 shows an example of wireline logs profile which is generally used to evaluate the subsurface condition of the area under consideration.

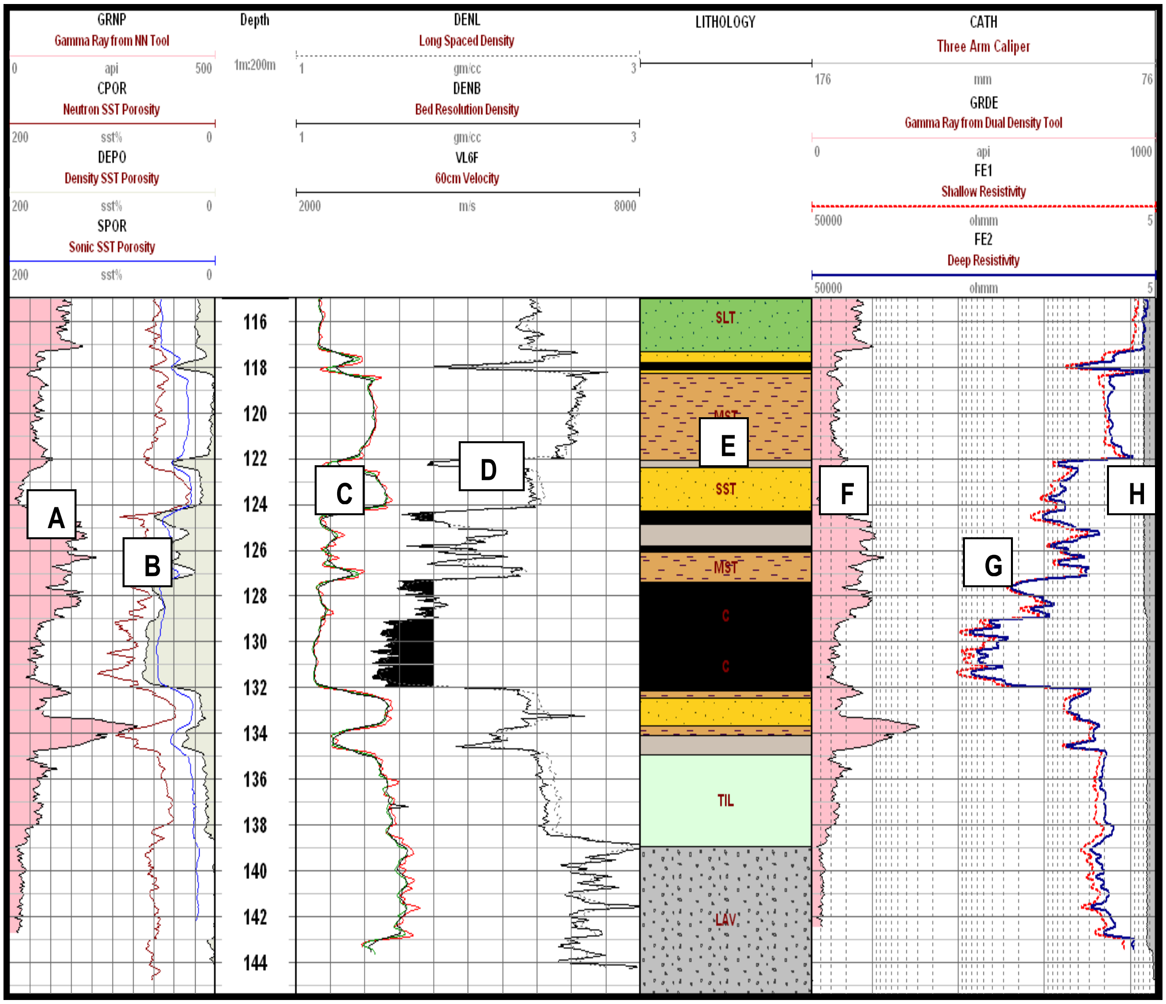

Figure 7: Example of geophysical wireline log profile

A: Gamma-ray log from neutron tool
B: Porosity logs – CPOR porosity from neutron log
SPOR porosity from sonic log
DEPO porosity from density log
C: Velocity log
D: Density log
E: Lithology log – derived from core logging
F: Gamma-ray from density tool
G: Resistivity logs- deep and shallow resistivity
H: borehole diameter log- calliper log

3.2.3 Principles of Borehole Logging

One of the most important attributes of borehole wireline logging is the ability to make several different physical measurements in a borehole using different logs. The application of this method is suitable for detecting the underground profile.

The general logging method for borehole wireline logging technique is described in detail by Kobr *et al*., (2005); Kearey and Brooks (1991); Thomas (2002); Timur and Toksoz (1983) and many other authors. The summary is as follows: At the exploration site or any target area, cored boreholes are drilled using any of the several drilling methods available. The measurements are made by lowering different types of tools (sondes) into a borehole and electrically transmitting data in the form of either analog or digital signals to the surface, where they are recorded as a function of depth or distance along the borehole. The measurements are then related to the physical and chemical properties of the rocks surrounding the borehole and the properties of the fluid in the borehole. Figure 8 illustrates the field set-up of borehole wireline logging method.

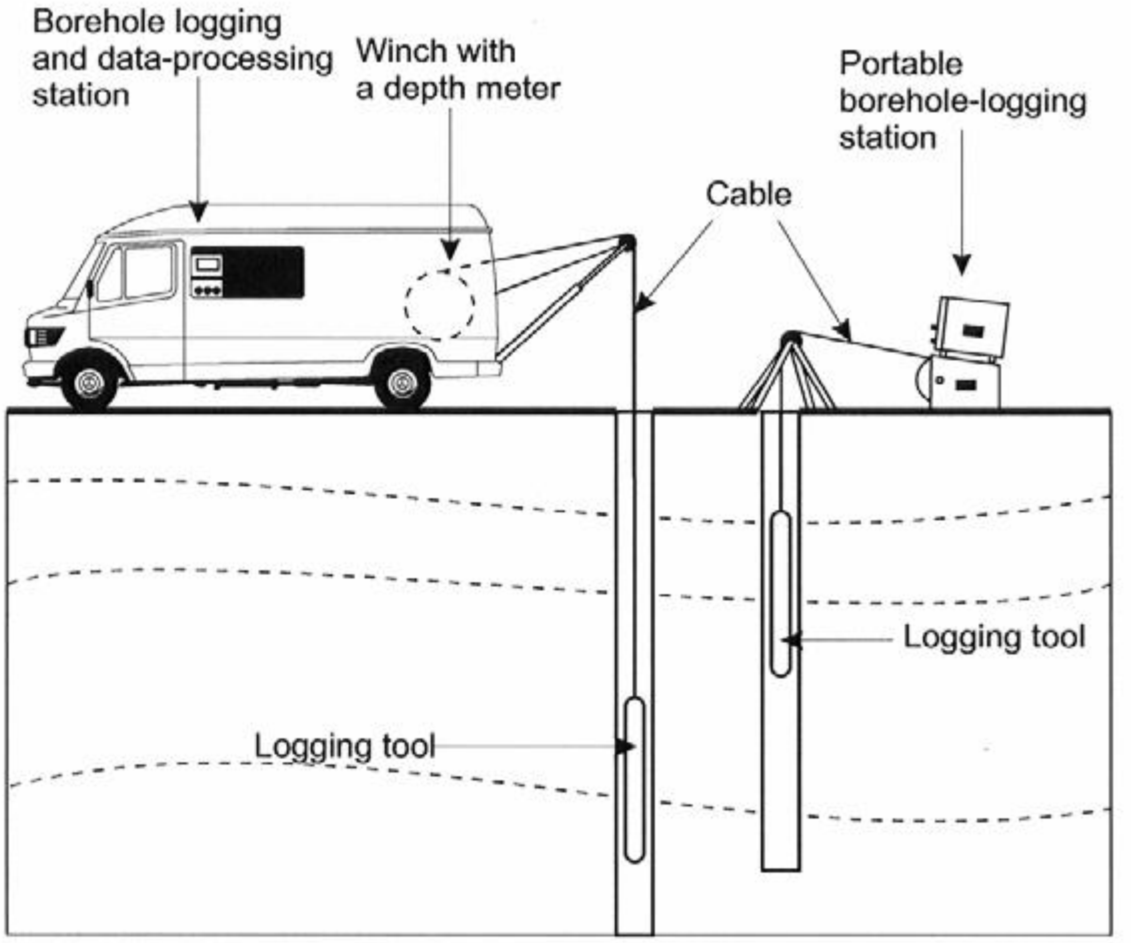

Figure 8: Borehole geophysical wireline logging method in a borehole on site (Wonik and Olea, 2009)

3.3. Methodology

The current study is conducted to illustrate the feasibility of wireline logging method in the evaluation of the geological and geotechnical properties of coal deposit and its surrounding rock formation, using an exploration site in the Highveld coalfield South Africa.

3.3.1 Wireline Logging Method: Exploration Site Evaluation

For the purpose of this study, processed log data from three exploration boreholes (BH1, BH2 and BH3) from the Highveld coalfield were provided for site evaluation by one of the South African wireline logging companies; the exact location of the borehole is unknown. The log sheets indicate the total depths of the boreholes to range from 170 m to 176 m from the surface with the diameter variation of between 90 mm and 95 mm.

The following suites of borehole geophysical wireline logging probes were used in obtaining the log's raw data from the three exploration boreholes:

- 3-arm Calliper log
- Natural gamma ray log
- Density log
- Neutron log
- Sonic log (Full wave sonic log)

The geophysical data produced after the survey was completed was sent to a computerised data capture system where it was processed using different software in order to produce a detailed log sheet. From the log sheet different strata properties determined by different geophysical wireline log probes can be deduced. The geological and geotechnical information obtained is used in the evaluation of the target area.

3.4 Results and Discussion

The results of boreholes (BH1, BH2 and BH3) are shown in Tables 11, 12 and 13 and in Figures 9a and 9b, 10a and 10b and 11a and 11b. The lithological profile in Figures 9 - 11 was derived from the manual core logging method of the cores from the boreholes. In coal exploration by means of borehole wireline logging, coal seams and their surrounding strata are differentiated by their geophysical characteristic responses (Thomas 2002). According to Yegireddi and Bhaskar

(2009) the variation in the log signatures produced by different coal seams and the surrounding rock formations are due to their variation in physical and chemical properties as well as their depositional environment. In the case of coal seams their variation in the log signature is mostly based on the coal quality.The average values for gamma ray log, density log, uniaxial compressive strength log, shear wave and porosity logs of borehole BH1 are listed in Table 11. Sections of geophysical signatures of different logs obtained from the survey of borehole BH1 are shown in Figures 9a and 9b, with the complete log profile in Appendix C.

Table 11: Geotechnical data obtained from geophysical log of borehole1 (BH1) of the Highveld coalfield South African

Depth (m)	Gamma-GRDE (API)	Density-DENB (gcm^{-3})	Velocity (m/s)	Uniaxial Compressive Strength-UCS (MPa)	Shear Wave (usec/m)	Porosity (%)	
						DEPOS	POR
0 - 9.55	116.6	3.4	-	-	-	6.8	-
9.55 - 10.70	177.4	3.4	-	-	-	2.9	-
10.70 - 12.10	185.3	3.5	-	-	-	5.9	-
12.10 - 15.17	192.3	2.7	-	-	-	5.5	-
15.17 - 47.42	28.8	3.2	5892.6	167.1	300.6	0.0	0.0
47.42 - 49.62	185.5	2.7	3400.4	43.9	533.7	1.7	21.3
49.62 - 67.50	245.1	2.6	2784.5	26.2	675.8	9.0	40.5
67.50 - 68.02	201.4	2.7	3603.4	42.4	539.4	3.1	21.0
68.02 - 68.50	184.9	2.7	3679.1	49.6	498.2	2.9	21.2
68.50 - 69.31	138.3	2.8	4061.7	64.7	445.8	0.0	15.0
69.31 - 69.96	158.1	2.7	3932.9	61.4	448.0	3.2	17.3
69.96 - 70.91	87.6	2.6	4423.3	69.2	417.8	6.5	12.8
70.91 - 73.10	73.3	2.8	5427.0	114.7	346.4	0.0	1.5
73.10 - 82.10	236.1	2.7	3654.5	50.4	497.7	3.1	15.8
82.10 - 83.37	201.2	2.6	3989.7	49.6	496.2	5.5	17.3
83.37 - 94.08	194.2	2.7	3841.7	55.8	472.6	2.9	17.9
94.08 - 94.90	237.8	2.6	3623.9	46.6	511.2	5.2	21.4
94.90 -115.89	169.6	2.8	3871.9	62.1	454.6	0.0	17.3
115.89 -116.00	191.1	2.6	3566.0	27.8	691.1	18.1	19.3
116.00 -116.51	163.3	2.2	2513.8	11.7	928.0	30.2	39.6
116.51 -147.08	176.4	2.7	3756.3	52.8	485.4	2.7	19.2
147.08 -148.50	265.6	2.7	3595.5	45.6	515.5	6.7	22.3
148.50 -158.77	168.4	2.8	3804.4	58.0	468.5	3.8	16.5
158.77- 160.96	198.2	2.6	3658.9	45.5	516.8	7.2	21.0
160.96 -161.15	139.9	1.7	3221.4	12.8	831.2	43.5	24.5
161.15 -162.12	122.3	2.6	3497.7	36.6	571.5	6.9	31.4
162.12 -163.35	81.5	2.7	3797.0	52.6	483.8	2.9	17.8
163.35 -165.38	196.1	2.7	3553.2	40.7	539.4	7.4	22.7
165.38 -165.68	120.8	2.5	3613.6	41.1	534.6	17.6	21.3
165.68 -168.22	106.4	1.5	2434.9	4.5	1311.7	62.5	50.2
168.22 -168.31	93.4	1.5	2420.0	3.8	1379.7	62.0	39.8
168.31 -169.5	75.5	2.6	3746.4	47.4	504.9	10.1	19.0

Note: Highlighted are coal seams/layers determined by their geophysical readings

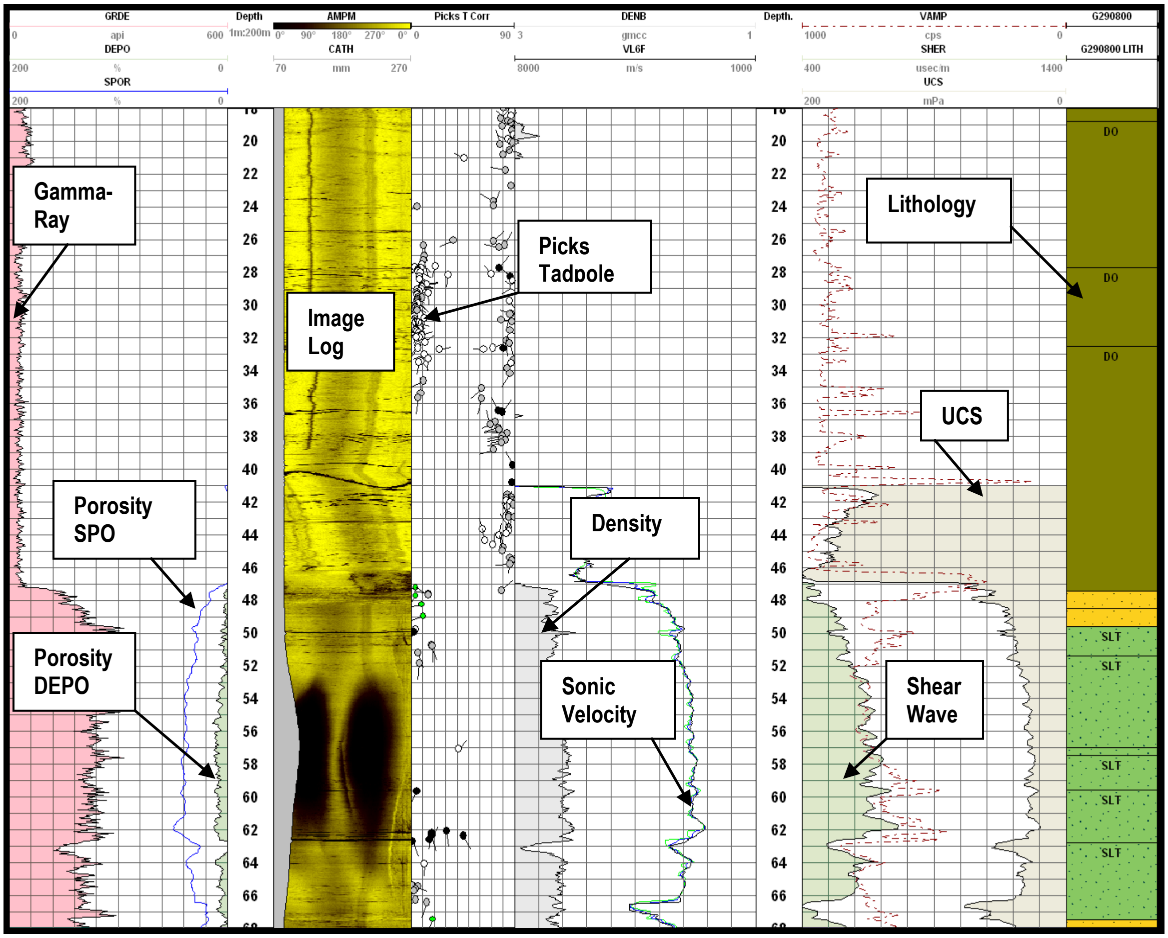

Figure 9a: Geophysical wireline log profile of BH1 (Top section). Different logs signatures used in evaluation of geological and geotechnical properties of a target area. Log measurement which increases to the left include SPOR- Sonic porosity log, DEPO- Density porosity log, VL6F- Sonic Velocity log, UCS- uniaxial compressive strength and VAMP- ATV image log. Log measurements that increases to the right include the following: GRDE-Gamma ray from density log, AMPM- ATV log, Picks tadpole and SHER- Shear wave log as indicated in the log. Core-derived lithology.

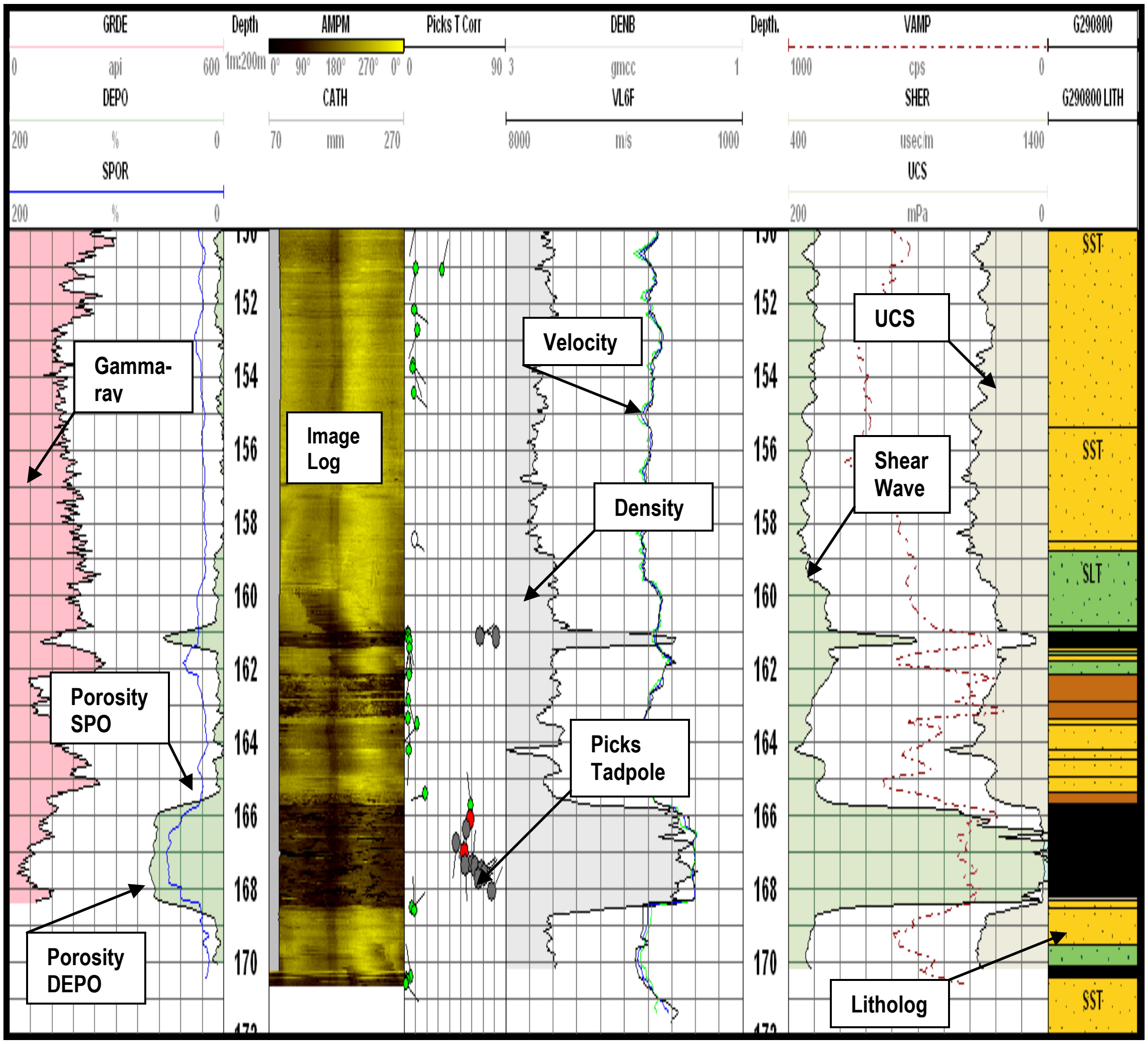

Figure 9b: Geophysical wireline log profile of BH1 (Bottom-Section). Different logs signatures used in evaluation of geological and geotechnical properties of a target area. Log measurement that increases to the left include SPOR- Sonic porosity log, DEPO- Density porosity log, VL6F- Sonic Velocity log, UCS- uniaxial compressive strength and VAMP- ATV image log. Log measurements that increases to the right include the following: GRDE- Gamma ray from density log, CATH Caliper log, AMPM- ATV image log for picks tadpole and SHER- Shear wave log

Figures 9a and 9b show different log signals given out by different probes used in the survey. The types of logs used in this survey include gamma ray log (GRDE) on the far left, sonic porosity log (SPOR) on the left, density porosity log (DEPO) on the left, caliper log (CATH) on the left, AMPM-ATV image log and polar plots for fractures and bedding in the centre, density log in the centre, sonic velocity log in the centre to the right, sonic shear wave log on the right, ATV (Vertical amplitude) log on the right and Uniaxial compressive strength log (UCS) far right. The lithology log on the far right of the diagram show different rock types encountered in the borehole and it has been determined by means of core logging. Borehole BH1 intersected a compact hard rock followed by sedimentary sequence comprised of sandstone, siltstone, gritstone and coal beds in Figures 9a and 9b. Natural gamma radiation of the compact dolerite unit observered in BH1 is very low compared to that of sedimentary sequence.

Table 12 shows the average logs values resulting from wireline logging of borehole BH2 as a function of depth. The highlighted section is the coal seams/beds.

Table 12: Data obtained from geophysical wireline logging of borehole BH2 of the Highveld coalfield South African

Depth	Gamma-GRDE	Density- DENB	Velocity	Uniaxial Compressive Strength-UCS	Shear Wave	Porosity (%)	
(m)	(API)	(gcm^{-3})	(m/s)	(MPa)	(usec/m)	DEPO	SPOR
0 - 13.00	124.1	3.4	-	-	-	12.8	-
13.00 - 13.82	98.2	3.4	8771.1	505.9	180.1	3.5	-
13.82 - 15.76	160.9	3.3	7284.0	341.2	248.2	0.0	0
15.76 - 50.43	29.7	3.1	6008.9	184.8	282.2	0.0	0
50.43 - 52.65	236.1	2.7	3369.4	41.0	552.7	2.5	26.8
52.65 - 62.26	237.4	2.6	2917.0	29.1	645	7.0	36.8
62.26 - 62.41	237.5	2.6	2917.1	28.0	651.9	9.1	38.1
62.41 - 70.90	209.4	2.6	2946.4	30.4	640.9	6.0	36.4
70.90 - 71.33	207.0	2.6	3583.0	43.2	533	4.9	25.0
71.33 - 72.60	173.2	2.7	3583.0	48.1	516.1	1.4	22.1
72.60 - 82.04	163.1	2.7	3757.6	54.2	485.5	0.2	19.5
82.04 - 82.41	154.5	2.6	4045.0	71.3	113.2	6.6	17.1
82.41 - 121.42	157.8	2.7	3674.5	46.2	554.2	5.2	20.5
121.42 - 122.20	148.0	2.1	2413.5	10.6	987.2	39.2	48.5
122.20 - 122.61	98.1	1.8	2660.2	10.8	1268	47.5	29.6
122.61- 136.92	123.4	2.6	3524.6	41.9	532.6	9.3	23.2
136.92 - 136.98	176.5	2.5	3595.2	41.0	534.3	8.3	0.0
136.98 - 150.83	224.8	2.7	3820.9	54.5	480.3	0.7	13.1
150.83 - 151.45	275.6	2.7	3526.7	44.3	526.7	5.4	23.3
151.45 - 152.90	245.1	2.7	3618.8	46.6	513.6	4.0	21.5
152.90 - 153.35	267.6	2.6	3517.8	42.0	535.8	7.0	23.5
153.35 - 164.09	166.1	2.8	3767.6	54.3	483.6	0.6	19.0
164.09 - 166.09	282.7	2.6	3469.5	40.7	543.8	7.1	22.4
166.09 - 166.55	167.7	1.7	3152.1	22.6	543.8	44.5	19.1
166.55 - 167.30	170.8	2.6	3729.4	46.9	509.1	8.2	1853.0
167.30 - 169.17	161.5	2.7	4051.0	59.2	457.8	1.7	14.8
169.17 - 171.04	212.8	2.7	3547.1	44.0	528	5.0	18.0
171.04 - 174.93	79.9	1.5	2433.6	4.2	1320	64.1	52.9
174.93	000	2.6	4099.9	56.1	461.1	7.1	5.5

Note: Highlighted are coal seams/layers determined by their geophysical readings

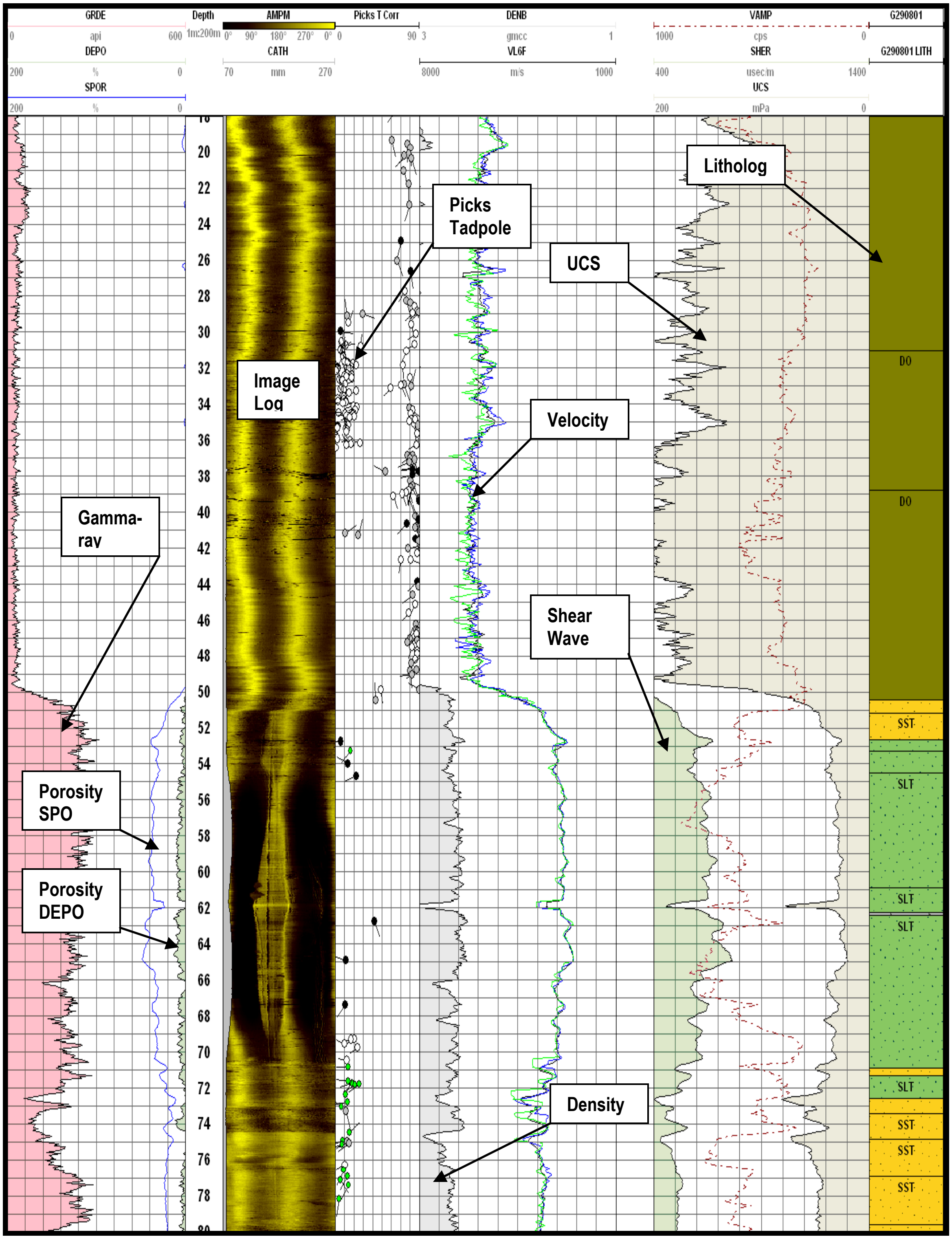

Figure 10a: Geophysical wireline log profile of BH2 (Top-Section). Log measurement that increases to the left include SPOR- Sonic porosity log, DEPO- Density porosity log, VL6F- Sonic Velocity log, UCS- uniaxial compressive strength and VAMP- ATV image log. Log measurements that increases to the right include the following: GRDE- Gamma ray from density log, CATH Caliper log, AMPM- ATV image log for picks tadpole and SHER- Shear wave log

Figure 10a shows the top sections of the logging results for borehole BH2, using the same logging probes as in BH1. The full log profile is in Appendix A. The major geological units encountered in this section are dolerite, siltstone and sandstone. The gamma radiation in dolerite is very low as compared to siltstone and sandstone which show to have high and similar gamma radiation. The porosity value of dolerite is almost zero, meaning that this lithology is not porous. Siltstone and sandstone porosity values are almost the same; the porosity in this case is observed to be very low. The ATV image in Figure 10a is brighter showing the presence of stronger geological units. Polar picks derived from ATV image show many minor fractures in dolerite and major fractures in siltstone. Layering is observed in sandstone. Higher density and sonic velocity is observed in dolerite unit, density and sonic velocity values for sandstone and siltstone are observed to be almost the same. Dolerite is observed to have the lowest value of Shear wave and higher value of uniaxial compressive strength compared to silt and sandstone.

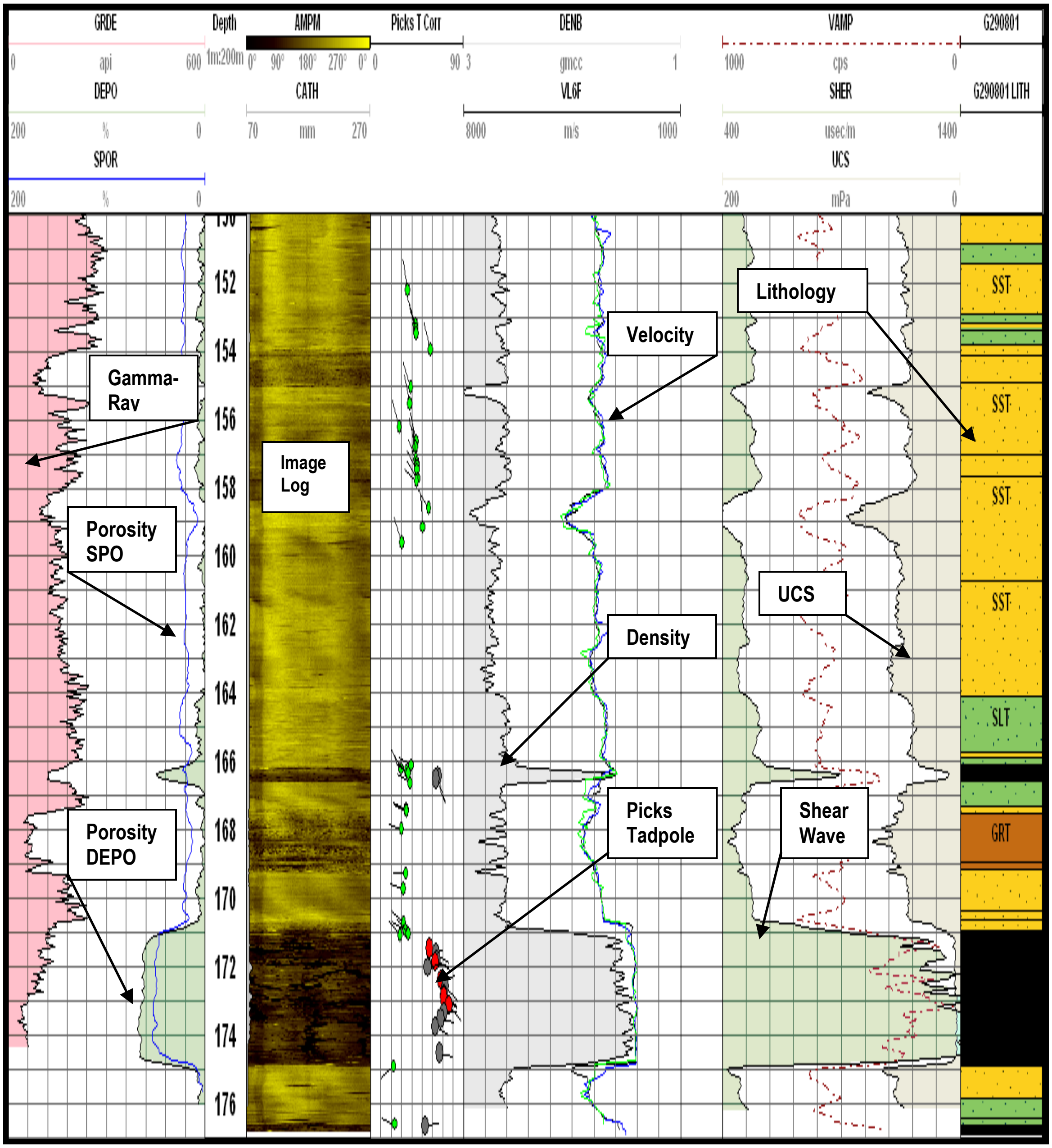

Figure 10b: Geophysical wireline log profile of BH2 (Bottom-Section). Log measurement that increases to the left include SPOR- Sonic porosity log, DEPO- Density porosity log, VL6F- Sonic Velocity log, UCS- uniaxial compressive strength and VAMP- ATV image log. Log measurements that increases to the right include the following: GRDE- Gamma ray from density log, CATH Caliper log, AMPM- ATV image log for picks tadpole and SHER- Shear wave log

Figure 10b show the bottom sections of the logging results for borehole BH2. The geological units encountered in the borehole in Figure 10b include sandstone, siltstone, gritsstone and coal beds. Since siltstone is imbedded in sandstone it produces same gamma radiation, gritstone have lower gamma radiation as well as the coal beds. Porosity is lower in sandstone, siltstone and gritsstone but is observed to be higher in coalbeds. AMPM-ATV image along the borehole show brighter colours for sandstone, siltstone and gritsstone but dark colour is observed on coal units. Tadpole plots show layering in sandstone and siltstone rock units and a number of open fractures in coal units. Density value for coal is observed to be low compared to the density of sandstone, siltstone and gritsstone which are found to be almost the same. Coal units are observed to have high value of shear wave and the lowest value for uniaxial compressive strength as compared to siltstone, sandstone and gritsstone with shear wave and uniaxial wave values which are almost the same.

Table 13 presents the average log values for borehole BH3.

Table 13: Data obtained from geophysical wireline logging of borehole BH3 of the Highveld coalfield South Africa

Depth (m)	Gamma-GRDE (API)	Density-DENB (gcm^{-3})	Velocity (m/s)	Uniaxial Compressive Strength-UCS (MPa)	Shear Wave (usec/m)	Porosity (%)	
						DEPO	SPOR
0 -13.80	120	3.4	8771.1	472.4	183.2	17.5	15.5
13.8 -14.14	94.2	3.6	8771.1	505.0	100.1	11.0	15.5
14.14 -15.69	159.62	2.8	877.1	308.8	205.0	7.3	15.5
15.69 - 48.09	33.05	3.1	5668.7	180.0	233.6	0.0	0.0
48.09 - 50.47	192.76	2.7	2564.6	40.6	523.7	5.9	26.0
50.47 - 64.62	239.05	2.6	2804.7	26.7	680.1	12.2	38.5
64.62 - 65.00	145.34	2.8	4160.3	70.1	431.3	8.8	20.1
65.00 - 68.74	192.54	2.7	3048.8	33.8	611.7	9.2	33.0
68.74 - 93.84	161.09	2.7	3663.2	52.8	483.8	9.6	19.1
93.84 - 94.08	160.71	2.7	3845.3	54.1	479.2	6.5	18.1
94.08 - 116.26	198.15	2.7	3678.0	51.5	479.0	4.7	20.7
116.26 -116.37	165.94	2.9	2851.4	33.6	624.5	3.4	28.0
116.36 -116.40	168.24	2.9	2550.0	27.4	694.7	3.9	33.6
116.40 -116.84	165.36	2.5	2465.0	18.1	816.7	22.6	45.5
116.84 -117.10	182.22	2.2	2463.0	13.0	874.8	36.0	50.8
117.10 -117.35	175.57	2.2	2502.0	13.2	877.5	42.5	50.1
117.35 -117.81	82.17	1.6	2461.8	4.1	1391.6	60.5	50.0
117.81-129.46	168.49	2.6	3578.1	42.2	532.4	13.0	22.4
129.46 -129.55	177.96	2.6	3726.2	47.8	503.3	12.4	20.3
129.55 -129.59	161.91	2.6	3712.7	47.3	505.6	12.1	20.6
129.59 -148.70	156.46	2.7	4023.9	61.9	461.6	6.0	15.7
148.70 -149.07	230	2.7	3611.3	47.4	511.2	8.8	21.6
149.07 -159.40	173.19	2.6	3820.8	56.4	475.5	4.3	18.3
159.40 -161.41	212	2.6	3436.3	39.6	550.3	11.7	25.1
161.41 -161.50	263.02	2.7	3338.3	41.6	548.9	27.5	27.0
161.50 -161.59	222.28	2.3	3315.9	26.6	638.2	33.9	28.0
161.59 -161.65	167.15	1.9	3074.5	12.5	833.5	41.5	31.9
161.65 -161.90	117.7	1.8	2882.3	9.0	979.6	55.9	37.4
162.03 -162.15	185.38	2.6	2710.3	25.3	691.8	22.2	42.0
162.15 -162.57	245.8	2.6	3055.8	31.9	621.4	12.5	31.7
162.57 -162.68	142.03	2.6	3386.5	39.2	554.9	88.1	24.8
162.68 -163.26	82.89	2.6	3663.0	44.6	517.2	10.4	20.5
163.26 -163.35	152.26	2.7	3704.9	50.6	496.4	8.3	20.1
163.35 -164.25	62.63	2.6	3740.1	47.6	503.3	9.3	19.6
164.24 -164.40	146.91	2.7	3841.0	54.1	479.5	10.1	18.4
164.40 -164.70	106.84	2.6	3766.5	45.3	509.2	11.9	19.7
164.70 -166.10	130.95	2.7	3648.1	43.1	529.1	9.0	23.6
166.10 -169.60	94.28	1.6	2491.4	4.2	1318.2	69.9	49.1
169.60 -169.67		1.6	1247.9	4.7	1263.6	70.7	43.2

Note: Highlighted are coal seams/layers determined by their geophysical readings

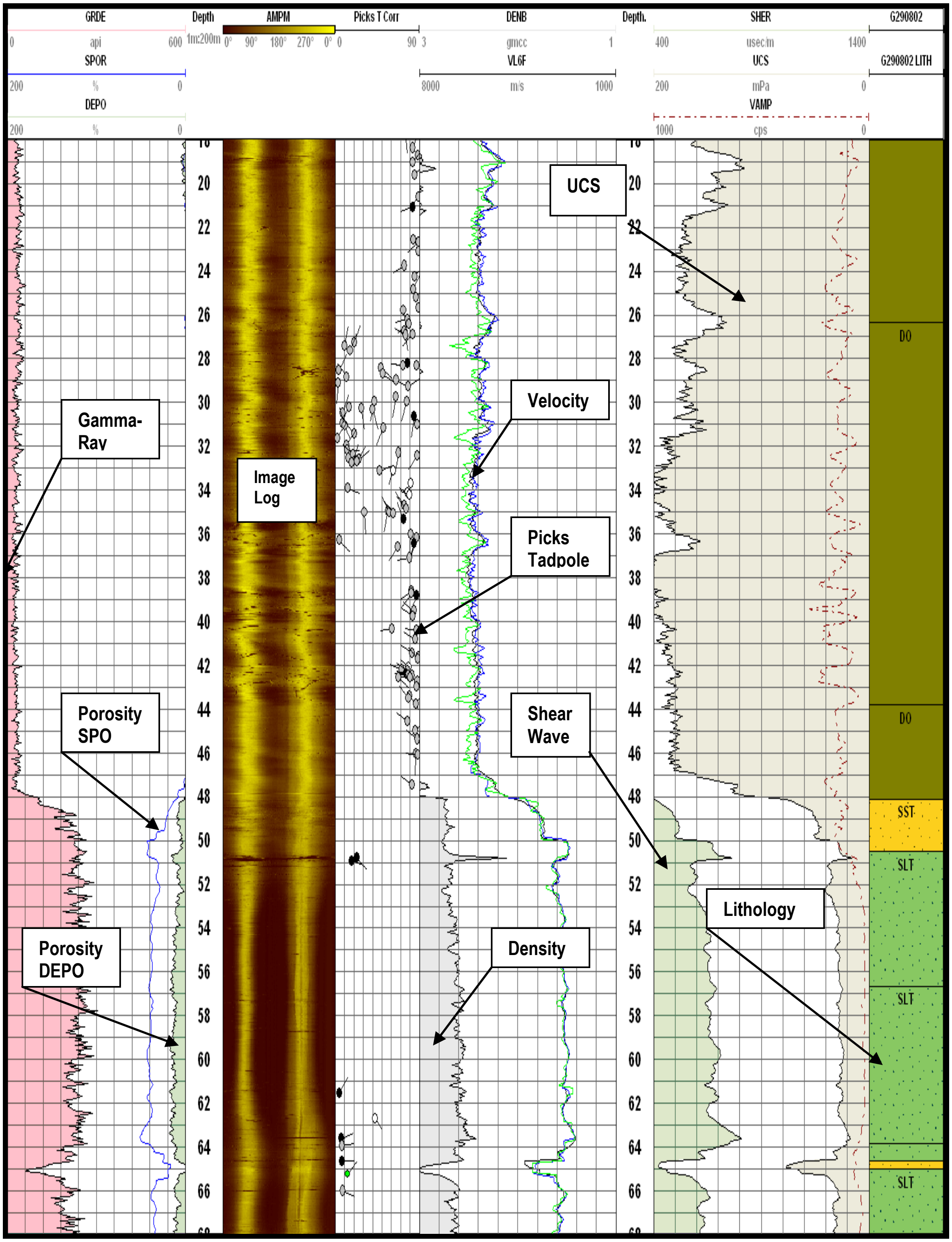

Figure 11a: Geophysical wireline log profile of BH3 (Top-Section). Log measurement which increases to the left include SPOR- Sonic porosity log, DEPO- Density porosity log, VL6F- Sonic Velocity log, UCS- uniaxial compressive strength and VAMP- ATV image log. Log measurements that increases to the right include the following: GRDE- Gamma ray from density log, AMPM- ATV log, Picks tadpole and SHER- Shear wave log

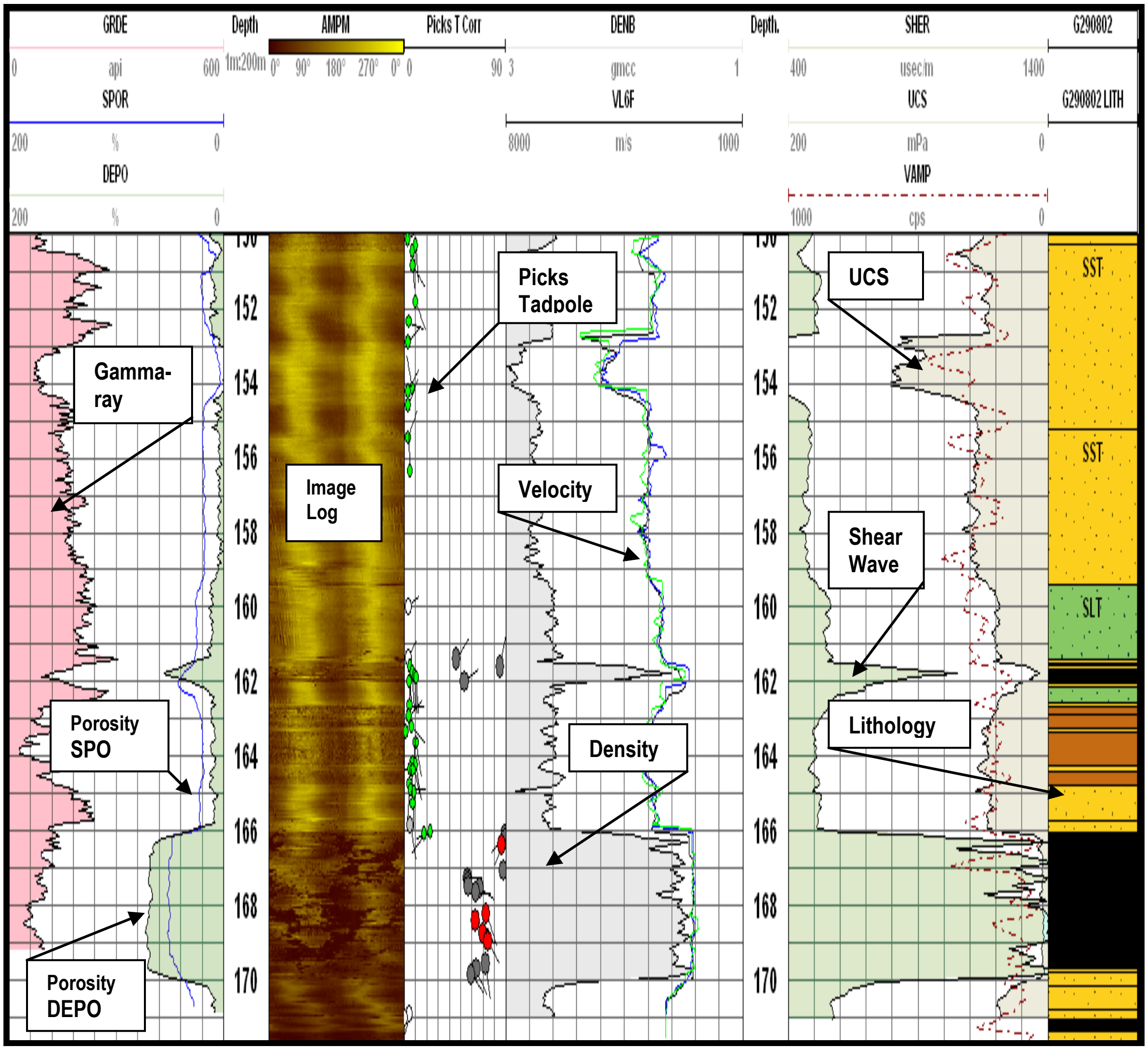

Figure 11b: Geophysical wireline log profile of BH3 (Bottom-Section). Log measurement which increases to the left include SPOR- Sonic porosity log, DEPO- Density porosity log, VL6F- Sonic Velocity log, UCS- uniaxial compressive strength and VAMP- ATV image log. Log measurements that increases to the right include the following: GRDE- Gamma ray from density log, AMPM- ATV log, Picks tadpole and SHER- Shear wave log

Figures 11a and 11b illustrate the top and bottom section of geophysical responses of wireline log probes run in borehole BH3; the full profile of the log is in Appendix C. In Figure 11a, the geological unit encountered in the borehole includes dolerite, siltstone and sandstone. The geophysical properties observed in Figures11a and 11b of BH3 are similar to those observed in borehole BH1 in Figures 9a and 9b and borehole BH2 in Figures 10a and 10b.

3.4.1 Log Evaluation

3.4.1.1 Lithological Boundaries: (Geological Formations)

Natural gamma log and density log are widely used for the identification of lithological boundaries in the borehole in relation to the borehole depth (Kamali and Mirshady, 2004). Natural gamma ray log measures the natural radioactivity of the rock formation which is usually due to uranium, thorium and potassium enrichment (Hagan and Gibson, 1983). Density log measures the bulk density of the rock formation, different rock types will give out different density readings. Figures 9a and 9b, 10a and 10b, and 11a and 11b show the lithological log derived from core logging, thickness of coal beds and major rock layers as defined by gamma ray log and density log readings.

The logged rock sequence primarily consists of dolerite, sandstone, siltstone, gritstone and coal units. A similar sequence of layers is observed in all three boreholes. Coal beds are found at almost the same depth in all boreholes. The stronger dolerite strata seem to be overlying the entire area as it is the first solid rock formation encountered after a huge weathered overburden rock material. The compact dolerite unit ranges in thickness between 31.2 m to 35.4m in relation to the log scale and is characterised by high density value (3.06 gmcc) and the lowest gamma reading of 35.43 API (See Tables 11, 12 and 13).

Thick layers of sandstone and siltstone alternate at great depth with almost the same density readings of between 2.4 – 2.76 gmcc and gamma ray values that ranges between 180 and 240 API. The clean layers of these rock formations were noted by low gamma readings within the layers. Three coal beds have been observed as indicated in Tables 11, 12 and 13 (highlighted rows). The thicker bed is at the base as shown by gamma and density readings and AMPM-ATV image log in Figure 9, 10, and 11. This coal bed is locked within the sandstone layers and characterised by low gamma value (180 API) and a density value of 2.6 gmcc. The other coal beds are thinner and record high gamma ray and low density readings.

3.4.1.2 Formation Porosity (Density, Sonic and Neutron Porosity logs)

The porosity of the rock formation around the vicinity of the borehole is determined using density, sonic and neutron porosity logs. The logs are all calibrated for clean sandstone. Porosity determined from neutron log is greater than that determined from density log because the neutron porosity is affected by water bound within the clay minerals. Sonic log is sometimes used in porosity determination.

Coal beds are observed to be the most porous rock formation encountered in the borehole with the porosity value of over 50%. The compact dolerite is observed to be non-porous with the porosity value of less than 1%. Siltstone and sandstone recorded porosity values the ranges from 9 to 32%.

3.4.1.3 Rock Strength Analysis: (Sonic log)

Sonic geophysical log is used for the determination of rock formation strength through the uniaxial compressive strength, sonic velocity and sonic shear wave (Oyler *et al*., 2009). Sonic log has been widely used in rock strength analysis. Coal seams represent the weakest rock formation in the sedimentary sequence because of its brittle and porous nature. Generally porous rocks are found to be weaker than compact rocks. The uniaxial compressive strength (UCS) values of coal in this case ranges from 4 to 27 MPa and has slower sonic velocity of 1600 m/s. Dolerite shows to be the strongest rock formation with the highest UCS values of 505.9 MPa and attaining the highest sonic velocity value of 5600 m/s, as seen in Tables 11, 12 and 13 and Figures 9a and 9b, 10a and 10b and 11a and 11b. Sonic velocity value for sandstone units ranges from 3200m/s to 2400 m/s with the minimum UCS values of 40 MPa while siltstone shows sonic velocity values that range from 3200 m/s to 2000m/s and the lowest UCS value of 30 MPa.

3.4.1.4 Structural Analysis (ATV log and Tadpole)

The structural information around the vicinity of the borehole is obtained from acoustic televiewer (ATV) or borehole televiewer (BHTV) logs (Maliva *et al*., 2009). ATV provides an orientated image show showing the fractured zones of the borehole wall. Tadpole (Picks T Corr log) determines structures such as fractures and layering of the formation. From the ATV log fractures are predominant in dolerite unit in Figures 9a,10a and 11a. Coal is observed to be highly fractured with major and open fractures dominating the coal unit. In sandstone and siltstone layering is observed.

3.4.2 Application of Borehole Wireline Logging Technique on UCG

In UCG exploration, site characterization is one of the challenging steps in the identification of suitable UCG sites and may assist in avoiding possible environmental consequences such as groundwater pollution and subsidence. Geophysical wireline logging is a tool that can be successfully used in the evaluation of the geology and hydrogeology condition of the area under consideration. Wireline logging determines the composition, variability and physical properties of the coal seam and rocks around the borehole. The overlying and the underlying strata that bounded the coal beds should be very competent to control and contain the reaction (Ghose and Paul, 2007), wireline logging method can be used to evaluate the competence of those strata's.

3.5 Benefits and Limitations of Wireline Logging in UCG

The major benefit of using wireline logging is its ability to provide accurate geological information about the formations surrounding the borehole (Chopra *et al*., 2002). Wireline logging is also regarded as the fastest method for acquiring subsurface information, which can be used for investigation of subsurface condition. In UCG, knowledge about the subsurface is important since the whole process take place underground, therefore the use of wireline logging in site investigation is essential.

The well known limitation of wireline logging method is the need for a borehole to operate in. In the case of UCG, where a larger geological area is investigated, several boreholes are used, and as a result the drilling capital is determined by the number of boreholes required for investigation. Another drawback of using wireline logging is its operation cost, whereby the cost of logging is dependent to the borehole depth and the type tools to be logged. In UCG, deeper coal seams are preferred, in order to acquire information about the coal seam and the surrounding rocks, deeper boreholes are drilled through the coal seam and a suit of wireline probes are logged. This means that the cost of drilling borehole and logging in UCG will be much higher.

3.6 Summary and Conclusion

In this study (Phase 2) the feasibility of geophysical wireline logging to acquire information about the subsurface condition was evaluated. Three boreholes (BH1-BH3) from Highveld coalfield were used to serve this purpose. Different wireline probes were used to acquire different properties of the rock formation in the boreholes. Gamma-ray and density logs identified the geological units in the boreholes to primary consist of dolerite, sandstone, siltstone and coal. The information of the wall rock strength was determined by the use of AMPM-ATV image log and sonic log (sonic velocity, UCS, shear wave); dolerite was found to be the strongest rock formation and coal layers are identified as the weakest formation. Density and neutron logs were used to determine formation porosity; dolerite was found to be non porous when compared to other formations; sandstone and siltstone were found to be less porous whilst coal was identified as the porous formation in the borehole. Based on the selection criteria for a potential UCG site presented in Table 7, the rock formation properties identified by means of geophysical wireline logging in this area show some qualities of a potential UCG site. Geophysical wireline logging has been proved to be a feasible technique for acquiring data that can be useful in the evaluation of the subsurface condition of area under consideration. The feasibility of wireline logging to acquire direct information about the subsurface condition has been confirmed by other researchers in exploration field (Fullugar *et al*., 2004 and Schepers *et al*., 2001).

Chapter 4

Coal Characterisation

This chapter (Phase 3) describes the methods involved in the characterization of coal properties suitable for UCG processes. The characterization techniques employed in this study include petrography and gas adsorption (BET) for physical analysis; proximate and ultimate analysis for chemical analysis; mineral analysis was carried out using X-ray diffraction (XRD). Sample preparation methods for the analytical techniques employed in this study are also described. The key objective of this chapter is to understand the nature of coal and its physical and chemical properties, and to determine coal suitability for UCG process.

4.1 Introduction to Coal Characterisation

Coal is a heterogeneous material made-up of a variety of organic and inorganic materials (Saikia *et al*., 2009; Thomas, 2002). The physical and chemical properties of coal vary with its location. Such properties are determined by the nature of the original organic and inorganic matter accumulation as well as the degree of digenesis it underwent. The large varieties of organic and inorganic materials involved in coal formation lead to the differences in physical and chemical structure of coals of different regions in the world. Coal characterisation is the most important activity in coal utilisation; it includes both physical and chemical evaluation of coal prior its usage.

4.2 Coal Properties for UCG Process

Based on the heterogeneous nature of coal, it is highly possible that individual properties of coal will have an effect on the behaviour of coal during UCG processes (Juntgen, 1987). Coal properties discussed in this case include the following: Coal nature and surface area in section 4.2.1, coal petrography in section 4.2.2, mineral matter in coal in section 4.2.3 and chemical composition in section 4.2.4.

4.2.1 Coal Nature and Surface Area

Coal in nature is a porous solid material (Gan *et al.,* 1972). The pore structures in coal can vary from big cavities to very small pores that even helium atom cannot fill at ambient temperature. According to Yaman *et al*., (2000) pores in coal are classified based on their diameter length as follows:

- Submicropores (< 8 Å)
- Micropores (8 - 20 Å)
- Mesopore (20 – 500 Å)
- Macropore (> 500 Å)

The pore size distribution of coal is closely related to the coal rank. Low rank coal generally consists of macropores while high rank coal consisting mostly of micropores (Yaman *et al.,* 2000). According to Kwiatkowska *et al*., (2006), gas adsorption is commonly used to determine the surface area and pore volume as well as the pore size distribution of micro - and mesoporous materials. A number of different isotherms have been used for interpretation of adsorption data; the theory by Brunauer-Emmett-Teller (BET) is the most frequently used theory (Kwiatkowska *et al.,* 2006). The micropore volume, micropore specific surface area and micropore size distribution can be determined on the basis of adsorbed gas at various pressure steps (Amarasekera *et al*., 1995)

The coal particles surface area is a product of the monolayer capacity and the area occupied by a single adsorbed molecule. The monolayer capacity is the number of molecules necessary to cover the adsorbent surface with a complete monolayer (Karr, 1978).

4.2.1.1 The Effect of Coal Nature and Surface Area in UCG

Coal as microporous heterogeneous material is characterised by having high surface area (Marsh, 1987). The pore network present in coal serves as path for reagent to gain access to the interior of coal structure. Knowledge on coal surface area, pore volume and pore size distribution is essential for understanding the behaviour of coal in many different utilisation processes including UCG (Siauw *et al*, 1984). Since UCG process involves transportation of the product gas through production well via the coal seam matrix, the physical structure of coal is of great importance.

Gas adsorption is used to determine the physical properties of coal. In coal seams underground, coal exists as very large layers that may attain thickness of between 1.0 to 5m and more. The large layers of coal allow the adsorption of gas on the coal surface and passing of liquid/gas through the transporting channel formed by the macromolecule structure of coal. Coal porosity affects the conversion process of coal since most reaction between coal and gas occurs in pores.

4.2.2 Coal Petrography

As stated in section 4.1, coal is a mixture of organic and inorganic materials. The organic part of coal is made up of macerals while the inorganic is mainly mineral matter contributing to the ash content of coal (O'Brien *et al.,* 2003). Macerals in coal are classified into three different maceral groups that include vitrinite, liptinite and inertinite (Falcon and Falcon 1987). The relation between different maceral groups is based on the degree of their oxidation during peat formation as shown in Figure 12.

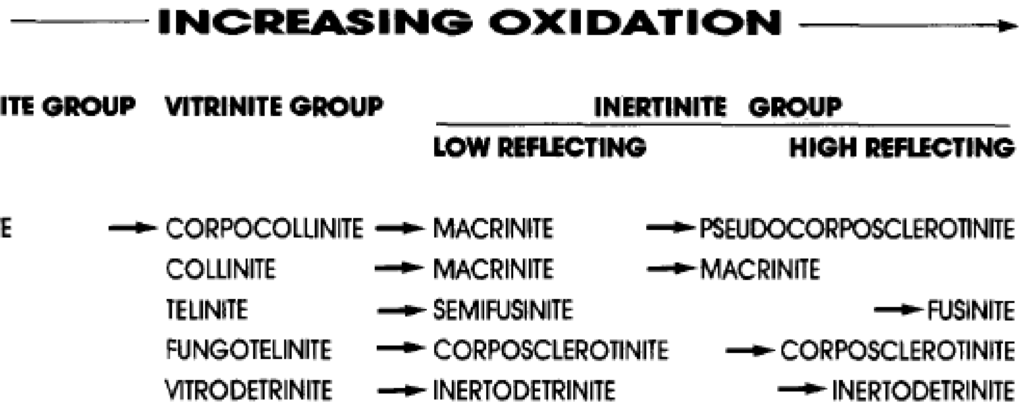

Figure 12: Genetic relationships between macerals as a result of the variable degree of oxidation (Snyman, 1989)

Coal petrography is the microscopic study of microscopic organic and inorganic constituents present in coal and the degree of metamorphosis (rank) (Falcon and Snyman, 1986; O'Brien et al., 2003). Petrography has become a major assessment tool for understanding coal properties and quality in coal industry (O'Brien *et al*., 2003; Snyman, 1989). Petrographically South African coals are characterized by low contents of liptinite and high contents of high reflecting inertinite (macrinite, fusinite and sclerotinite) and with low vitrinite contents. The vitrinite content varies between the different coalfields, from 10% to almost 100% (Snyman, 1989).

Petrographic analysis enables the determination of maceral, microlithotype, mineral groups, and rank by vitrinite reflectance (Korwin-Kossakowsi, 1990). Coal petrography is essential for the characterization and classification of coal in terms of type, grade and rank for the determination of technical behaviour and utilisation potentials of the materials. The petrographic composition of coal can greatly influence the behaviour of coal during gasification.

4.2.2.1 The influence of petrographic composition and coal rank on UCG

Organic matter, which is the combustible fraction of coal, has significant influences on the behaviour of coal during gasification. Maceral composition of coal influences its surface area, pore volume, pore size distribution. Using electron microscope technique, Harries and Yust (1976) found vitrinite maceral in high volatile bituminous coal to be micro and mesoporous and inertinite to be mostly mesoporous and liptinite is found to be less porous.

Coal rank has major influence on coal reactivity (Juntgen, 1987; van Heek and Muhlen, 1985;). In UCG process, the gasification reactivity of coal based on rank is as follows: Lignite has the highest reactivity followed by bituminous coal and then anthracite with the lowest gasification reactivity. Low rank coals have high contents of moisture and volatiles, which during gasification are readily released as result of heating which in turn cracks or break down the coal seam forming loosened structure with high reaction area. The pore structure of low rank coal enables cracking of the coal seam at high temperature and allows reagents to diffuse to fresh coal surface thus improving the reaction rate. It is clear that rank has an effect on the UCG behavior of coals.

4.2.3 Mineral Matter in Coal (X-Ray Diffraction Analysis)

Mineral matter present in coal can be investigated by means of XRD and other similar techniques (Ward *et al,* 2001; Ward *et al.,* 2005). XRD was one of the first techniques applied in the identification of minerals in coal samples (Ruan and Ward *et al.,* 2001; Ward, 2002). Generally XRD has been regarded as having limitations in the evaluation of mineralogical data on quantitative bases. The limitations are based on the changes in diffractogram characteristics resulting from ionic substitution, variation in mineral crystallinity, grain size of different particles, preferred orientation in the sample mount and differential absorption of X-ray by the various minerals in the mixture (Ruan and Ward, 2002; Ward, 2002). Rietveld methodologies in X-ray diffraction analysis quantify the proportion of individual minerals in powdered mineral mixture.

4.2.3.1 The effect of minerals in UCG (XRD):

Mineral matter in coal is very significant to different coal utilisation processes. Mineral matter in coal assists with the understanding of coal genesis. The problems associated with coal utilisation are mostly related to mineral matter incorporated in coal. Mineral matter has a negative effect on coal porosity since it is assumed that organic matter dominates the pore volume in coal more than mineral matter. In conventional use of coal, mineral matter is responsible for the wearing of mechanical part in the boiler. In UCG process, some mineral matter in coal acts as catalyst in the gasification process reactions (van Heek and Muhlen, 1985).

4.2.4 Chemical Composition of Coal by Means of Proximate and Ultimate Analyses

Proximate analysis determines the inherent moisture, volatile matter, ash, and fixed carbon (by difference) content of coal. Ultimate analysis is used for the determination of chemical elemental composition of coal that includes the following: carbon, hydrogen, nitrogen, total sulphur and oxygen (by difference).

4.2.4.1 Influence of Chemical Composition of Coal in UCG:

The chemical composition of coal has a strong influence on its technical behaviour during combustion and gasification processes. The reactivity of coal based on its chemical composition is potentially very important for UCG (Perkins and Sahajwalla, 2006).

In UCG process moisture in the form of steam or ground water saturation in coal is required as part of the gasification reaction. As UCG processes can utilise high ash coal, the ash content of the coal is likely to have a minor effect as compared to the other properties. Volatile matter in coal plays an important role in UCG since it enhances the ignition character of coal during gasification as found by Zhou, 2005. Fixed carbon is not a major influential factor in UCG. Though coal with higher carbon content (fixed carbon) will have higher specific consumption of gasification reagents (oxygen/air and steam) and is assumed to have higher gas production in contrast to coal of low carbon content (Zhou, 2005).

4.3 Experimental Procedure

4.3.1 Sample Origin

Coal samples used in this study originate from the Highveld coalfield, South Africa. The coal from this field is mainly used for power generation by Eskom in the Matla and Kriel Power stations, and is also used by Sasol as a feedstock for the coal to liquid (CTL) process for the production of synthetic fuel and petro-chemicals. Coal of this region is also exported for steam generation to other countries (Jeffery, 2005). Five raw coal samples from two boreholes (BH1 and BH2) were used in this study. Coal samples were collected from cored seams. Samples 1- 4 were from the same drilled core of BH1 at different depth (sample 1 (116.6 m), sample 2 (161.5 m) sample 3 (166 m) and sample 4 (167.8 m)); and sample 5 was obtained from drilled core of BH2 at depth of 166.5 m. These samples were hand-picked and supplied to University of the Witwatersrand at the commencement of the project. Unfortunately due external constraints beyond the researches capacity no further samples were supplied. Hence the correlations between the coal layers determined in BH1, 2 and 3 discussed in Section 3 and the coal characterisation data was not suitable as envisioned. None the less the data is presented here and conclusions are drawn. Prior to analysis the samples were reduced to specific particle sizes required for different analyses that include petrography, ultimate and proximate analysis, XRD and Gas adsorption (BET) analysis, through grinding and screening.

4.3.2 Sample Preparation and Analytical Procedures

4.3.2.1. Blocks Preparation for Petrographic Analysis

Petrographic blocks were prepared in accordance with the ISO Standard 7404-2, (1985). Crushed coal particles between 1000 microns and 30 microns were used to prepare the blocks. About 200g of sample was poured into rubber mould and mixed with a mixture of epoxy resin and hardener (Ratio 7:1). The sample mixture was left to harden overnight at room temperate. The mounted sample blocks were polished using a Struers Tegraforce polisher using water, allegro largo, diapro dac and alumina (Al_2O_3) as lubricants. The polished petrographic blocks were prepared in the coal laboratory situated in the School of Chemical and Metallurgical Engineering at the University of the Witwatersrand.

4.3.2.2 Petrographic Analysis: Rank determination and Maceral analysis

Rank determination, or reflectance measurements, were done according to ISO standard 7404- 5 of 1994 and are based on the reflectance of vitrinite. Random vitrinite reflectance of coal gives a good indication of the rank of coal. Reflectance analyses are conducted using a Leica microscope which is interfaced with a J and M spectroscopic system. Maceral analysis is conducted in order to determine the organic and inorganic composition of coal. Reflected light microscopy is used for the analysis. Maceral groups in coal are quantified by a 500-point count technique, according to the ISO standard 7404-3 of 1994.

4.3.2.3 Gas Adsorption: BET-Surface Area

Gas adsorption was used for physical analysis. Coal samples were crushed and screened to particle size fraction of between 212 and 150 microns. The samples were sent to North West University for BET analysis using a Micromeritics ASAP-2020 analyzer. Low pressure gas adsorption measurements were conducted using carbon dioxide at a temperature of approximately 273.1 K. Surface area and pore volume were determined by carbon dioxide adsorption at 273.1 K using BET methods. The obtained adsorption isotherms were evaluated using BET methods.

4.3.2.4 Chemical Analysis

The chemical analysis in this study includes both proximate and ultimate analyses. Raw coal samples were crushed into particle size greater than 150 microns for ultimate analysis and pulverized samples with particle size of less than 75 micron were used for proximate analysis. The proximate and ultimate analyses were outsourced to Witlab, a commercial laboratory based in Witbank (the equipment at Wits was broken). The analyses were done following ISO standard methods shown in Table 14.

Table 14: Standards used in chemical analysis

Analysis	Standard
Proximate	
Moisture	SABS 925 (1978)
Ash Content	ISO 1171 (1997)
Volatile Matter	ISO 562 (1998)
Fixed Carbon	By Difference
Ultimate	
Carbon/Hydrogen/Nitrogen	ISO/TS 12902 (2001)
Oxygen	By difference

4.3.2.5. Mineral Analysis: X- Ray Diffraction (XRD)

XRD analysis was conducted to determine mineral mater content in the coal samples. Powder coal samples were sent to XRD Analytical and Consulting in Pretoria for XRD analysis. Samples were analysed using a PANalytical X'Pert Pro powder diffractometer. In this study the crystalline mineral matter in coal was investigated. The relative amount of each mineral was estimated by means of the Rietveld method.

4.4 Characterization Results and Discussion

The results obtained from the different characterising techniques used in this study are presented and discussed below. The physical properties of coal which includes petrographic composition as well as surface area and pore distribution are given in section 4.4.1. The results of proximate and ultimate analysis showing the chemical properties of coal samples are given in section 4.4.2, while the result on mineralogical composition of the sample determined by means of XRD are discussed in section 4.4.3.

4.4.1 Physical and Petrographic Analysis

4.4.1.1 Physical Analysis: Gas Adsorption (BET Method)

The D-R and BET surface area were determined from carbon dioxide adsorption isotherms measured at 273 K (Table 15). The monolayer capacity was determined using the D-R method. This method was found to be more suitable compared to the BET method because it is based on the adsorption of carbon dioxide; hence it is expected to give results that relate well with the adsorption measurements since the adsorbate is the same.

Table 15: Surface area results that includes monolayer capacity, micropore surface area and pore volume for samples 1- 5

Sample ID	**Monolayer Capacity cm^3 g $^{-1}$**	**Micropore Surface Area m^2. g $^{-1}$ (D-R)**	**Micropore Surface Area m^2. g $^{-1}$ (BET)**	**Maximum Pore Volume (cm^3 g $^{-1}$)**
1	34.47	157.48	103.69	0.033
2	22.58	103.15	67.29	0.022
3	34.08	155.66	99.26	0.033
4	27.81	127.02	83.76	0.027
5	26.15	119.44	80.54	0.025

D-R Represents: Dubinin Radushkevich method; BET Represents: Brunauer-Emmett-Teller method

The results of the adsorption measurements are presented in Table 15. This results show distinct differences in the adsorption capacities and micropore surface area of the samples. Sample 2 has the lowest adsorption capacity value (22.58 cm^3 g $^{-1}$) and micropore surface area (D-R 103 m^2. g^{-1} and BET 67.29 m^2. g $^{-1}$). Surface area determined by D-R method is much greater than the surface area determined by BET method. For the maximum pore volume, samples show minor differences in their values though sample 2 is found to have the lowest pore volume value at 0.022 cm^3 g $^{-1}$.

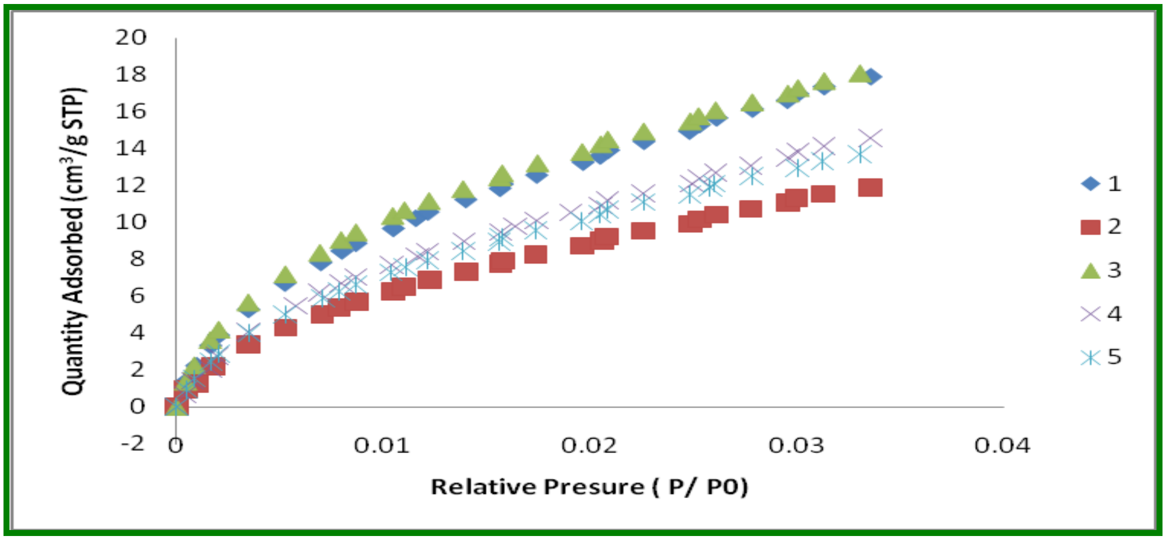

Figure 13: Illustrating low pressure carbon dioxide isotherms for coal 1 – 5.

Low pressure carbon dioxide adsorption isotherms of coal samples are presented in Figure 13. The isotherms show similar adsorption capacities that correspond to Type I BET classification isotherm which is typical of microporous solids (Brunauer *et al.,* 1938). At low pressures the coal samples began to adsorb CO_2. As the pressure increases the adsorption capacity of the coal samples increases. Sample 1, 3 and 4 show to have a higher adsorption capacity as compared to samples 2 and 5. This is because sample 1,3 and 4 have high surface area compared to sample 2 and 5 which have the lowest surface area (as shown in table 15). Coal properties in Table 7 do not include surface area and gas adsorption capacity due to lack of information in literature. Surface area and gas adsorption analysis uses particle sizes which does not simulate condition prevailing on the underground coal layer to give an idea of the surface area and gas adsorption mechanism of coal.

4.4.1.2 Petrographic Analysis

The petrographic analysis results are presented and discussed in this section. These include the results on the vitrinite reflectance and maceral analysis.

4.4.1.2 (a) Vitrinite reflectance analysis

The results for the random vitrinite reflectance measurements, along with the standard deviations are presented in Table 16. The vitrinite reflectance histograms are presented in Appendix C.

Table 16: Random vitrinite reflectance

Sample ID	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
RoVmr%	0.62	0.58	0.68	0.61	0.55
δ	0.055	0.081	0.056	0.040	0.054

RoVmr%: Mean random reflectance, δ: Standard deviation.

The samples show no significant difference in their random vitrinite reflectance. Samples 1, 3 and 4 are ranked according ranking classes in Falcon and Snyman (1986) as medium rank C bituminous coals with the random vitrinite reflectance of greater than 0.60%. Samples 2 and 5 are ranked medium rank D bituminous coal because their random vitrinite reflectance is below 0.60 %. The standard deviation of all coal samples is below 0.1 indicating single coals with no heat affect. The rank difference confirms the adsorption behavior of the coal samples as observed in Figure 13. The petrography results show the samples to be medium rank bituminous coals which are regarded suitable for UCG process and are in agreement with the coal properties in Table 7.

4.4.1.2 (b) Maceral Analysis

The results from maceral group analysis of coal are presented in Table 17. As outlined in Section 4.3.2.2, maceral analysis gives the organic component of coal sample which is the combustible part of coal.

Table 17: Maceral composition of coal (% Volume)

	Sample ID				
Maceral Group	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**
Vitrinite	48.4	23.8	22.8	43.8	27.8
Liptinite	11.2	8	4.2	4.2	16.6
Inertinite	31.2	51.4	53.6	20.4	48
Minerals Matter	9.2	16.8	19.4	31.6	7.6

In general South African coals contain lower vitrinite and higher inertinite content as compared to coals of the northern hemisphere. Liptinite makes up the smallest contribution to the macerals content of the coals. Sample 1 has the highest vitrinite content (48%) as compared to the other samples with sample 3 having less vitrinite content of 22.8%. Samples 3 and 4 contain relatively low content of liptinite of below 5% while sample 1 and 5 contain liptinite content of above 10%. Except for sample 1 and 4 all the other samples have inertinite content of above 40%. Sample 4 was found to have higher mineral matter content as compared to other samples. The maceral composition of these samples show that sample 1 and 4 will be preferred for gasification process as compared to sample 2, 3 and 5. Maceral composition in coal also plays a role in the gasification process, because it has an effect on the gasification reactivity of coal. Though not included in the selection criteria in Table 7, maceral composition of coal in UCG have effect on the reactivity of coal.

4.4.2 Chemical Analysis

The proximate and ultimate analyses were conducted to determine chemical component of the coal samples. According to Falcon and Ham (1988) proximate and ultimate analyses were used as major coal evaluation methods for industrial purposes.

4.4.2.1 Proximate Analysis:

As outlined in Section 4.2.4, proximate analysis gives out composition of coal based on inherent moisture, Ash content, volatile matter and fixed carbon by difference. The results from proximate analysis are presented in Table18.

Table 18: Proximate analysis

	Proximate Analysis (As received basis (Weight %))				
Chemical Composition	**1**	**2**	**3**	**4**	**5**
Inherent Moisture (%)	4.7	3.4	4.6	3.5	3.4
Ash (%)	16.5	34.2	22.4	37.5	22.9
Volatile Matter (%)	31.3	24.1	23.3	25.3	30.4
Fixed Carbon (%)	47.6	38.3	49.6	33.6	43.2

The moisture content of these coals varies from 3.4 to 4.7 % (as received base) while the ash content in a range of 16.5 to 37.5 %. The volatile matter concentration ranges from 23.3 to 31.3 %

(as received base). Fixed carbon varies from 33.6 to 49.6 %. The samples show no significant differences on their inherent moisture contents, whilst the samples show a great difference of about 21% on their ash contents. The volatile matter and ash content of the samples used in this study as determined by means of proximate analysis were found to be in agreement with the properties in Table 7 except the moisture content that was found to be lower.

4.4.2.2 Ultimate Analysis:

As stated in Section 4.2.4, ultimate analysis is used for the determination of elemental composition of coal that includes the amount carbon, hydrogen, oxygen, nitrogen and sulphur contained in coal (Falcon and Ham, 1988). The results from ultimate analysis of coal are presented in Table 19.

Table 19: Ultimate analysis results of coal sample 1 - 5

Ultimate Analysis				
Sample ID	**Carbon (%)**	**Hydrogen (%)**	**Oxygen (%) [a]**	**Nitrogen (%)**
1	62.50	4.65	30.9	1.95
2	48.04	3.64	47.01	1.31
3	57.81	3.71	36.79	1.69
4	41.74	3.40	53.65	1.21
5	57.49	4.29	36.64	1.58

a: Calculated by difference without the value of sulphur

In the ultimate analysis results, it was found that the organic composition of the coal does not vary significantly. Sample 1 has the highest carbon, hydrogen and nitrogen content and lowest oxygen content as compared to the other samples. Whilst sample 4 has shown to have the highest oxygen content with the lowest nitrogen and carbon content as compared to the other samples. Ultimate analysis is useful in determining the varying contents of organic element in coal which in turn gives an idea of coal maturity. Low rank coals contain high oxygen and hydrogen content whilst high rank coals generally contain high carbon content (Juntgen, 1987). The elemental composition of coal does not form part of the selection criteria in Table 7. Hence it is not discussed in details.

4.4.3 Mineral Analysis: X-Ray Diffraction

The XRD analysis gives the crystalline minerals in coal. Figure 14 show the inorganic crystalline phase detected in the coal samples (1 - 5). Graphite show the crystalline pure carbon content of the samples. The results indicate that the coal samples are largely dominated by kaolinite which seems to be forming almost half of the crystalline mineral material.

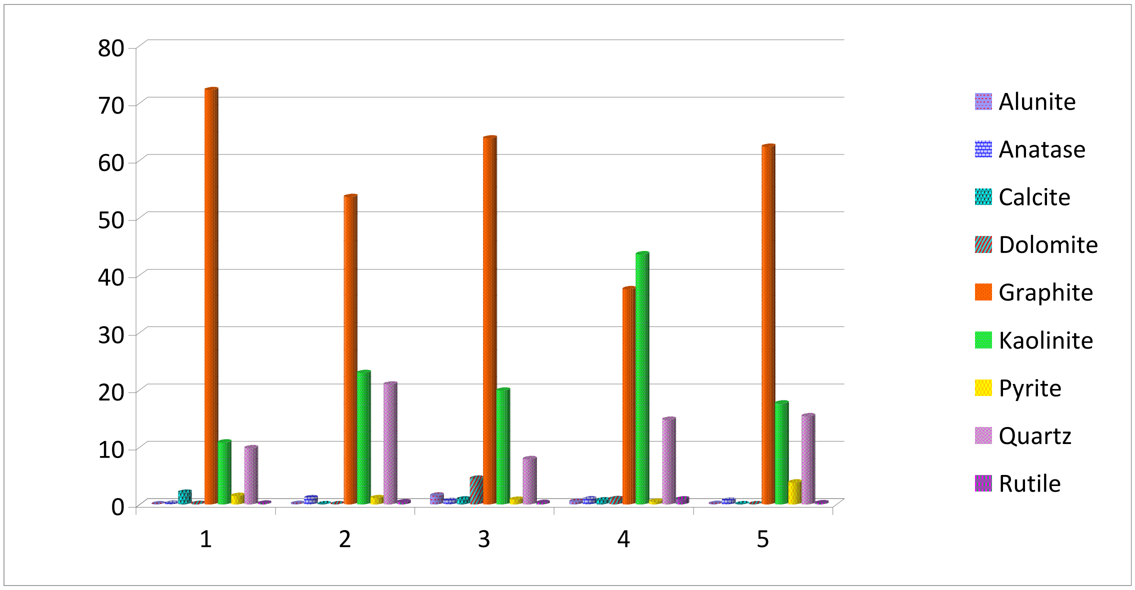

Figure 14: Mineral composition of coal from X-Ray Diffraction analysis

The other significant mineral groups include quartz and pyrite, with minor contributions from minerals such as anatase, alunite, calcite and dolomite. According to Pinetown *et al*., (2007) mineral matter (inorganic) dominating South African coal are clay minerals mainly kaolinite and illite followed by quartz, carbonates, dolomite and siderite. Mineral matter composition of coal is not included as a selection criterion for UCG coals, but its importance in UCG lies in giving an insight into the coal formation environment. Some mineral matter in coal acts as catalysts thus improving reaction kinetics of coal during gasification process.

4.5 Summary and Conclusion

Fundamental components of coal and its properties play a major role in coal utilisation. In most cases the technological use of coal is influence by its chemical and physical make-up. In this chapter the importance of different coal properties in UCG process was discussed. Coal samples from two boreholes (BH1and BH2) of Highveld coalfield were used. Different techniques were used to characterise physical and chemical properties of these coals. This included coal petrography, BET, XRD, ultimate and proximate analyses. The results from petrography showed that the samples were of the same rank which is medium rank C and D bituminous with varying maceral and mineral content. From BET analysis results, it was found that the samples were mainly microporous material with an average monolayer capacity of 29.02 $cm^3.g^{-1}$. The mineral composition of coal was determined by means of XRD analysis; the results showed the coal samples to contain high kaolinite and quartz content. Proximate analysis results showed that the samples to contain high volatile matter and high ash content. Organic composition of coal samples was determined by means of ultimate analysis. Table 7, in Chapter Two highlighted the properties of coal that are regarded to be suitable for UCG process. The highlighted properties include coal rank, chemical composition in terms of ash content, volatile matter and moisture content. The coal characterisation results shows the samples to be of medium rank containing ash content of less than 60%,low moisture content. The properties of the coal samples fall within the suitable range for UCG process as per Table 7.

Chapter 5

Summary, Conclusions and Recommendations

In this chapter the general summary and conclusions of the study are discussed as well as the recommendations for the future. The conclusions are based on the key elements of the study which include the following: Criteria for UCG site selection, feasibility of wireline logging in UCG and coal properties for UCG Process.

5.1 Study Summary

An output of this study was to create a table containing criteria which can be used to select potential UCG sites in South Africa. A detailed literature analysis based on past UCG experiences all over the world was conducted in order to gain knowledge on UCG. Wireline logging methods were investigated for their feasibility in the evaluation of the subsurface condition of the UCG site under consideration. Coals from the Highveld coalfield were analysed using a variety of analytical techniques in order to determine coal properties suitable for UCG process. Geophysical data obtained by means of wireline logging of three boreholes (BH1-BH3) in the Highveld coalfield and coal properties data determined by the use of different characterisation techniques are compared with the data in Table 7, and were found to fall within the range of the suggested properties for UCG process. Thus the aims and objectives of this project have been met, and the research questions presented in Chapter 1 (Section 1.3) have been addressed.

5.2 Conclusion

The conclusions drawn from the study are discussed below:

1. Literature analysis on the past UCG trials reveals that natural factors play a decisive role on the selection of area suitable for UCG process. These factors include coal geology, physicochemical properties of coal and geological and geotechnical condition of the target area. For South African conditions, factors which can be used to determine potential UCG sites are based on the UCG experiences of Australia and Russia which are conducted on similar conditions. The factors which are taken into consideration for selection of South

African coals also include the coal geology, physicochemical properties of coal and the geology and geological condition.

In the case of coal geology, literature analysis allowed the following recommendations:- coal depth of over 100m, Coal seam thickness of greater than 1m, and dipping coal seam are mostly preferred. The geology as well as the geohydrological condition of the area under consideration have a major influence on the UCG process.

2. Wireline logging method was investigated for its feasibility in the evaluation of the subsurface condition of the target area. Three boreholes drilled in the Highveld coalfield were used to investigate wireline logging as a site evaluation tool. Different wireline probes were used to acquire different properties of the formation encountered in the borehole. Log profile obtained by means of wireline logging gives an insight into the condition prevailing underground. Thus wireline logging technique proved to be a useful tool for subsurface evaluation but limited to the vicinity of a borehole.

3. Literature analysis reveals that coal characterization is very important in UCG, because the nature of coal and its properties have significant influences on its behaviour during gasification. According to literature, the preferred coal properties for UCG include low rank, high volatile matter and non swelling coals. In this study different analytical techniques have been used to determine physical and chemical properties of five coals from Highveld coalfield and their suitability for UCG process. These include proximate and ultimate analysis, XRD, BET, and petrography analyses. From the petrographic results, the coals were found to be of the same rank (medium rank bituminous), inertinite rich, containing low vitrinite content and very low liptinite content. BET analysis showed the coals to be mostly composed of microporous materials, having different adsorption capacity. Chemically these coals were found to contain high ash content as well as high volatile matter and low moisture content. From the XRD analysis the coals were found to mostly contain kaolinite and quartz.

The results obtained from this study serve as an indication that the condition of the geological units in the Highveld coalfield as well as their coal properties fall within the range of the parameters considered suitable for UCG process shown in Table 7. Due to the fact that this study was limited to three boreholes and five coal samples from two of the available borehole, at this point the potential for UCG in Highveld coalfield cannot be clearly stated. The results show that there is a possibility for further investigation where several boreholes and coal samples are to be used.

5.3 Recommendations

The recommendations for the future study on UCG technology are suggested below:

1. South African coal quality and the geology vary across coalfields. Potential for UCG in South Africa should be investigated for each coalfield, especially those coalfields which are not largely exploited, for example the Waterberg and Limpopo coalfields because they occur at depth favouring UCG process.

2. Wireline logging method can be successfully used as a site evaluation technique since it is capable of revealing the subsurface nature of area under consideration. The combination of wireline logging and other geophysical techniques (e.g. seismic) is recommended, because is believed to provide a powerful technique for evaluation of the subsurface condition.

3. Literature reveals that coal properties are important criterion in UCG. Coal characterisation is conducted in order to understand the nature of coal and its properties, and to determine its suitability in the UCG process. In this study standard coal characterisation technique such as XRD, BET, petrography, ultimate and proximate analyses were used. It will be of great benefit to utilise advanced coal characterisation techniques to give more detailed coal properties.

Overall the study thus intended to formulate criteria for the selection of potential UCG sites in South Africa. This can contribute toward research and development of UCG technique in South Africa since it is regarded as a technology which is able to exploit the unminable coal resources.

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7. Appendices

Appendix A: Geophysical Logs

Wireline log profile for Borehole Number 1

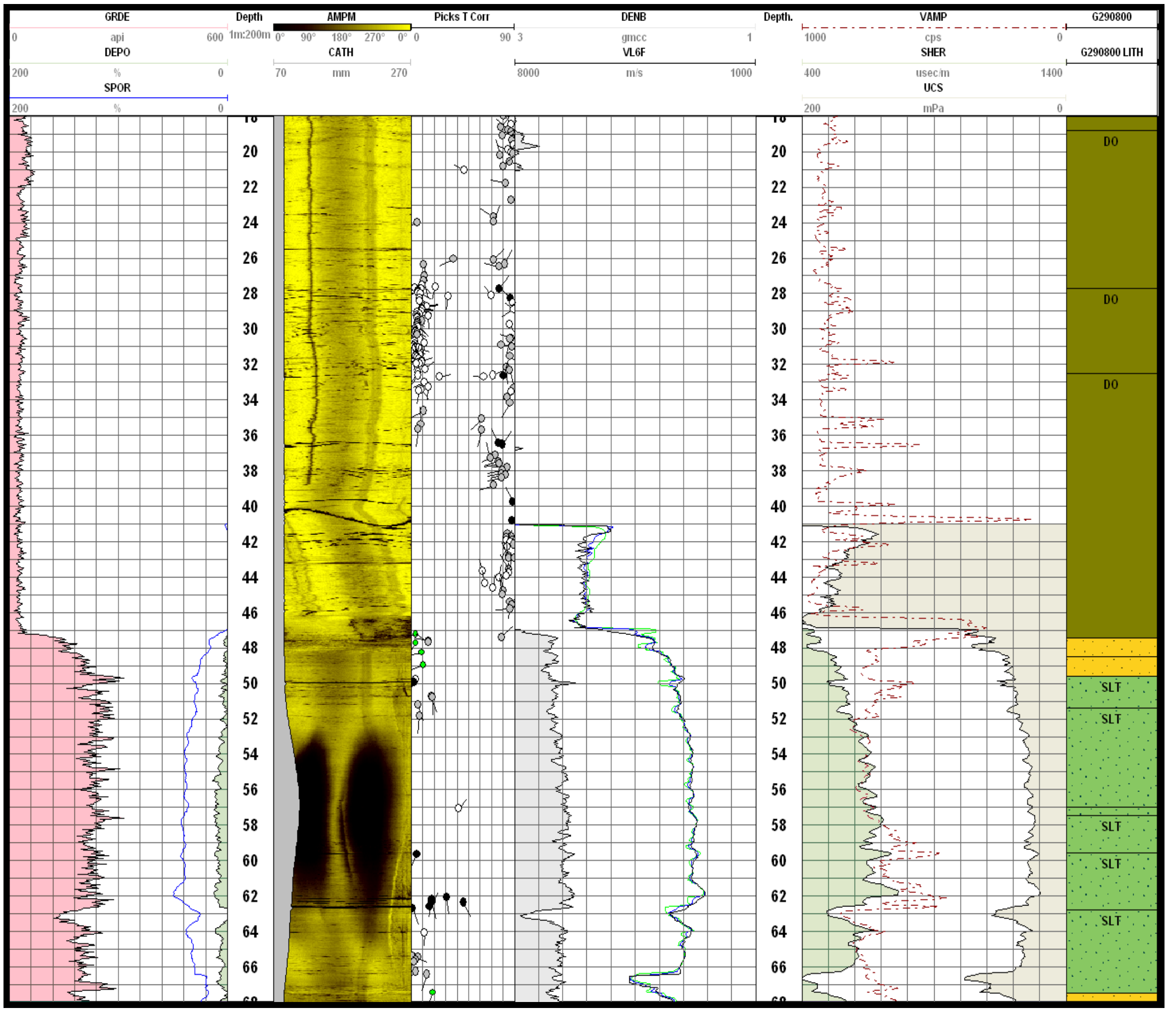

Figure A1: BH1 wireline log from 18m to 68m

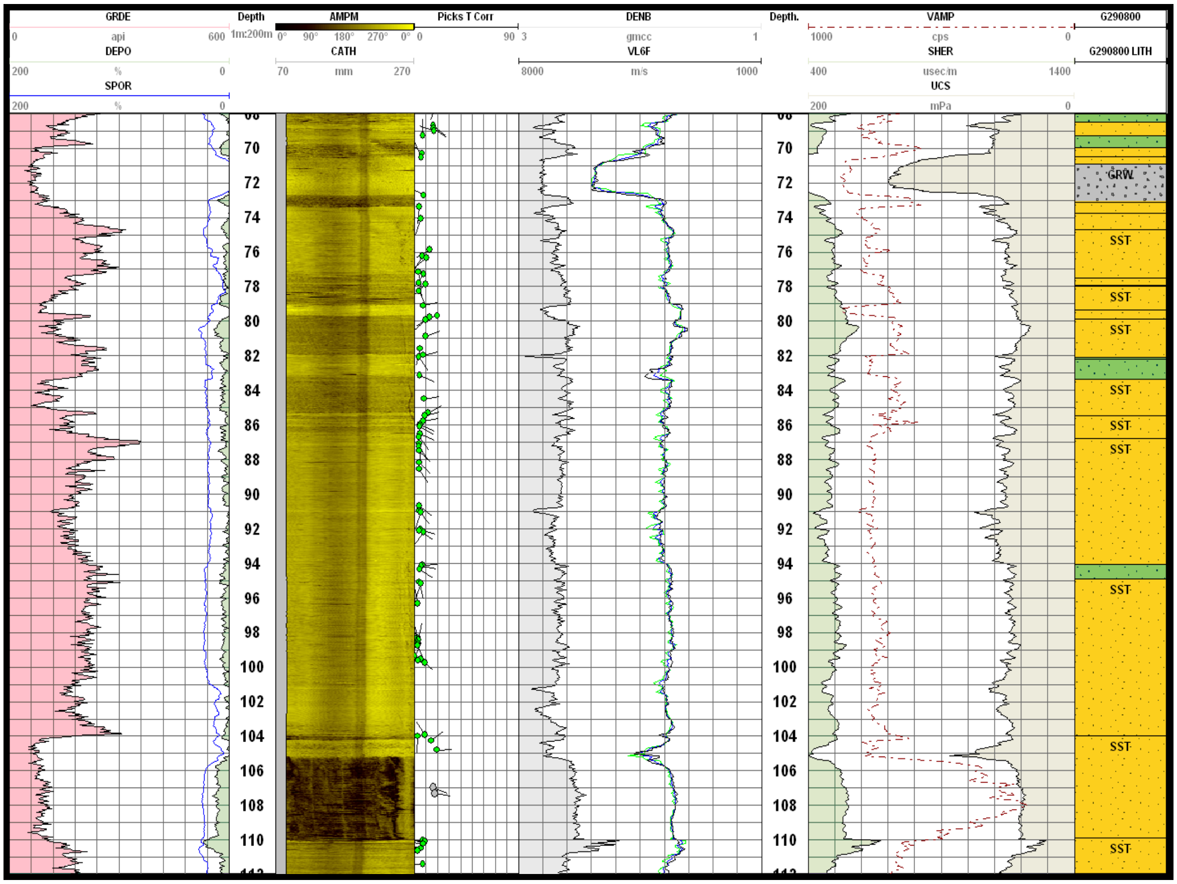

Figure A2: BH1 wireline log from 68m to 112m

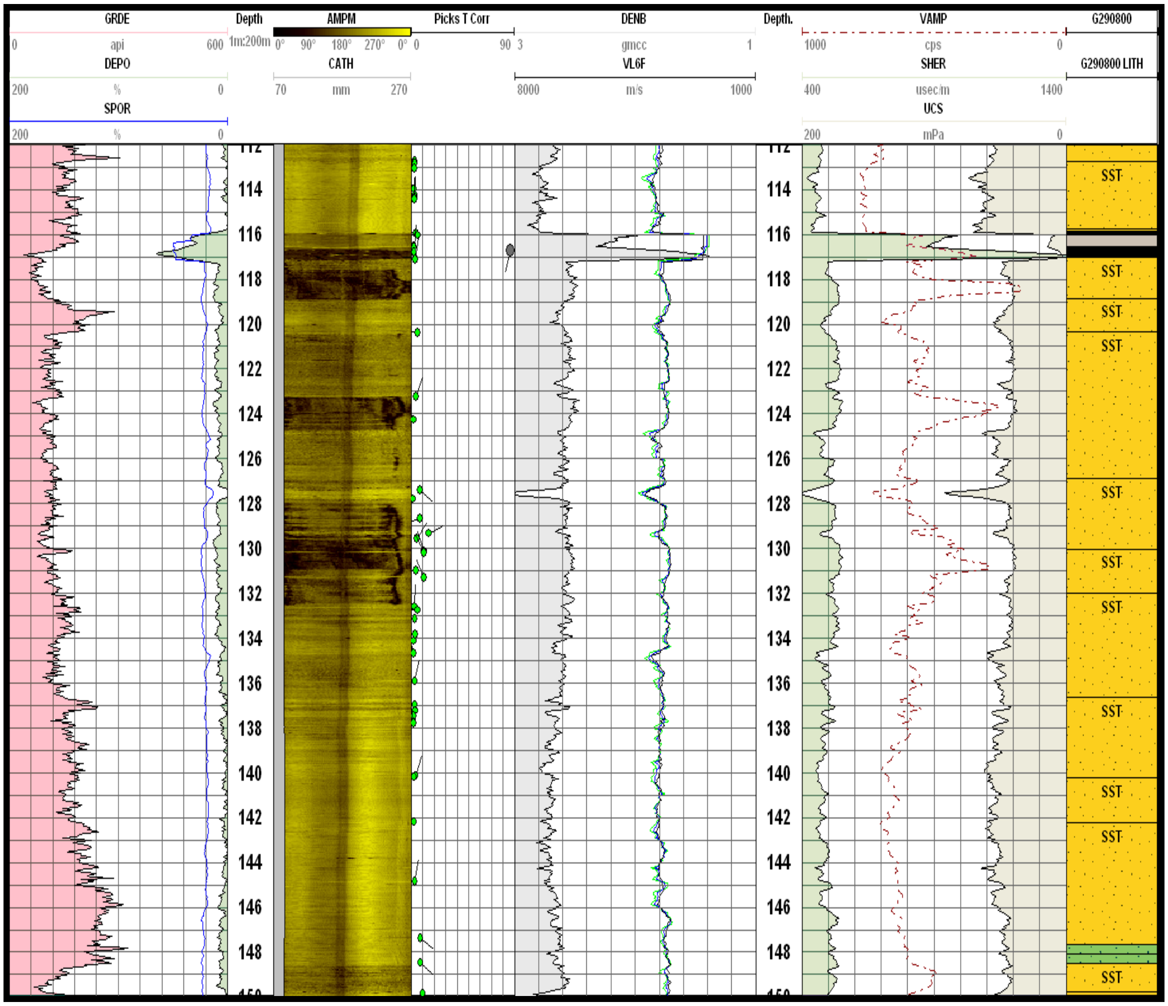

Figure A3: BH1 wireline log from 112m to 150m

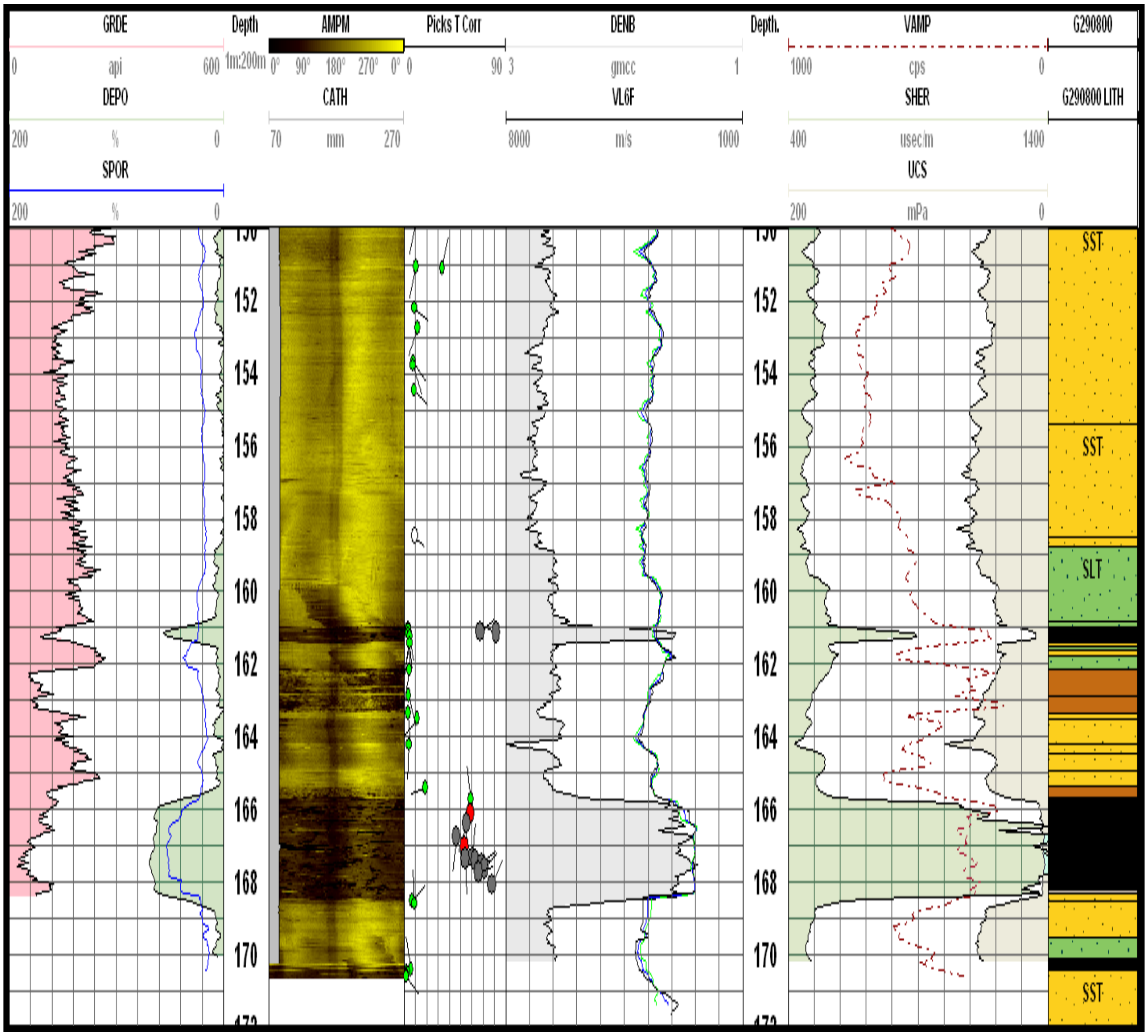

Figure A 4: BH1 wireline log from 150m to 172

Wireline log profile for Borehole Number 2

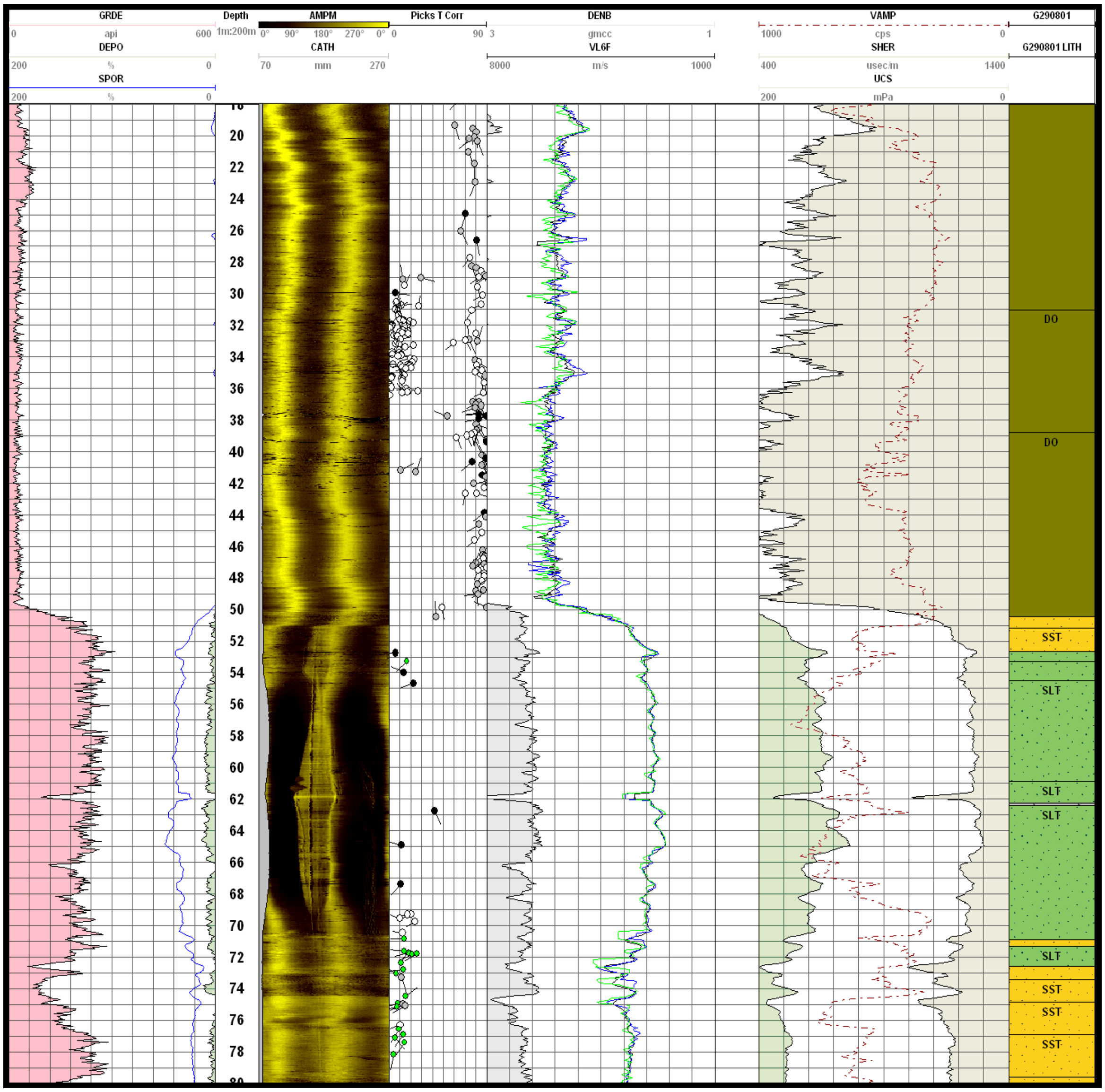

Figure A 5: BH2 wireline log from 18m to 80

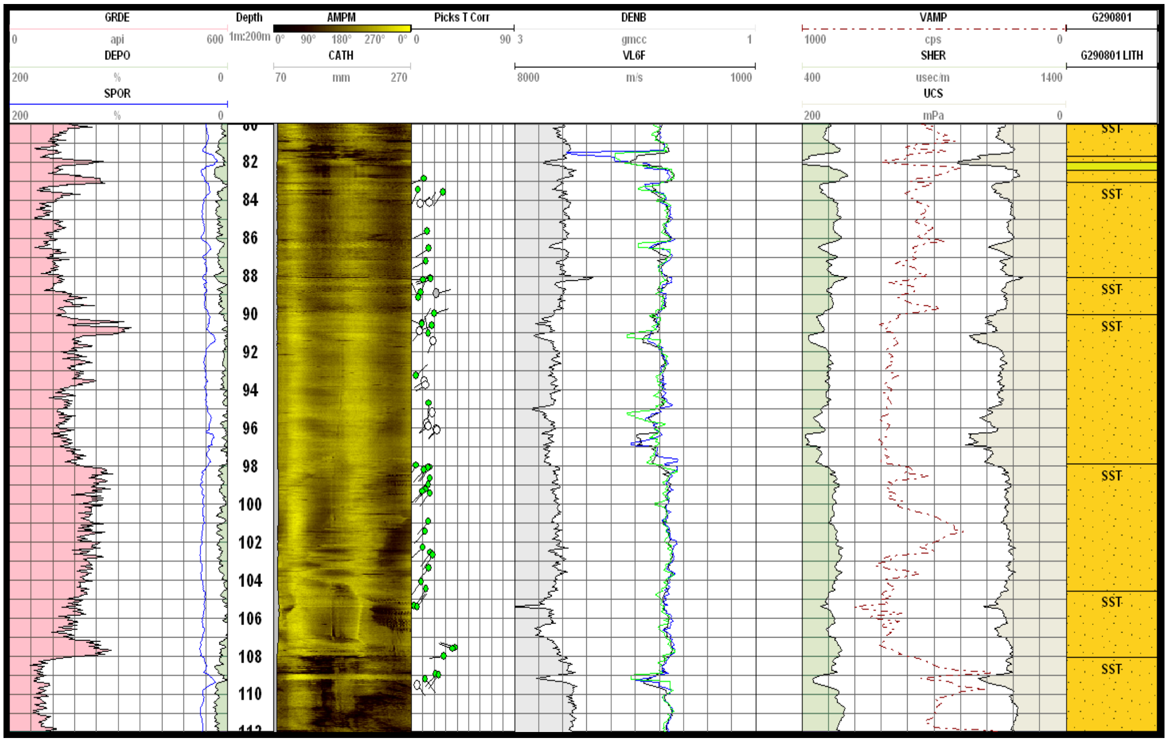

Figure A 6: BH2 wireline log from 80m to 112m

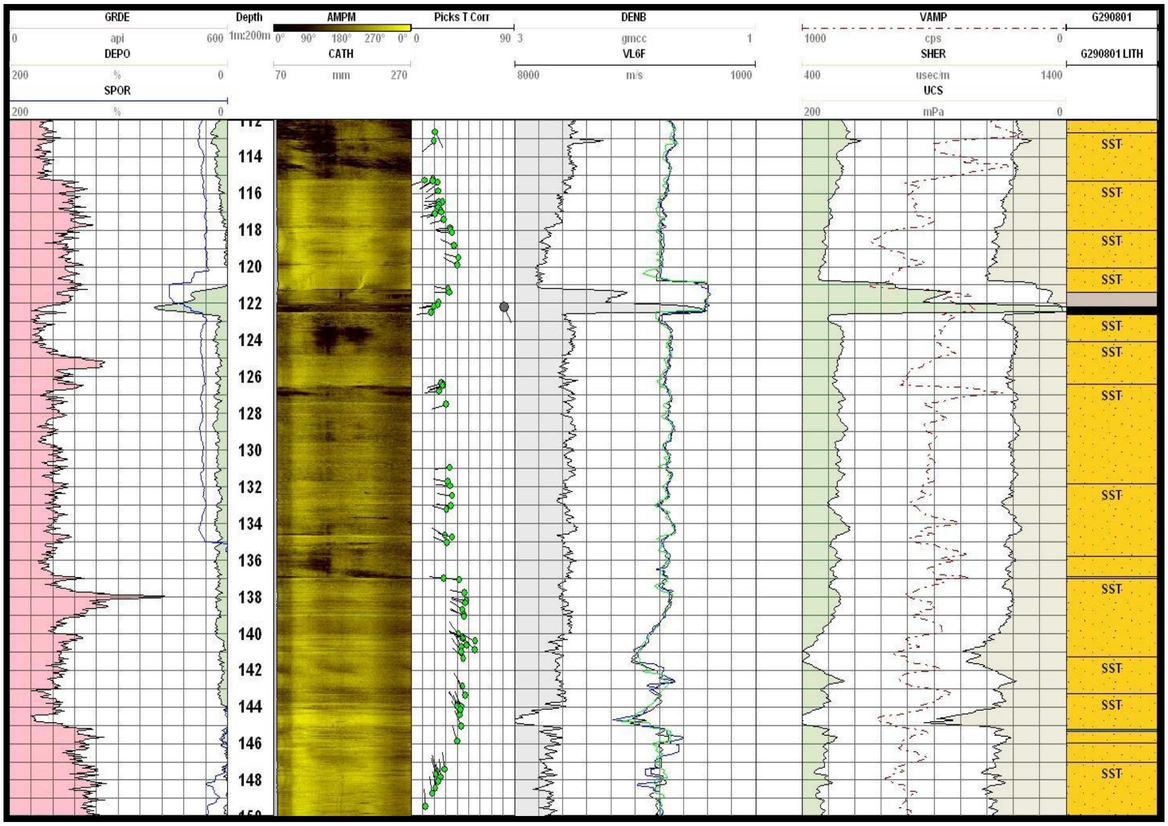

Figure A 7: BH2 wireline log from 112m to 150m

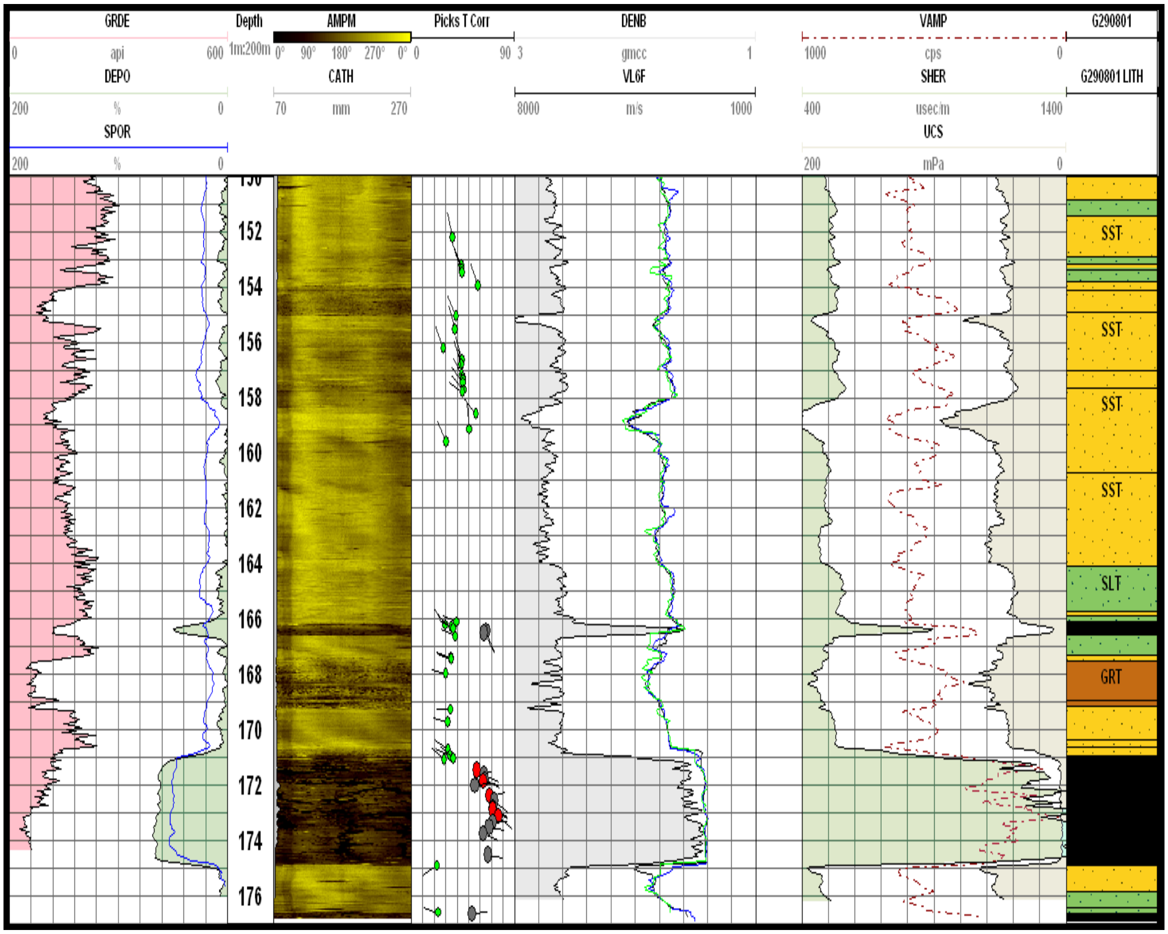

Figure A 8: BH2 wireline log from 150m to 170m

Wireline log profile for Borehole Number 3

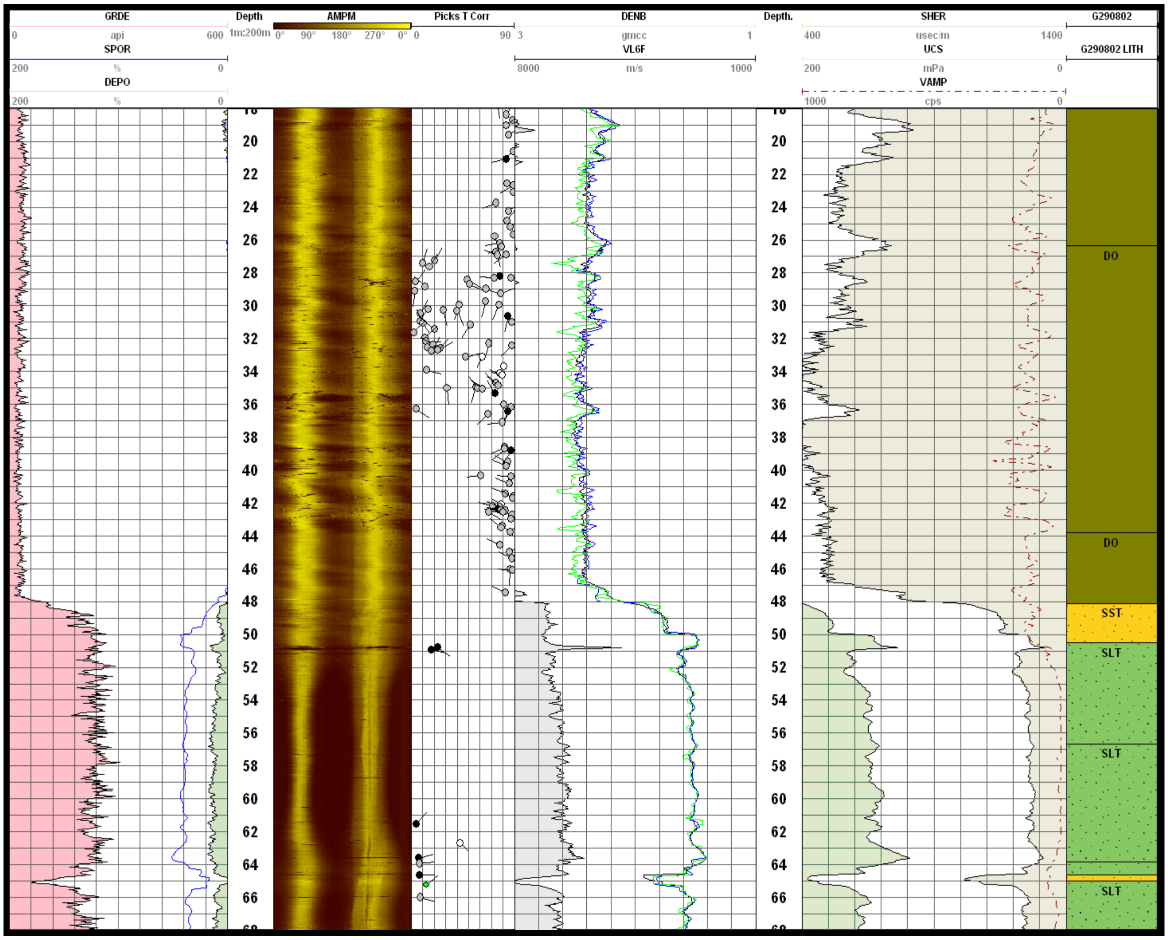

Figure A 9: BH3 wireline log from 18m to 68m

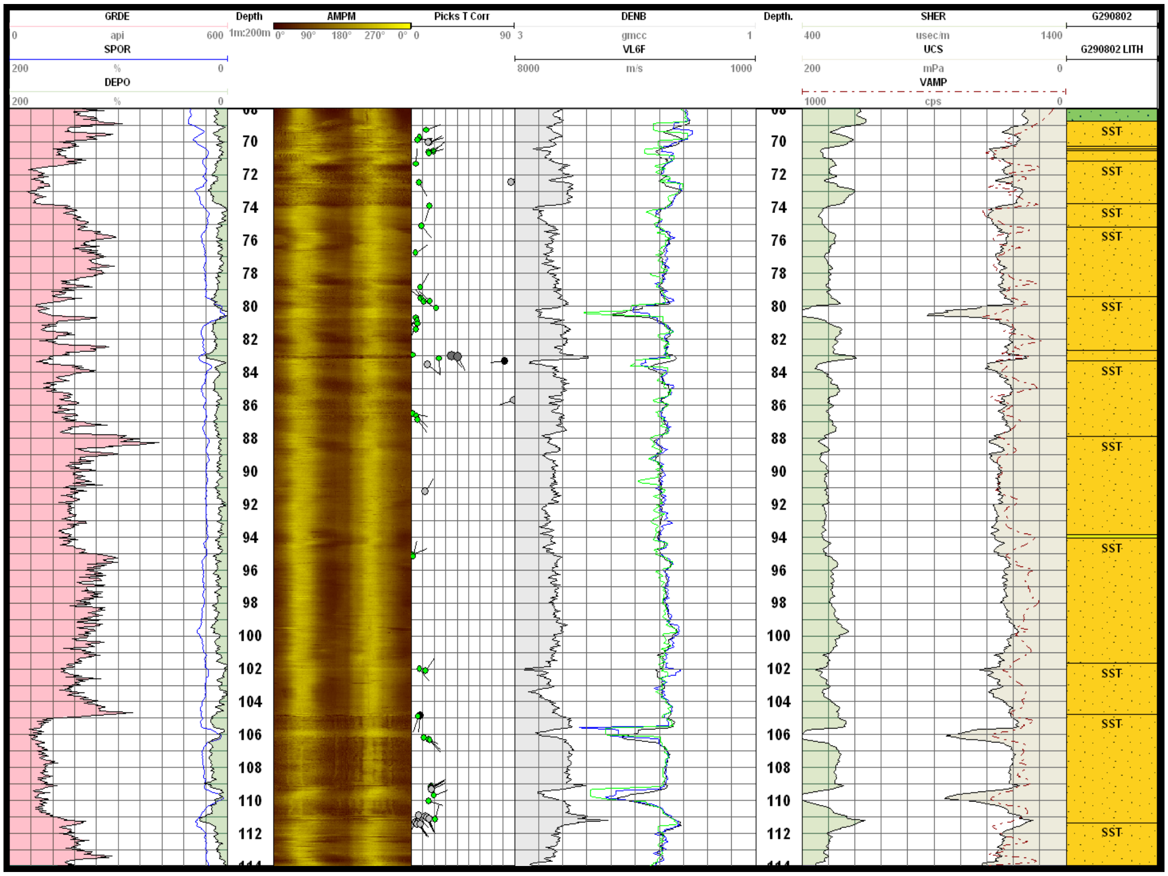

Figure A 10: BH3 wireline log from 68m to 114m

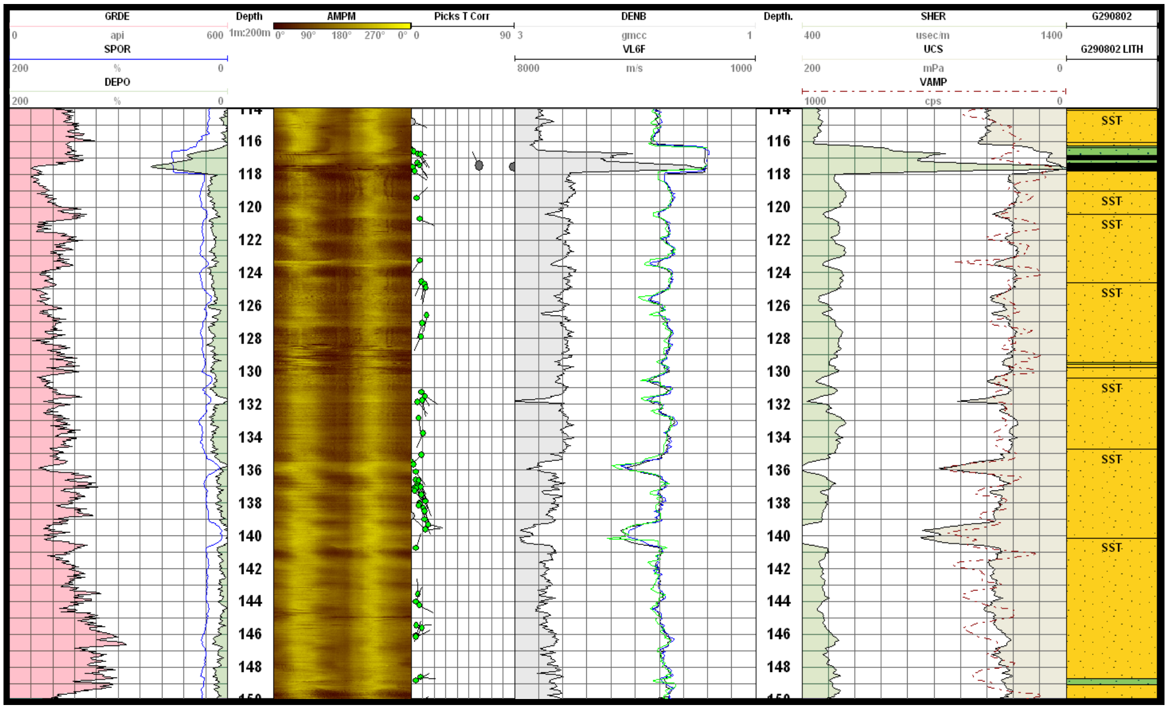

Figure A 11: BH3 wireline log from 114m to 150m

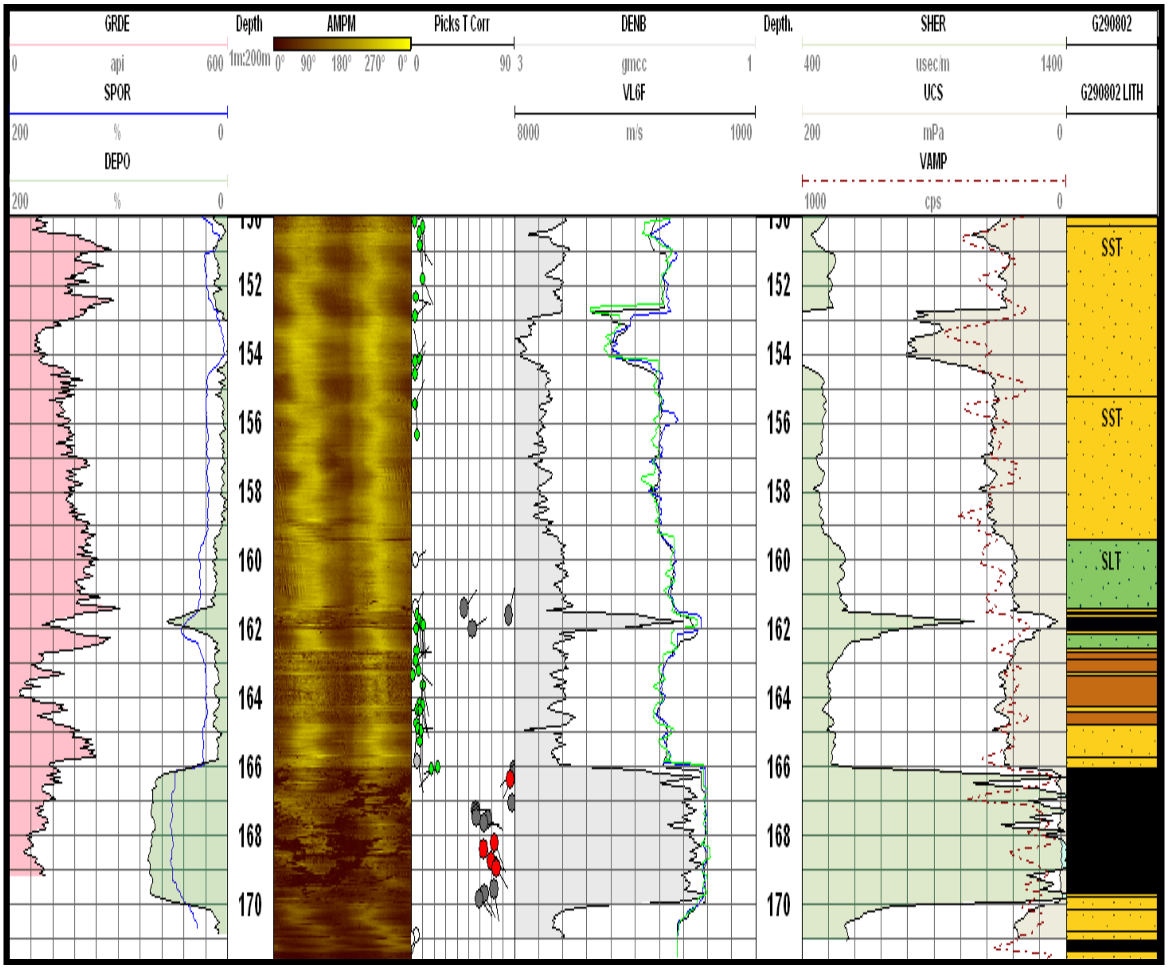

Figure A 12: BH3 wireline log from 150m to 171m

7.2 Appendix B: Mineralogical results: XRD

Table B1: Mineral composition of coal from X-Ray Diffraction analysis

X-Ray Diffraction analysis for crystalline minerals in coal samples (weight %)									
Sample ID	Alunite	Anatase	Calcite	Dolomite	Graphite	Kaolinite	Pyrite	Quartz	Rutile
1	0	0.15	2.02	0.09	72.26	10.77	1.44	9.79	0.12
2	0.09	1.06	0	0	53.60	22.92	1.09	20.91	0.35
3	1.50	0.58	0.86	4.47	63.84	19.85	0.81	7.87	0.22
4	0.44	0.87	0.66	0.90	37.50	43.60	0.46	14.76	0.85
5	0.08	0.65	0	0	62.36	17.58	3.80	15.34	0.18

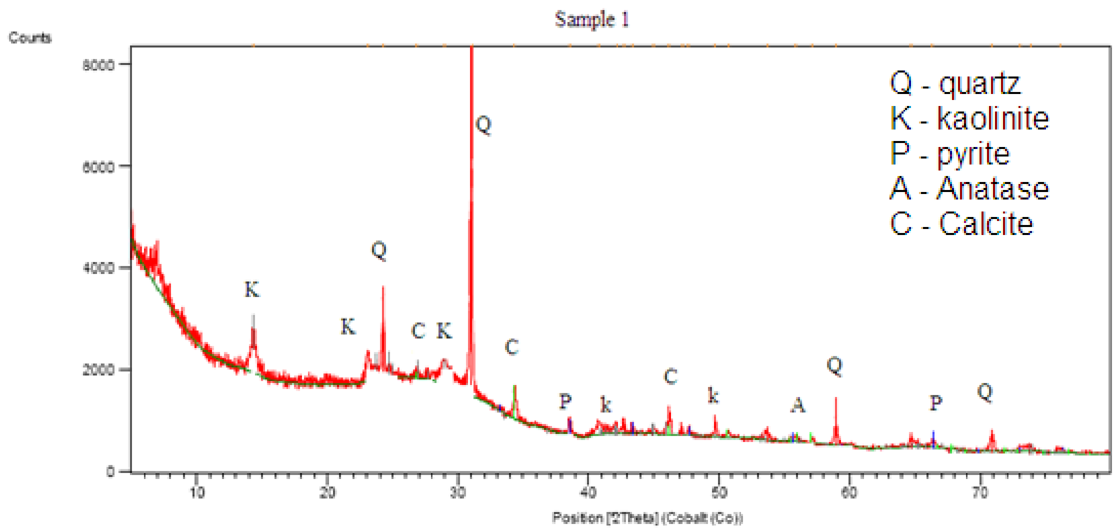

Figure B 1: XRD patterns for raw coal samples (1)

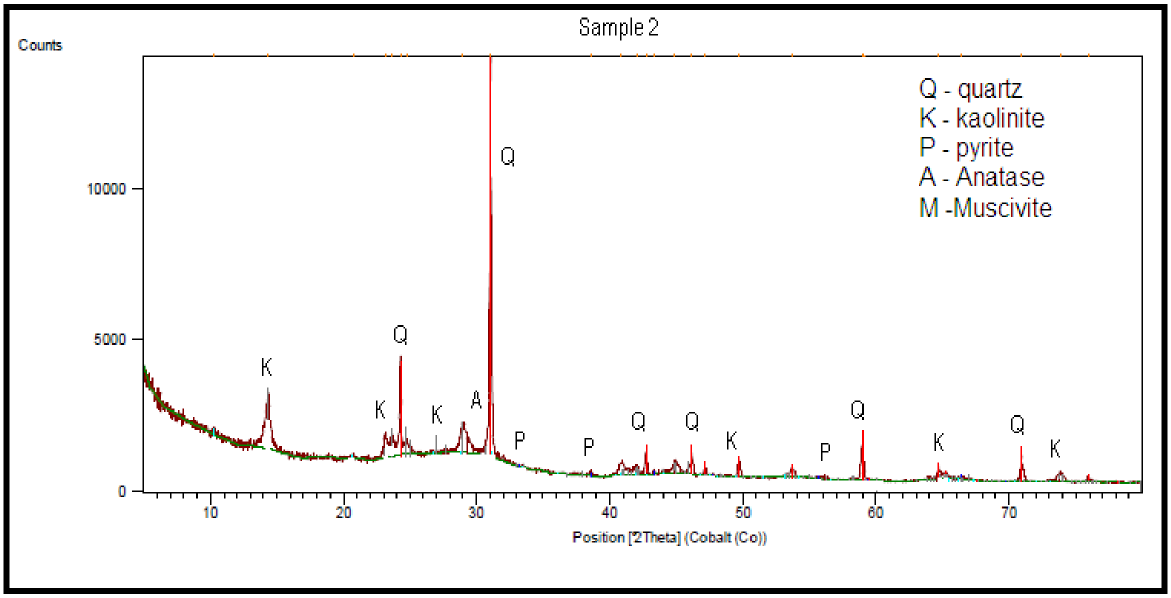

Figure B 2: XRD patterns for raw coal samples (2)

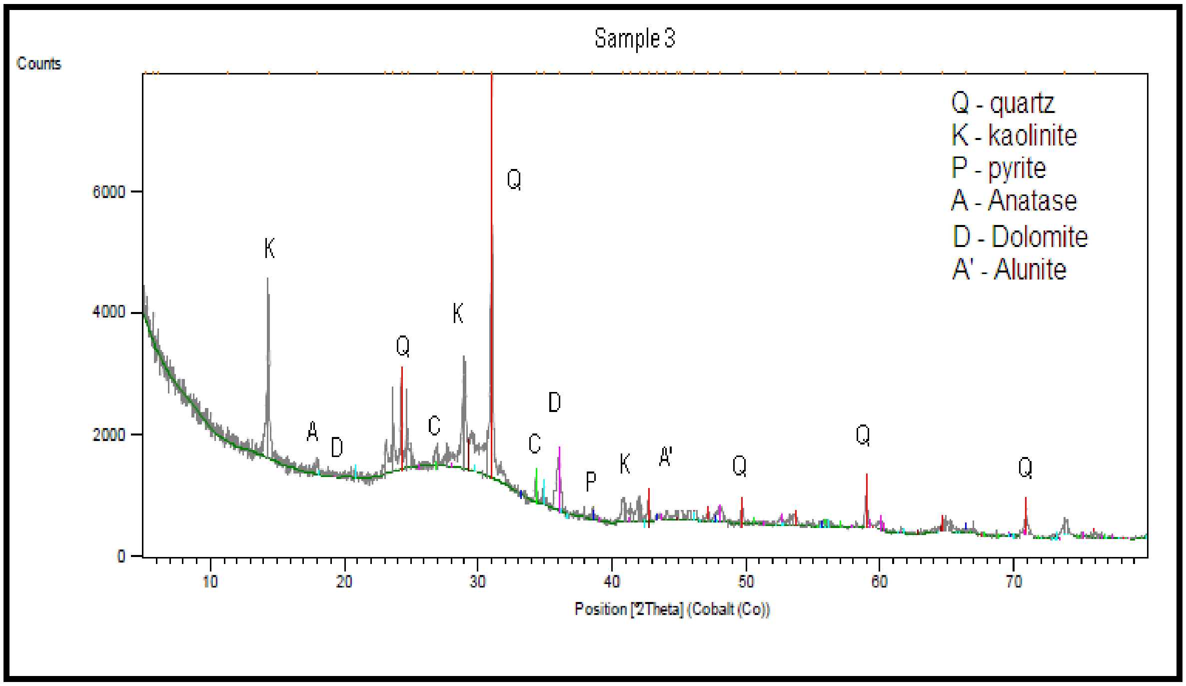

Figure B 3: XRD patterns for raw coal samples (3)

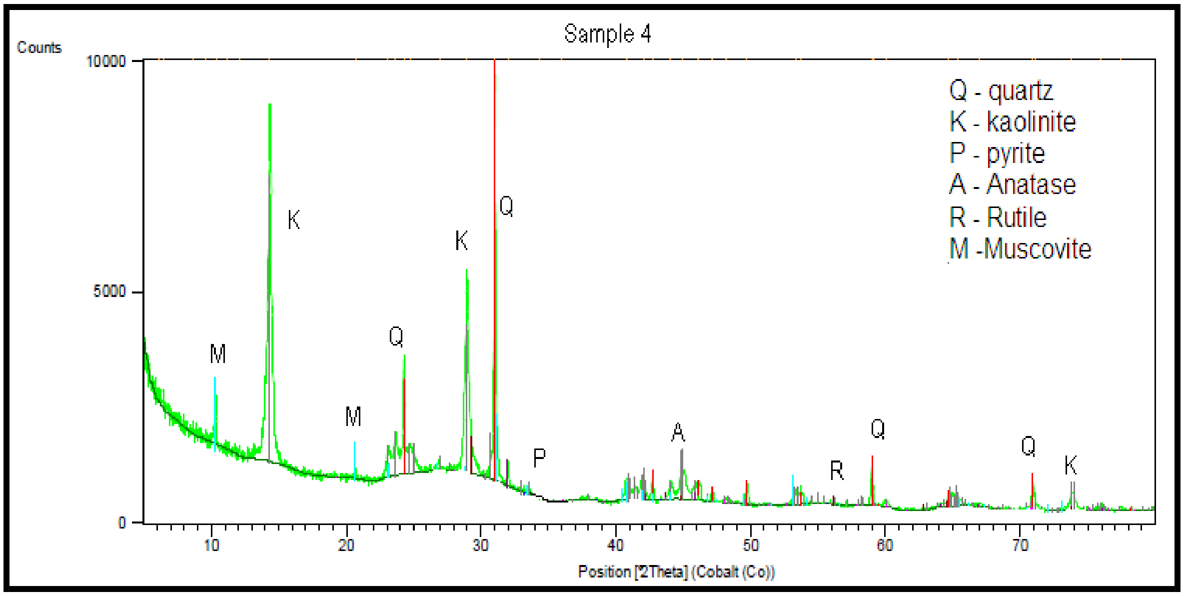

Figure B 4: XRD patterns for raw coal samples (4)

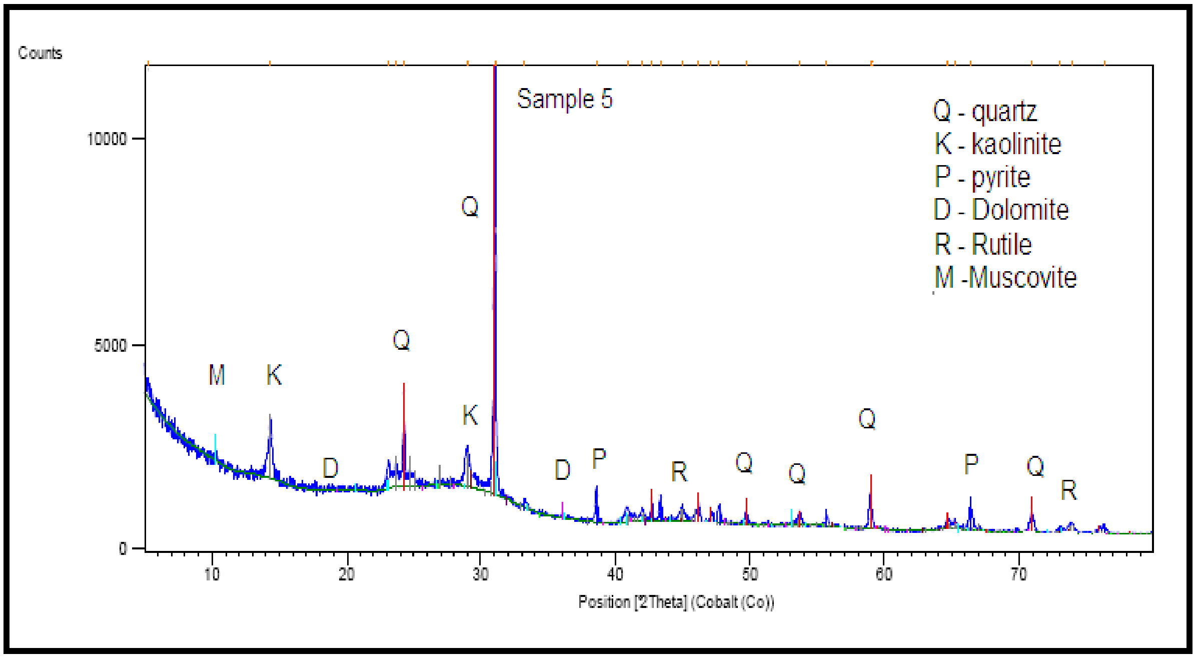

Figure B 5: XRD patterns for raw coal samples (5)

7.3 Appendix C: Petrography results

Table C 1: Petrography results that includes maceral analysis, vitrinite reflectance and mineral content

PETROGRAPHIC ANALYSIS						
MACERAL GROUP	MACERAL SUB GROUP	SAMPLE NUMBER / ID				
		SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	SAMPLE 5
VITRINITE	PSEUDOVITRINITE	45.6	23.6	22.8	43.0	27.8
	OTHER	2.8	0.2		0.8	
% TOTAL VITRINITE		48.4	23.8	22.8	43.8	27.8
LIPTINITE	S/R/C	11.2	6.6	4	4.2	16.4
	ALGINITE		1.4	0.2	0.0	0.2
% TOTAL LIPTINITE		11.2	8.0	4.2	4.2	16.6
INERTINITE	RSF	5.6	1	5.6	1	2
	ISF	12.4	11.4	19	10	10.8
	F / SEC	6	0.8	1.2	3.6	1.2
	MIC	0	0.2	1.4	0	0.4
	RINT	0.8	0.8	2	1	2.6
	IINT	6.4	37.2	24.4	4.8	31
% TOTAL INERTINITE		31.2	51.4	53.6	20.4	48
% TOTAL REACTIVE MACERALS		66.0	33.6	34.6	50.0	49
MINERAL MATTER	% TOTAL MINERAL MATTER	9.2	16.8	19.4	31.6	7.6

TABLE C 2: Rank Determination

TABLE 2: RANK DETERMINATION (ISO 7404 - 5, 1994)

Parameters		SAMPLE NUMBER / ID				
		1	2	3	4	5
RoVmr%	RoVmr%	0.62	0.58	0.68	0.61	0.55
Standard deviation		0.055	0.081	0.056	0.04	0.054
Range	low	0.49	0.425	0.555	0.518	0.443
	high	0.762	0.786	0.879	0.696	0.767
RANK CATEGORY		Medium Rank C Bituminous	Medium Rank D Bituminous	Medium Rank C Bituminous	Medium Rank C Bituminous	Medium Rank D Bituminous

Reflectance Measurements Histograms

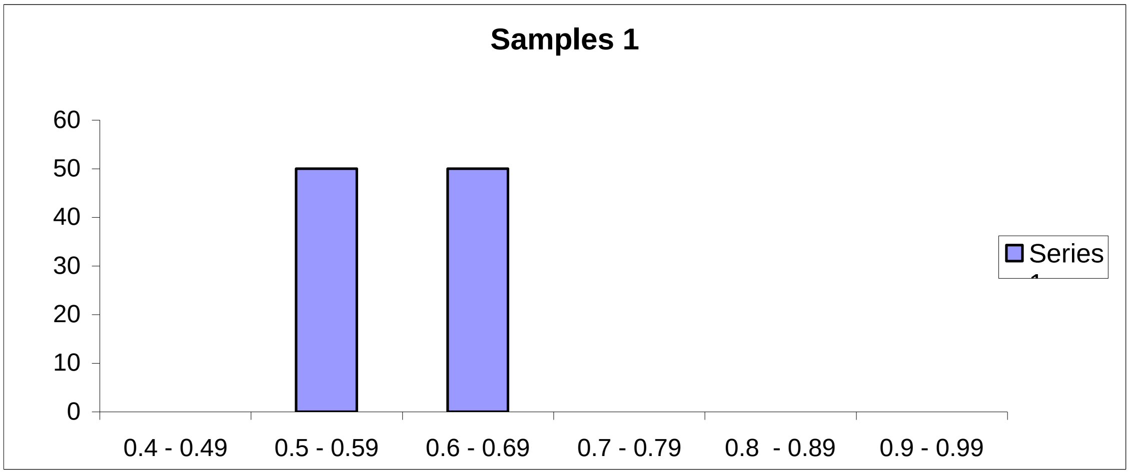

Figure C 1: Reflectance measurements histogram for sample 1

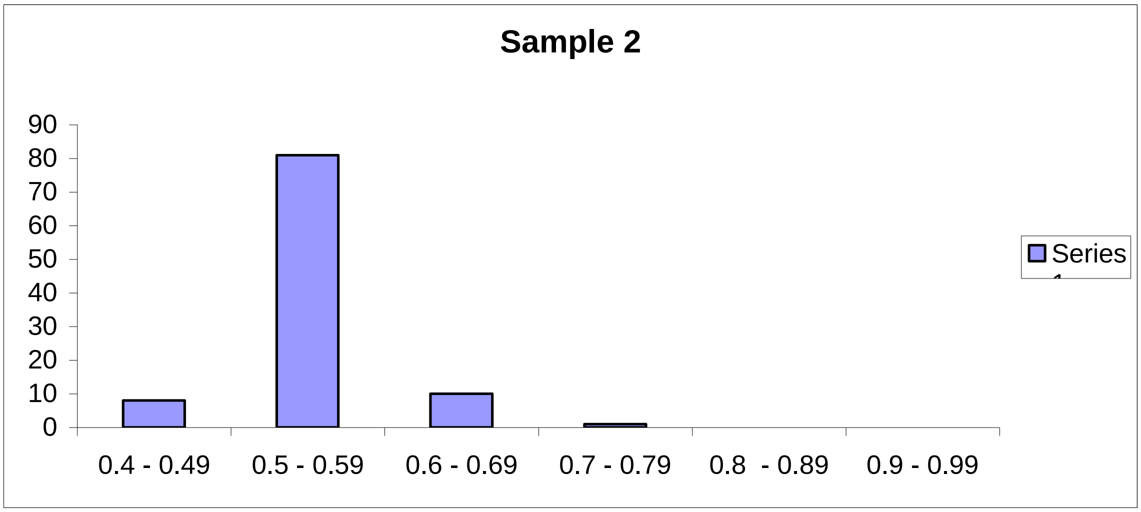

Figure C 2: Reflectance measurements histogram for sample 2

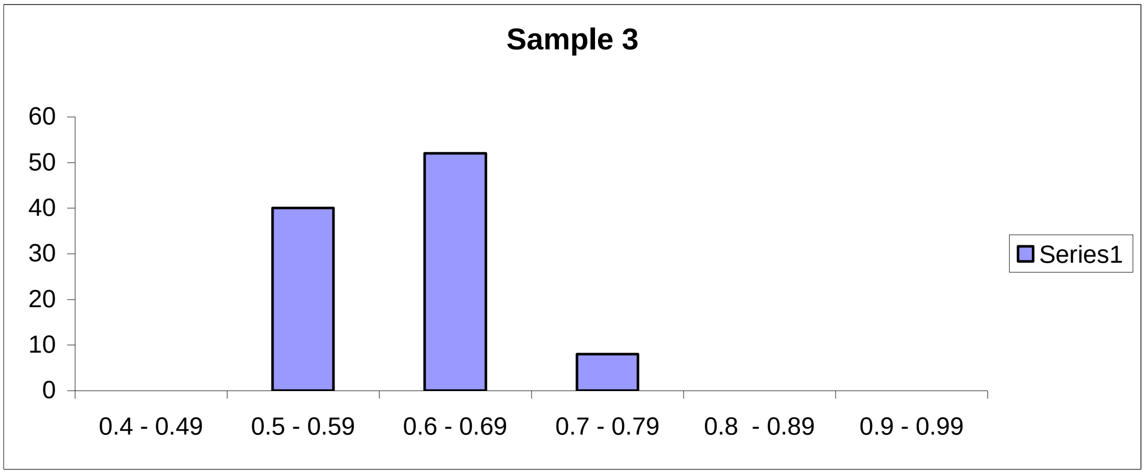

Figure C 3: Reflectance measurements histogram for sample 3

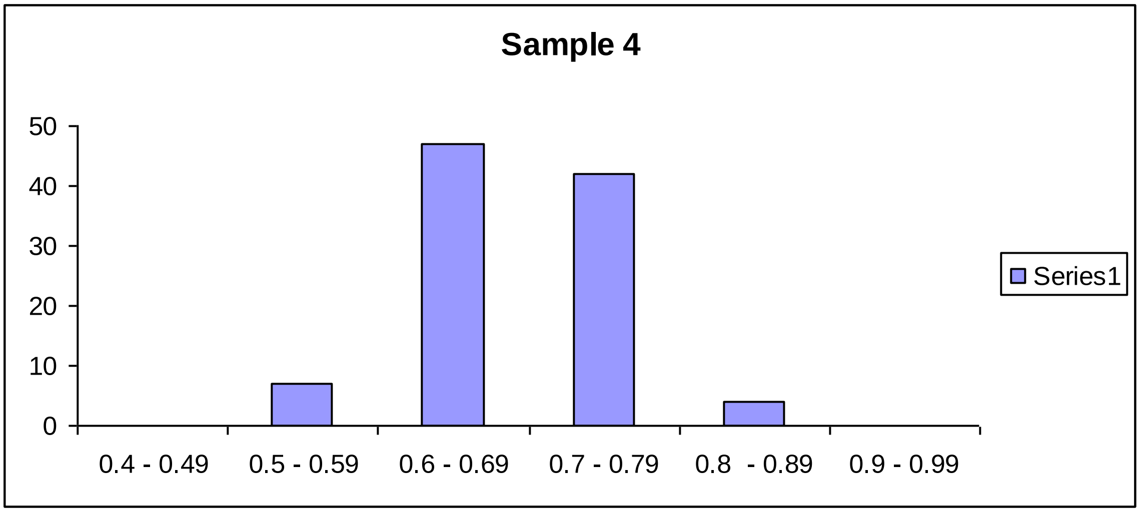

Figure C 4: Reflectance measurements histogram for sample 4

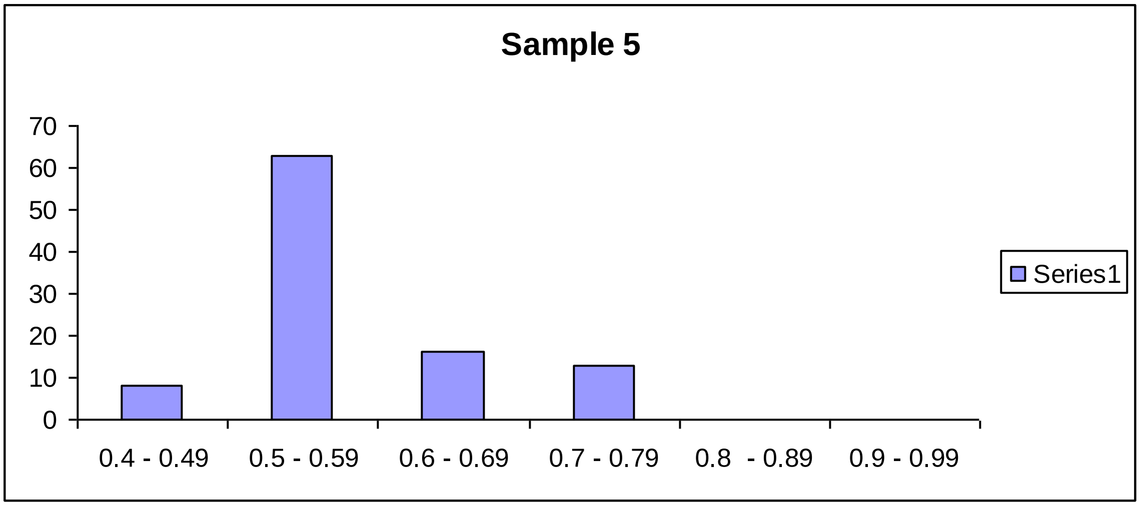

Figure C 5: Reflectance measurements histogram for sample 5