A large scale investigation into changes in coal quality caused by dolerite dykes in Secunda, South Africa- implications for the use of proximate analysis on a working mine

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Highlights

- Metamorphic aureoles vary greatly from dolerite to dolerite, and along strike.
- The metamorphic effect of dolerites is a combination of metamorphic systems.
- The strict application of dimension-based metamorphic effect may be incorrect.
- Proximate analysis should be used with caution when defining metamorphic effects.

ABSTRACT

The coalfields of South Africa contain numerous dolerite intrusions, which affected the quality of the surrounding coal through thermal processes, commonly believed to be controlled by the size of the magmatic body. Data gathered from a working coalfield in Secunda, South Africa, suggest that the relationship between intrusive sills and coal is complex and factors other than intrusion width must be considered in relation to the contact metamorphic effect. The study area contains multiple dolerite intrusions of Karoo age, of which three intrusions occur as sills intruded close to the main coal seam of the. A large database (>8000 boreholes) of coal quality data was used to investigate the presence or absence of a change in coal quality relative to dolerite proximity. Reduction in coal quality was defined using three proximate analysis values, namely the ash, volatile content and dry ash free volatile (DAFV) as defined in the coal industry. The resultant investigation showed no correlation between the position and thickness of the dolerites, and changes in coal quality as measured by proximate analysis. In the absence of a linear relationship between coal quality and dolerite proximity, two processes are proposed to explain the absence of the contact metamorphic effects expected from previous studies. Firstly dolerite emplacement dynamics may influence the size of the metamorphic aureole produced by an intrusion, invalidating intrusion size as a measure of thermal output. Secondly, hydrothermal fluids mobilised by the dolerite intrusions, either from the country rock or the intrusion itself may percolate through the coal and act as the metamorphic agent responsible for changing coal quality, by dissolving the volatile and semi-volatile components of the coal and transporting them to other locations. These two processes are sufficient to explain the lack of a clear "metamorphic effect" related to the dolerite intrusions. However, the perceived lack of a clear correlation between the coal quality parameters and the metamorphic effects associated with dolerite intrusion may also reflect the inadequacies of proximate analysis techniques in quantifying geological processes within the coal.

Keywords: coal metamorphism, devolatization, emplacement dynamics, metamorphic effect.

1. Introduction

Coal as a geological material has a unique response to thermodynamic changes in its environment, as metamorphic reactions have both an organic and inorganic dimension when they take place in response to changes in pressure and temperature. This coexistence of these vastly different chemical regimes has made it difficult to quantify the extent and dynamics of the metamorphism taking place within coal seams in contact metamorphic scenarios. To circumvent this complex situation, both industry and academia have used an approach which attempts to acknowledge both chemical regimes through the use of one test. This holistic approach first appeared in the late

1800s through authors such as Regault (1837) and Gruner and Bousquet (1911), with the goal of better defining the properties and origins of coal, both of which were still highly contested during that time period. The modern use of these techniques, now commonly known as proximate analysis, allows samples from different regions to be directly compared on the basis of a simple set of analytical data derived from thermogravimetric testing (Speight, 2007).

The major components of the proximate analysis technique describe the constituents of coal in terms of four main components:

- Moisture
- Volatiles
- Fixed carbon
- Ash

It is from these constituents that an estimation or approximation of the quality of the coal is deduced. Using this simple technique, it has become the norm in science and industry to calculate the effect of intrusive igneous bodies on coal seams, as it is accepted that the interaction of a high temperature body with the coal will alter the basic chemical constituents of the coal in a manner similar to partial or total combustion of coal. This relationship is shown in studies by authors such as Sadek and Herrell (1984), where various methodologies were applied to refine the proximate analysis technique. The alteration of physicochemical properties during the intrusion of the igneous body in close proximity to the coal is often termed devolatilization, based on the assumption that the heat from the igneous body causes a reaction of the organic constituents (or volatile matter) and alters or drives these components out of the coal completely.

Grade alteration in southern hemisphere coals is widely accepted as a devolatilization reaction caused by the effects of igneous intrusion, and the level of alteration has been directly connected to the size of the intrusive body with the contact thermal aureole being equated to ~1.5 times the width of the intrusion (Snyman and Barclay, 1988). The underlying assumption for this relationship is that the devolatilization or contact metamorphic effect of the igneous intrusion (at a specific temperature and composition) is thought to be directly related to the volume of the intrusive material which passes through the conduit at the time of emplacement, modified by the nature of the surrounding country rock material (Mussett and Khan, 2000**)**. Thus the greater the volume of magma passing through the dolerite conduit, the larger the metamorphic aureole that should be produced.

The application of this to the coal fields on the Highveld of South Africa is of great importance as the region is intersected by a vast and intricate dolerite dyke and sill complex forming part of the plumbing network of the Karoo Large Igneous Province (van Niekerk 1995; Riley *et al.,* 2006). The financial and safety implications related to the presence of these dolerite intrusions are dramatic; with diminishing coal resources and stricter environmental legislation it is imperative to improve the utilisation of these resources. This study was undertaken to quantitatively evaluate the effect of dolerite intrusions on coal in an effort to better understand the controlling factors and dynamics of the metamorphic relationship between the intrusions and the coal.

2. Approach and methodology

The approach taken in this study uses the accepted proximate analysis data as a representative quantification of the location and extent of coal quality deterioration or “devolatilization”. The specific region under investigation is hosted within the Karoo Supergroup in the province of Mpumalanga South Africa (figure 1 and 2). The area hosts several coal seams, but for the purpose of this study the focus was on the main mined seam, namely the C 4 Lower seam (C4L). The region is intruded by a complex network of dolerite dykes and sills which have been temporally and geochemically linked to the Karoo flood basalts (Jourdan *et al.*, 2004). The region hosts three main dolerite sill systems which have been given the codes DO4, DO8 and DO10, in accordance with terminology used in the local mines. The mineralogy and chemistry of these dolerites have been previously shown to have little variation, with discrimination between sills based solely on textural variations and generalised stratigraphic position (Marsh and Eales, 1984 and Van Niekerk, 1995). Figure 3 displays the basic stratigraphy of the region and the stratigraphic position of the main mined coal seam (C4L). The geochemical homogeneity of the dolerites coupled with the relatively uniform proximate analysis values of unaltered coal in this region allow for any variations to be directly linked to metamorphism.

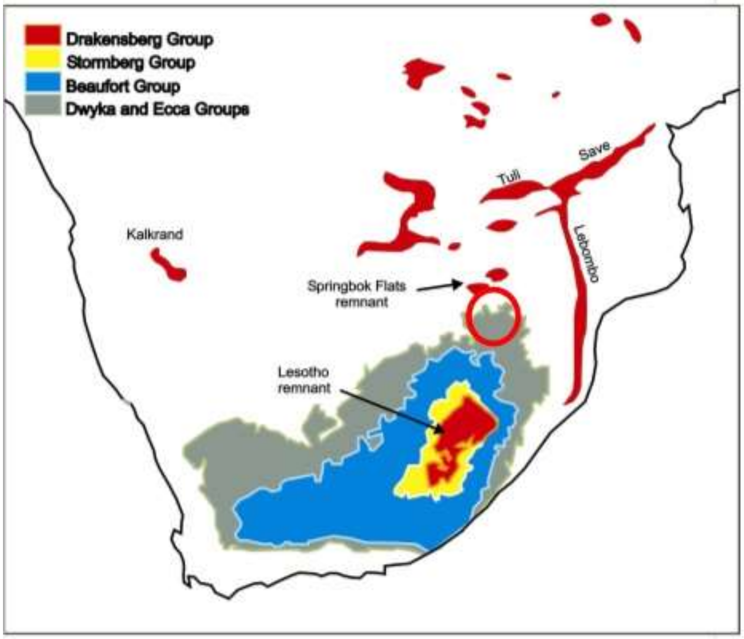

Figure 1: A map of Southern African showing the Karoo supergroup and associated volcanic rocks (modified from Hancox *et al.,* 2001). Highlighted in red is the sample area.

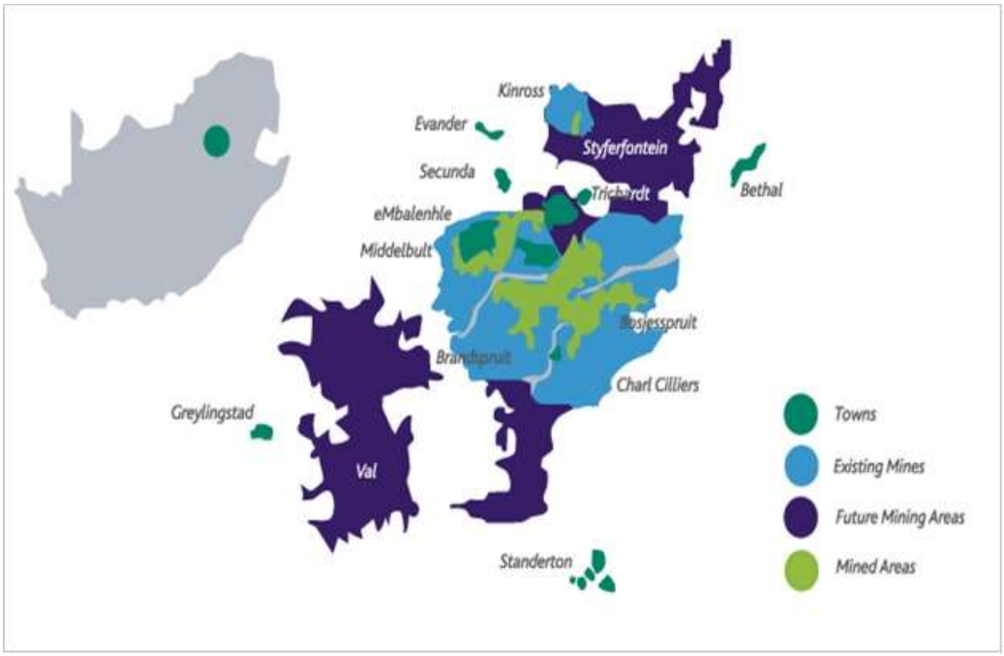

Figure 2: Detailed map of sampling area showing the current mining operations and local towns.

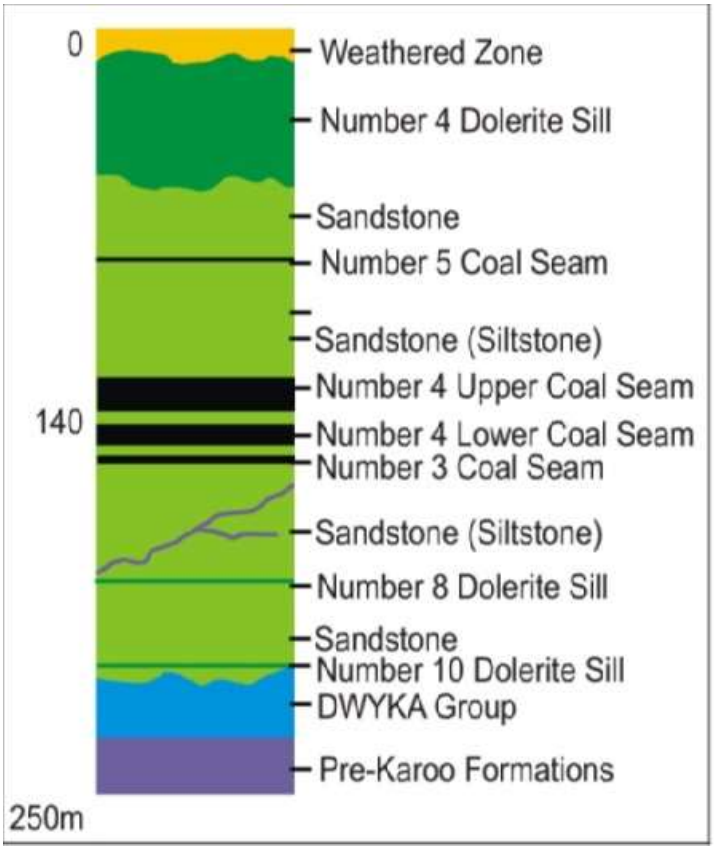

Figure 3: General stratigraphy of Secunda area

As a technique, proximate analysis has been standardized under the ASTM methods (ASTM D3172-D3189, 2002), and the process can be simply explained in three stages of temperature ramping:

- Stage 1: The sample is placed in a platinum crucible into the furnace at 30 °C and increased to 110 °C in a nitrogen-rich environment. The temperature is ramped at a rate of 30 °C per min to remove the moisture from the sample.
- Stage 2: The temperature is increased to 900 °C in a nitrogen- rich environment (as to prevent combustion). This stage is again at a rate of 30 °C per min and it is assumed that after this period all volatile components have been released.

- Stage 3: The sample is maintained at 900 °C in a now oxygen- rich environment for 1 minute so that the sample can be completely combusted. The remaining weight in the crucible is considered the inorganic material or “ash” content. The variation in weight between the end of stage 2 and 3 is termed the fixed carbon content (Speight, 2007).

From this process, mass can be plotted against time and the derivative of each stage calculated to produce a specific value. These final values are then used to quantify the level and area of effect of dolerite intrusion.

For this project, a substantial data set was obtained from Sasol Mining South Africa which contained ~15 000 borehole logs of the area which listed:

- Dolerite type
- Dolerite thickness
- Dolerite position
- Coal seam thickness
- Coal seam position
- Proximate analysis values for DAFV (Dry Ash Free Volatile), Volatile values and Ash content
- Geographic coordinates

To ensure an accurate analysis of the dolerite effect on the coal, the original data set was refined and filtered. Only boreholes which contained a single dolerite sill were selected, producing a set of

~8000 boreholes which were used to quantify possible metamorphic effects. The data set can be separated as follows:

- 3145 boreholes intersecting only the D04 dolerite sill
- 4663 boreholes intersecting only the DO8 dolerite sill
- 116 boreholes intersecting only the DO10 dolerite sill

The proximate analysis figures displayed in these logs were compared to the standards applied by Sasol during assessment of the coal in this region.

- DAFV: < 26 = Devolatilized
- Vols: < 16 = Devolatilized
- Ash: > 36% = Devolatilized

The relationship between the sills and the C4L seam in these boreholes was investigated through the use of three methods: firstly by geographic interpolation to identify areas of devolatilization in comparison to dolerite type and geographic position; secondly, bubble plots were drawn to obtain a three dimensional (distance, thickness and proximate analysis value) analysis of the devolatilization and finally, statistical analysis was used where the variable levels of devolatilization were compared to identify any implicit patterns within the proximate analysis data.

2. Results

The geographic devolatilization relationship made use of the DAFV value, interpolating the ~8 000 analysed core samples over the study area to show any spatial trends. The interpolation in figure 4 shows no correlation with regards to position of dolerites, type of dolerite and coal quality. This lack of correlation is strange, as regions on the map with high densities of dolerites were expected to correspond to an increase in devolatilization. A secondary note could also be made that there is no dolerite-specific metamorphic effect seen on this map, as regions populated with a majority of a singular dolerite group show the same variable devolatilization effects. This irregular relationship was initially inferred as being a result of sill thickness and position in relation to the C4L seam.

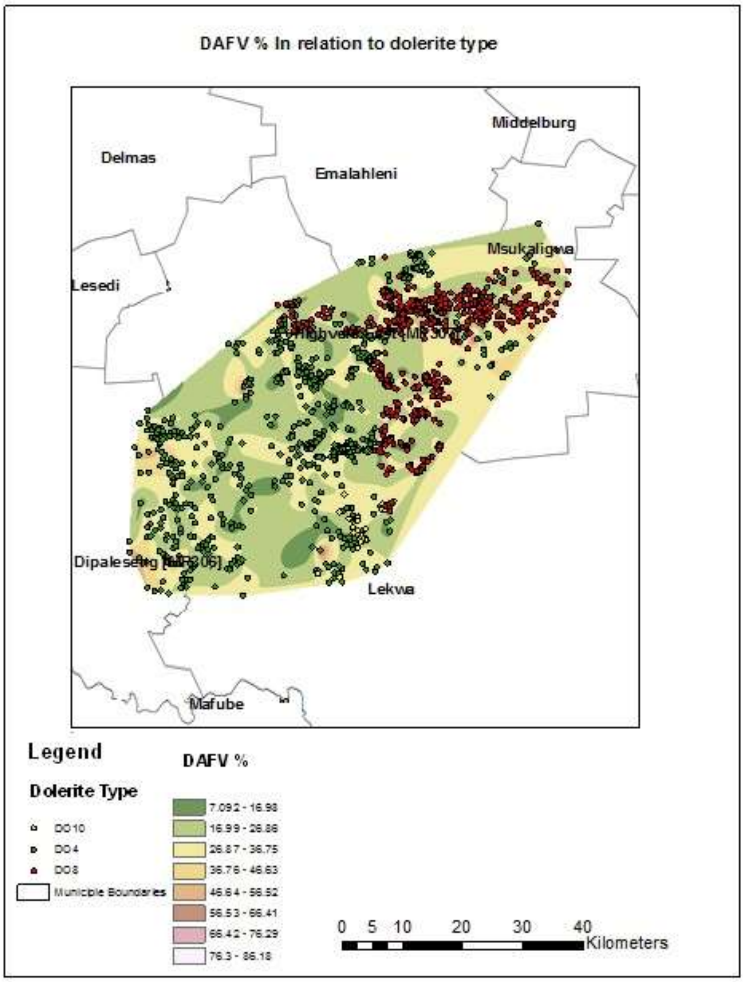

Figure 4: Dry ash free volatile concentration (DAFV %) in comparison to dolerite type and geographic position. Note that the numbers following area names are the municipal area codes.

To test this hypothesis, 3-component bubble plots were used to investigate the relationship between the proximity, thickness and type of dolerite relative to the proximate analysis values. It was expected that the bubble plots would show a simple linear trend, based on the principles of simple contact metamorphism, where an increase in volume or sill thickness and a reduction in distance would produce a greater metamorphic effect on the coal.

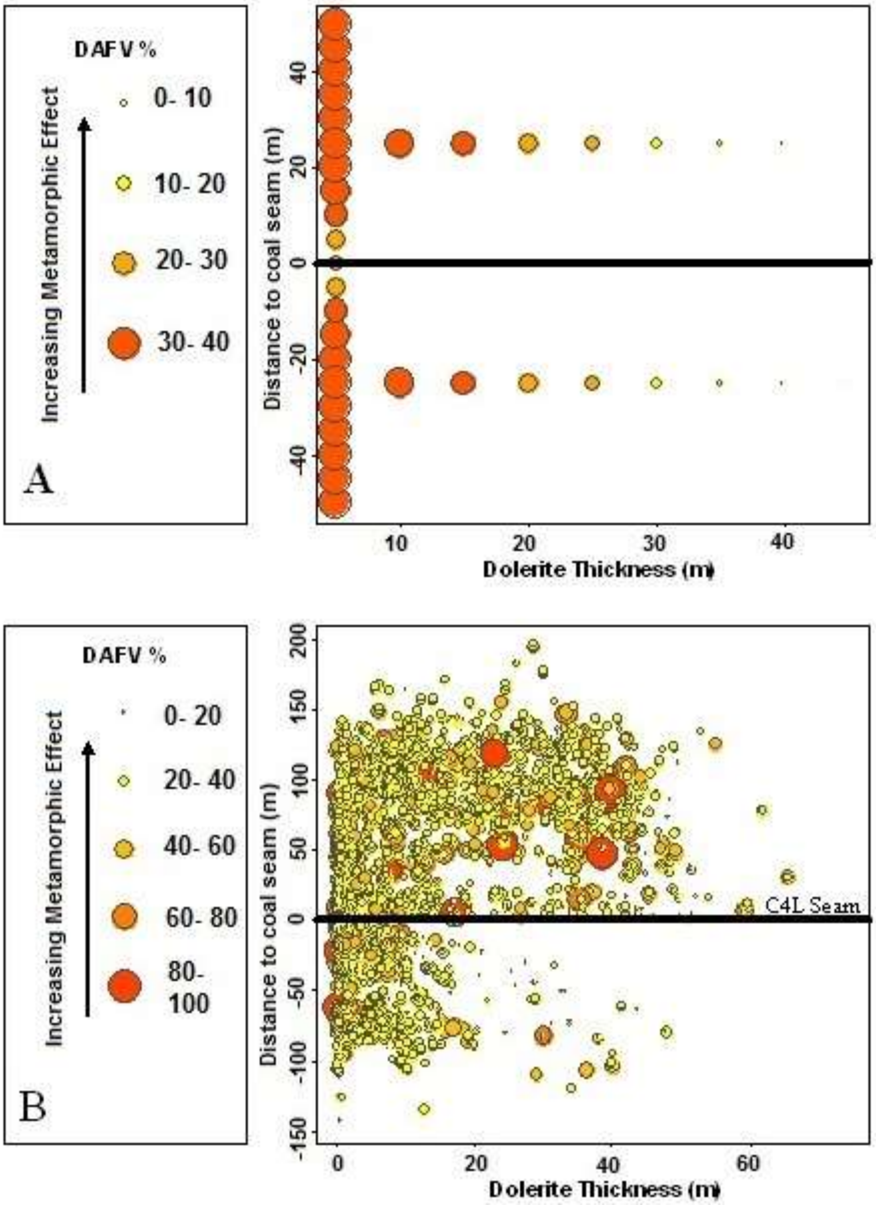

Figure 5: Dry ash free volatile percentage % (DAFV%) values in relation to the thickness of dolerite and the interval between the dolerite and the coal seam for all dolerites in the study area.

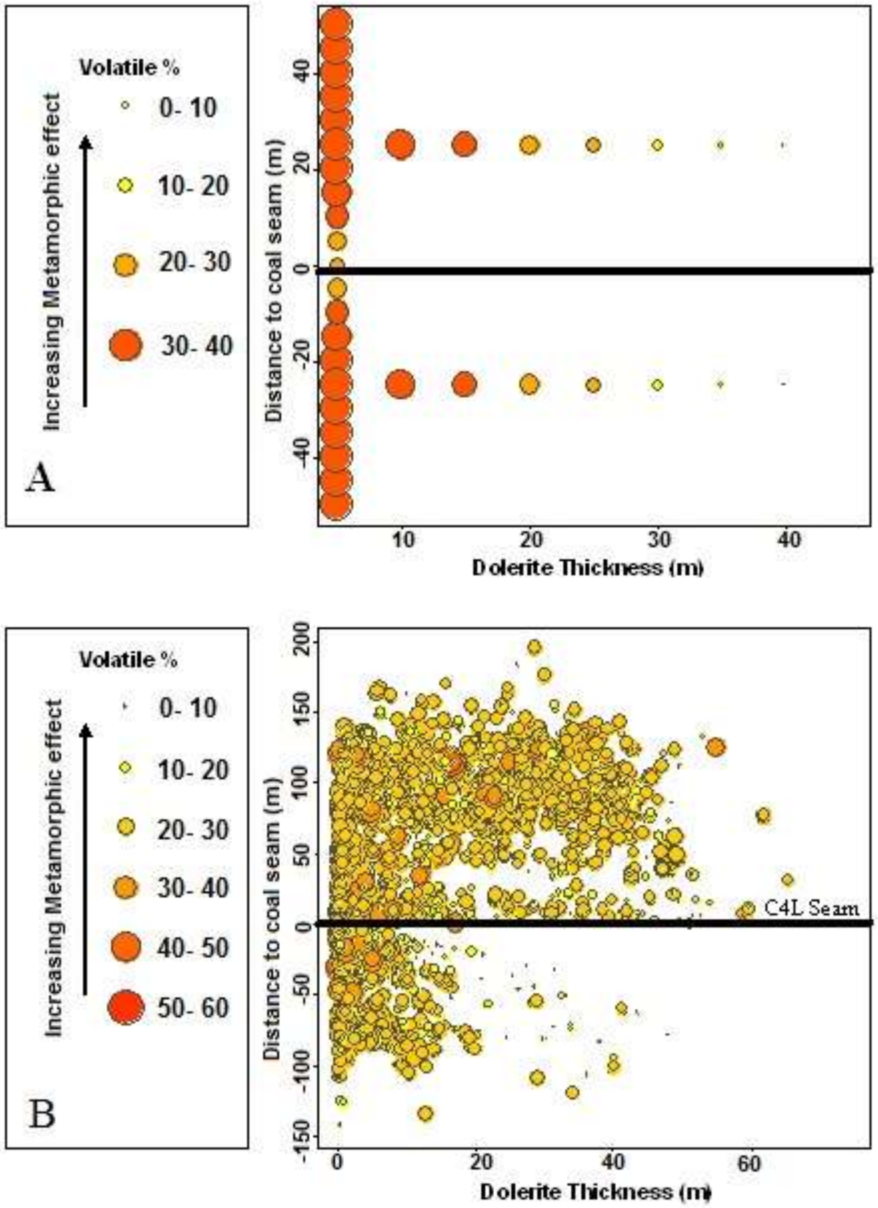

Figure 6: Coal Ash percentage in relation to the thickness of dolerite and the interval between the dolerite and the coal seam for dolerites in the study area. A) Expected linear trends in data; B) Measured values for the sampling area

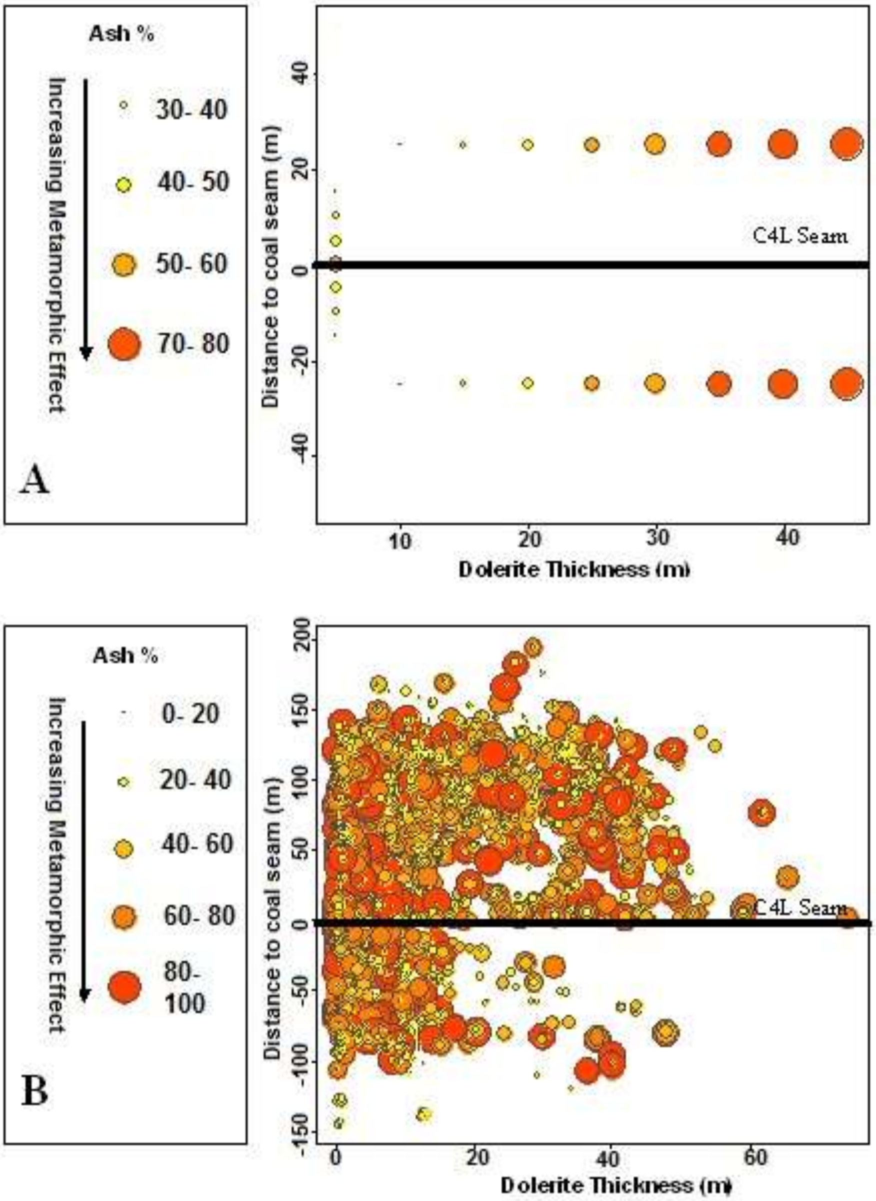

Figure 7: Coal Volatile percentage in relation to the thickness of dolerite and the interval between the dolerite and the coal seam for all dolerites in the study area. A) Expected linear trends in data; B) Measured values for the sampling area

Graphs were prepared for each of the three major proximate indicators (i.e. DAFV, Ash and Vols) and compared to the expected linear trends (figs. 5-7). The expected trends do not occur within the data and no correlation with regard to dolerite distance from the coal seam and dolerite thickness against any of the proximate analysis values investigated. It should be noted here that the relative paucity of data below the C4L seam in each of these diagrams reflects the limited number of boreholes drilled below the seam. In each case, the proximate analysis indicators appear randomly

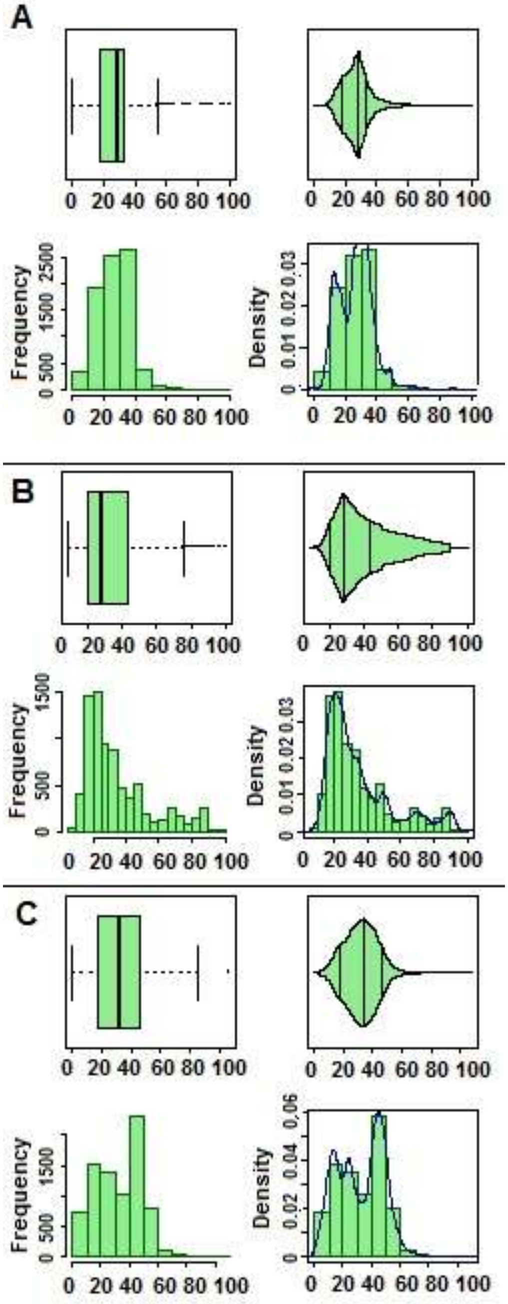

Figure 8: Graphical statistics on all dolerites in the study area. A) dry ash free volatile (DAFV) percentage %, B) ash %, C) volatile %

distributed, an observation supported by more detailed statistical work which is presented graphically in Figure 8 and presented in tabular form in Table 1. The graphical statistics show omplex histograms with multiple peaks and indicators of location showing mode, median and mean values well beyond the limits of normal distributions. The skewness and kurtosis values calculated for the data also indicate large deviation from normality.

Table 1: Summary statistics of DAFV, ash and volatile parameters for all dolerites in the study area

Statistical Measure	**DAFV %**	**Ash %**	**Volatile %**
Mean	26.55	34.77	16.11
Standard error	0.12	0.23	0.09
Median	28.46	27.70	16.60
Mode	25.00	50.00	12.00
Standard deviation	10.52	20.03	7.97
Sample variance	110.71	401.37	63.54
Kurtosis	2.52	0.96	-1.01
Skewness	0.60	1.33	-0.02
Range	100.00	92.10	53.70
Minimum	0.00	7.90	0.00
Maximum	100.00	100	53.70
Sample size	7924	7924	7924
Confidence level (95.0%)	0.23	0.44	0.18

Secondly no trends or groupings can be seen irrespective of the scale used to show dolerite distance from the coal seam. This is an important observation, which shows that there is no distinct radii to any metamorphic aureole that may be present around the intruding sills in the area. It would be expected that proximate analysis values would become more uniform (but not necessarily consistent, as the coal macerals are not uniformly distributed during formation) further away from the dyke, and that a systematic change would be present closer to the dyke. Since neither effect is visible in the data, the basic assumptions regarding the size and effect of the metamorphic aureole associated with the dolerite intrusions must be questioned.

Further separation of the data into individual dolerite types was conducted to investigate whether the lack of correlation could be attributed to dolerite- specific metamorphic effects, i.e. only certain dolerites affect the coal, but this analysis once again showed no discernible trends, correlations or groups (figures attached in an electronic appendix). This is in stark contrast to the generally assumed linear trends, but also does not follow any of the exponential trends proposed by authors such as Snyman and Barclay (1989).

Within the 7924 boreholes in which the three dolerites occur, devolatilization of the C4 lower seam occurs in 19.70% of the boreholes as seen in table 2. This value is derived by identifying all instances where the values of DAFV, Vols and Ash are beyond the levels set by Sasol for devolatilized coal, and then dividing this number of samples by the total number of boreholes studied within the area. The DO4 and DO8 dolerites also showed similar values in the devolatilization percentages in the summary statistics with ~18% and ~20% respectively, whereas DO10 returned a lower value of ~13%.

Table 2: Percentage of devolatised boreholes relative to each dolerite type, as well as for all dolerites in the study area

	Devolatilization %
All Dolerites	19.70
DO4	18.16
DO8	20.89
DO10	13.79

Both the summary statistics and graphical statistics indicate complex data which is far from normally distributed. This once again shows that any contact metamorphic effect caused by the dolerite intrusions deviates from an ideal contact metamorphic regime. The major inference that can be made about the Secunda sills and their effect on the quality of the C4 L seam are that the simplistic 1.5x rule applied within South African coal mines to account for the contact metamorphism of coal is unsupported by the data set, and that more complex processes are at work on the coal.

4. Discussion

The identification of devolatilized zones in South African coal fields has major effects on mine planning and thus on the final resource and reserve figures mining companies produce. The potential that regions of coal deemed devolatilized are in fact a feature of an inherently inaccurate analysis or misinterpretation of analytical results within a complex metamorphic scenario can potentially have dramatic financial implications. With this in mind, three possibilities have been identified as potential causes for the lack of correlation between coal quality and dolerite proximity. Firstly, the convoluted relationship may reflect a complex metamorphic regime where multiple variables beyond distance and thickness are needed to define the effect of the dolerites on the coal. Secondly the analytical approach may not accurately define the metamorphic effects caused by the dolerites, and thirdly a combination of complex metamorphism and a broad scale analytical approach have combine to produce an inaccurate depiction of the products of metamorphism in this regime. Each of these issues can be discussed separately.

4.1. Dolerite emplacement dynamics

The process of intrusion and propagation of the doleritic magma has major implications on the potential for that magma to transmit, retain and transfer thermal energy. With an abundance of complex factors controlling the dynamics of intrusion each of which potentially influences the metamorphic capabilities of the magma, it is important to take all these factors into account when attempting to understand the dynamics of the metamorphic regime produced. A prime example of the potential controls on metamorphic effect is the flow regime within the magma conduit, which is vitally important to how much country rock is assimilated. The Reynolds number (Reynolds, 1883), a dimensionless factor, defines whether a fluid experiences turbulent or laminar flow, as explained by the equation below:

$$e \equiv \frac{\rho_{liq}\overline{U}w}{\eta}$$

- $\overline{U}$ is the average velocity
- w is the half-thickness of the flow
- ρ_{liq} is the liquid density
- η is its viscosity

The emplacement properties of the dolerites regulate the associated metamorphic effect, so each dolerite has a unique contact metamorphic effect related to its intrusion dynamics. The Reynolds number is dependent on numerous factors, such as the distance the magma has travelled within its conduit, which will have a dramatic influence on the temperature of the magma. The continuous transmission of heat to the surrounding country rock will reduce the magma temperatures which will in turn the change the viscosity as magma temperature and viscosity are inversely proportional, and thus an increase in magma temperature will decrease the viscosity.

If the Reynolds number is high, turbulent flow will occur, whereas if the Reynolds number is low, laminar flow will occur (Kavanagh *et al*., 2006). The transition between laminar and turbulent flow can be anywhere in the range of 10-1000, but within mafic magmas this value is ~28 (Kavanagh *et al*., 2006).Thus if a dolerite magma was undergoing turbulent flow, a system of eddies would develop as the dolerite propagates. These eddies could allow for greater thermal erosion and assimilation of country rock, and during this process the magma would release a large component of its thermal energy by means of assimilation, thus reducing the size of the metamorphic aureole. If dolerite magma undergoes laminar flow, the amount of contamination and assimilation would be greatly reduced as the magma's thermal erosive impetus would be lower. This laminar flow regime would also allow the production of amorphous glass chilled margins, which would insulate the dolerite conduit. This insulating effect would allow for longer cooling rates and a greater amount of heat energy would be released by conduction, thus creating a more pronounced contact metamorphic aureole.

Along with temperature variations the density of the magma is directly related to the flow rate and the viscosity; the denser the magma the higher resistance to flow it will have, and thus the magma will have a higher viscosity. As the Reynolds equation indicates there is an inversely proportional relationship between flow rate and viscosity, in order to overcome an increase in viscosity and maintain a specific flow regime, there will also be an increase in rate of flow.

The gravitational force induced from the height differential of the magma conduit and the source of melting or piezometric pressure is a major source of pressure on the magma and thus on its potential flow rate. Thus a higher piezometric pressure will produce magma with a higher flow rate. The flow rate of the magma can be directly inserted into the Reynolds number equation, but this figure is also related to the other factors of propagation and emplacement. As with piezometric pressure the magma chamber overpressures will define the force with which the magma travels through the conduit, influxes of new magma, increased melting and variations in volatile gasses all influence the pressures of the chamber.

To summarize, if a dolerite liquid maintained a laminar flow it would create a large metamorphic aureole, whereas if it maintained a turbulent flow the contact metamorphic aureole would be much less pronounced. This flow regime-based metamorphism would be a dynamic system which could change along the length of the conduit, as the magma’s physical properties change owing to crystallisation and cooling.

Although contact metamorphic effects will surely be apparent when dolerites are in very close proximity to the coal, this type of metamorphism may not be the major process devolatising the coal. The intrusion of the doleritic magmas would also be associated with the production of heated fluids from the magmas and the surrounding sediments as the intrusions cool (Jamtveit *et al.,* 2004). These 100-300°C fluids would be mobile and able to percolate through the porous and permeable sedimentary strata surrounding the coal. A metasomatic hydrothermal agent could explain the lack of a linear relationship between dolerite proximity and coal quality, as fluids are more mobile and less homogenous, and so will not produce the same linear relationship as expected from contact metamorphism.

A more plausible scenario for the variation in coal quality relative to the dolerite intrusions is one where both the dynamic emplacement of the dolerite and the effect of hydrothermal fluids are taken into account. When these factors are combined, a complex situation is created where the dimensions of dolerite sill or dyke metamorphic “aureoles” (or rather the metamorphic range) are dictated by the way in which the dolerite was emplaced and what (if any) fluids were released or produced by that dolerite. These two factors would define how dramatic the effect of the intrusion’s presence would be on the coal’s chemistry and physical properties.

Essentially there would be four main or end member scenarios when both these factors are taken into account:

1. A fast flowing magma with turbulent flow which incorporates large amounts of country rock and produces a small metamorphic aureole, but creates large amounts of hydrothermal fluids during cooling and interaction with the sedimentary strata.
2. A fast flowing magma with turbulent flow which incorporates large amounts of country rock and produces a small metamorphic aureole, and produces only small amounts of hydrothermal fluids during cooling and interaction with the sedimentary strata.
3. A slow flowing magma with a laminar flow which produces an regular chilled margin and a larger metamorphic aureole, and produces large amounts of hydrothermal fluids during cooling and interaction with the sedimentary strata.

4. A slow flowing magma with a laminar flow which produces an regular chilled margin and a larger metamorphic aureole, and produces small amounts of hydrothermal fluids during cooling and interaction with the sedimentary strata.

4.2. Potential inadequacies and limitations with the proximate analysis approach

The proximate analysis procedure has changed little from when it was described by early authors such as Regault (1837) and Gruner and Bousquet (1911). Over the almost 200 years of use the technique it has been refined and standardized to allow for more accurate and comparable results. The most commonly used method today places a 10-15 mg sample in a thermogravimetric analyzer; the sample is exposed to a time- controlled temperature ramp from 30-900°C in a nitrogen- rich environment to prevent combustion, after which the system is purged with oxygen until the sample is fully combusted. This analysis produces a mass- time curve, and the derivatives of this curve over specified intervals allow the user to calculate the amount of moisture, volatiles, fixed carbon and ash contained in each sample (Donahue and Rais, 2009). The assumptions behind this analysis is that all volatiles released are organic, that all volatiles are only released over the specified volatile temperature interval, that there is no loss of inorganic material during combustion, and that no organic material remains at the end of the process.

Many of these assumptions can be questioned. The analysis procedure is done with little or no understanding of the organic composition of the coal itself and disregards the potential for reactions between organic volatile and semi-volatile components which may occur at lower temperatures than envisaged by the process steps. This removal or reaction of volatile and semi-volatile components at lower temperatures may dramatically alter the mass time graphic produced through TGA analysis and thus the derivatives thereof.

Inorganic reactions such as sulphation and recarbonation may also occur due to high sulphur oxide and carbonate concentrations, which may lower ash content values due to the production of CO_2 during sulphation, for example:

$CaCO_3+SO_3 \longrightarrow CaSO_4+CO_2$ (Warne, 1991 and Al-Otoom *et al.*,2005)

The third assumption, that all the organic material is combusted at 900° C, may not always be the case. The maceral composition of the coal material will have a large effect on the temperature of combustion, as coals with high levels of inertinite and fusinite may require temperatures in excess of 1200 °C before combustion takes place. The accumulation of all these factors can allow for dramatic fluctuations in the proximate analysis values and may aid in describing the complex data seen in the Secunda region.

4.3. The incompatibility of complex metamorphism and proximate analysis

The information gap present in the proximate analysis technique allows for a vast range of organic/inorganic metamorphic reactions to take place. Combined with a complex metamorphic environment, it would be difficult to discern any meaningful trends within the proximate data produced, as the amount and type of volatile and semi-volatile reactions induced by the dolerite intrusion cannot be identified through the proximate technique. Taking this into account, a third potential explanation of absence of the generally accepted linear relationship between the proximate analysis and dolerite dimensions could be as a result of a complex metamorphic regime being poorly displayed by a non-specific analysis technique.

Without a clearer description of the volatile and semi-volatile components hosted within the coal, a result displaying "volatile %" as determined by proximate analysis leaves room for misleading definitions of the metamorphism which may have affected the coal seam. As there is the potential for both contact and hydrothermal metamorphism during the intrusion of the dolerite, the type of organic reactions derived from these different mechanisms would differ greatly. Due to the complex and often heterogeneous organic composition of coal the type of organic molecules hosted within will have a wide variety of physicochemical properties; as such some molecules will have greater reactivity in thermal environments while others may have an affinity toward high temperature saline fluids.

The fact that proximate analysis is effectively "unfit for purpose" in areas affected by large scale intrusion of dolerite has major implications for mining in such areas. In particular, the 1.5x rule has no empirical basis in such an area. In the South African context where most of the Karoo coalfields are riddled with dykes and sills, the immediate implication of this study is that useable coal close to dolerite intrusions has most likely been left in-situ during mining, while unusable (i.e. devolatilised coal) has been extracted in places. Neither scenario is ideal in a mining context, and, as mining enters more structurally complex areas with a greater density of intrusive features, it is likely that the problem will get worse. In these areas, proximate analysis will need to be supplemented with further work, in order to ensure efficient extraction of viable coal.

5.Conclusion

The data shown here may be viewed in three ways:

One, the accepted metamorphic effect of dolerites on coal has been grossly oversimplified.

Two, the application of proximate analysis, as a tool to quantify the effect of dolerite intrusions on coal, produces results with potential for large information gaps often overlooking both organic and inorganic reactions taking place and should be used with caution as a quantitative tool.

Three, an oversimplification of the metamorphic system acting on the coal in combination with an analysis technique which is overly interpreted has produced variable and complex results.

In all three cases the current view point and application of the 1.5x rule currently used in mining must be reviewed, and the efficacyof proximate analysis improved or supplemented with other methods.

The currently applied dimension based metamorphic estimation applied in a vast majority of coal mines has been shown to be potentially invalid. The lack of expected linear relationship between the proximate analysis figures, dimensions and position of the doleritic intrusives can be interpreted in multitude of ways, but cannot be ignored. Thus the final conclusions of this manuscript are:

- Dolerite metamorphic aureoles are dolerite specific, and geographically specific. Each dolerite conduit will maintain its own unique metamorphic signature which will differ at every individual point within the length of its conduit.
- The metamorphic effect of dolerites of the Secunda region cannot be ascribed solely to contact metamorphism, but possibly to a combination of metamorphism by hydrothermal fluids produce by the dolerite, and contact metamorphism.
- The strict application of dimension based metamorphic effect may be incorrect.
- The use of proximate analysis as a definition of metamorphism should be used with caution. Although the data may give an approximation of metamorphism, the information gap within the organic metamorphic reactions cannot be ignored.

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Supplementary Data

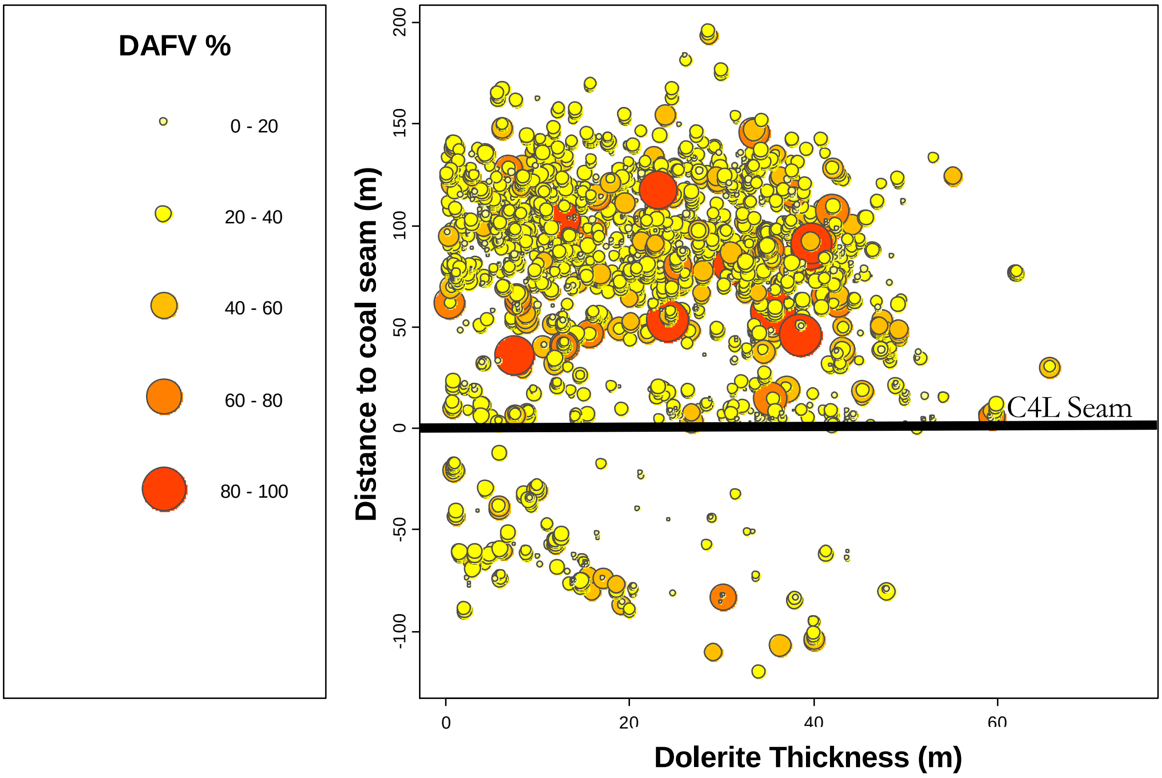
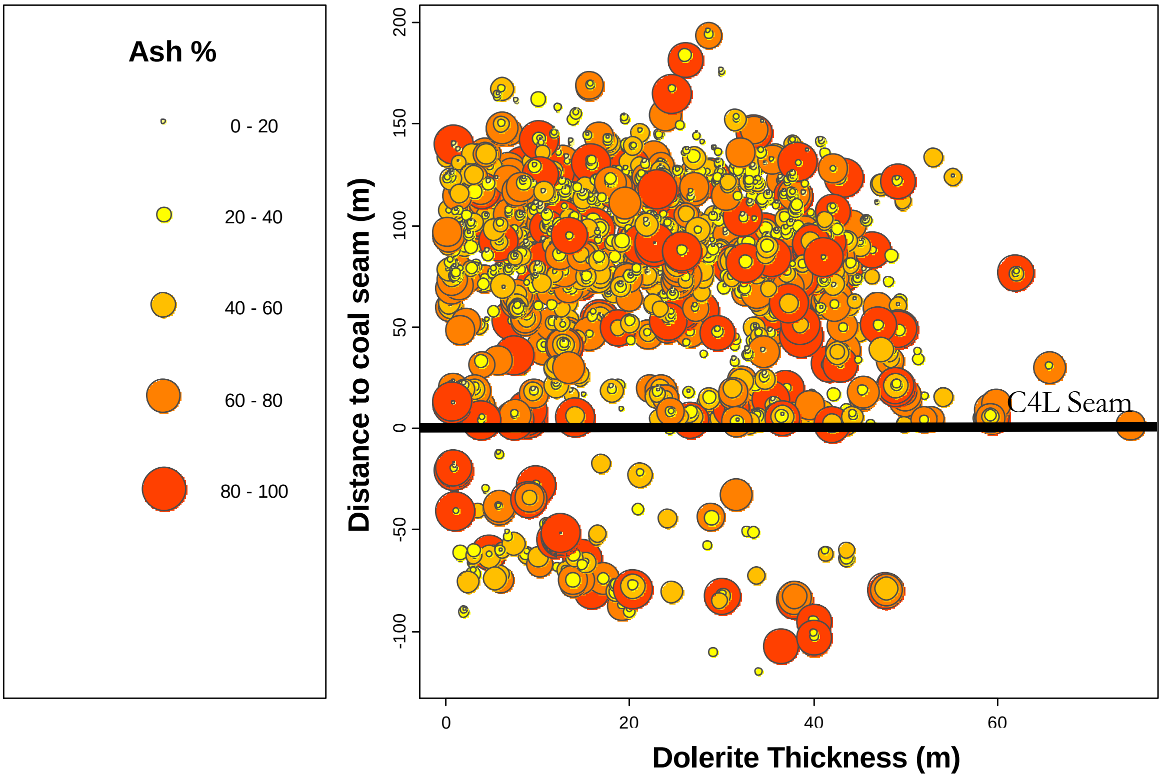


Figure 1: Coal dry ash free volatile percentage in relation to the thickness of dolerite and the interval between the dolerite and the coal seam for the DO4 dolerite



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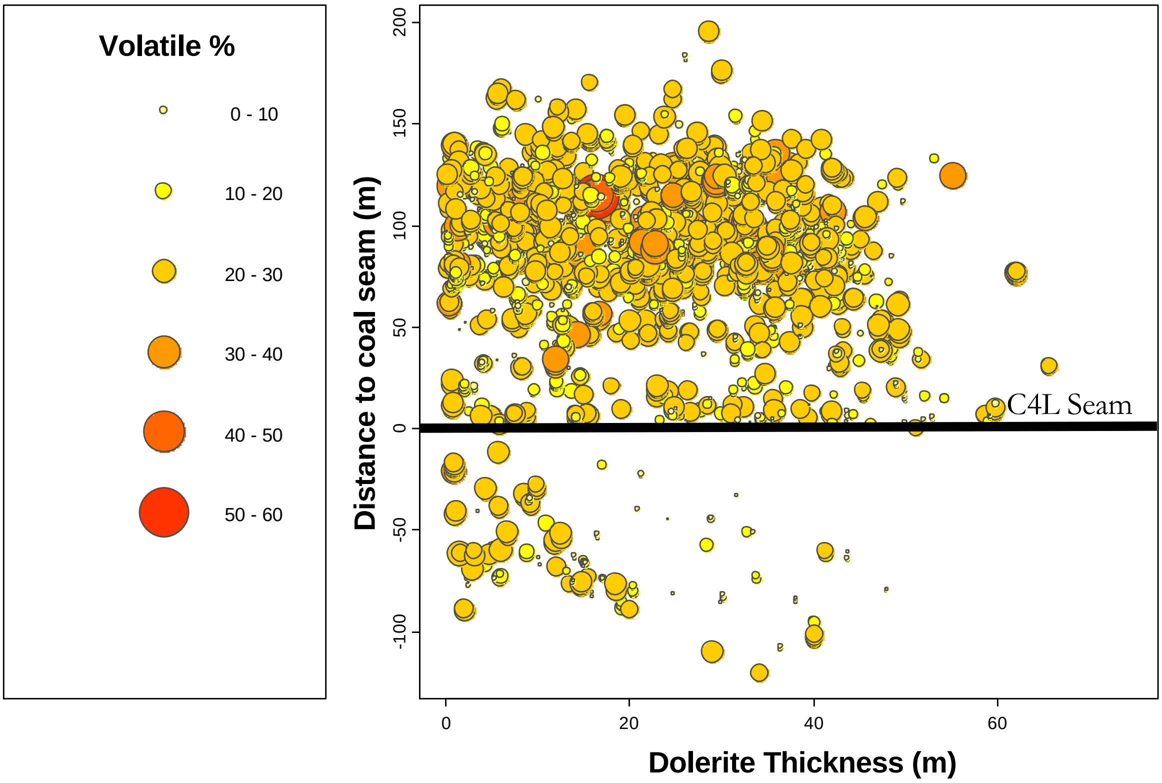

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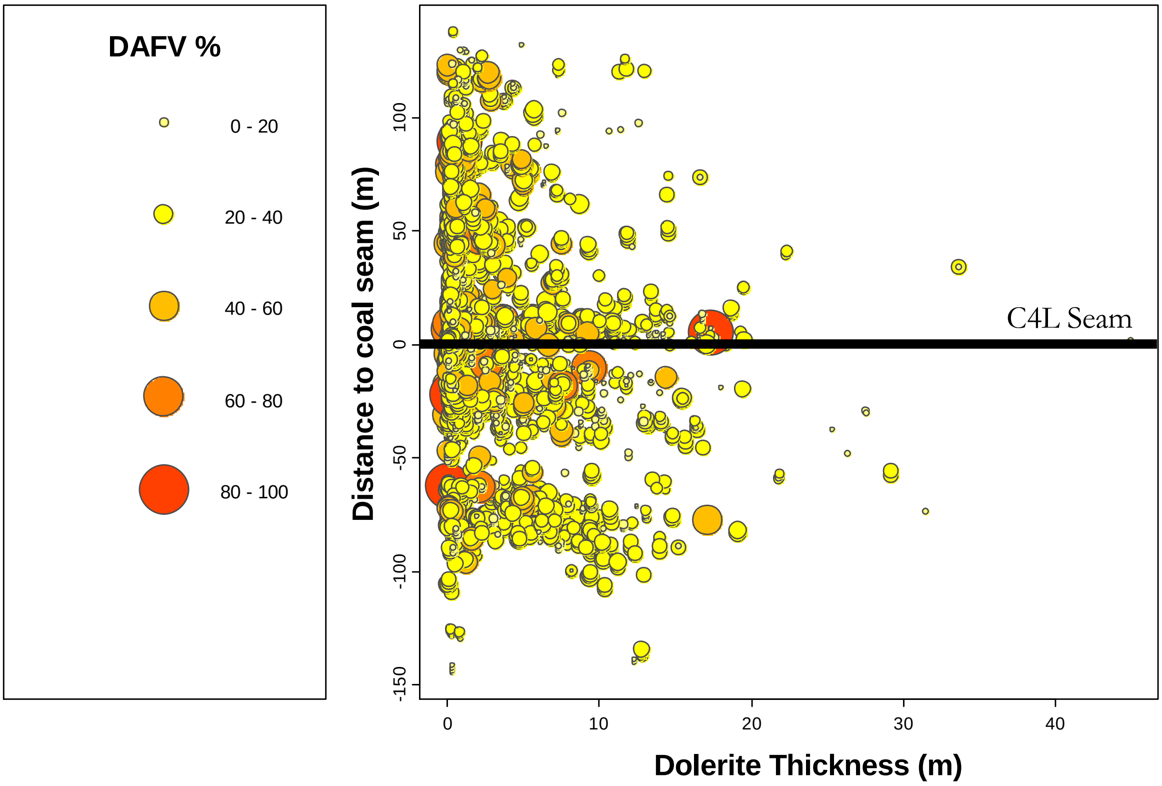

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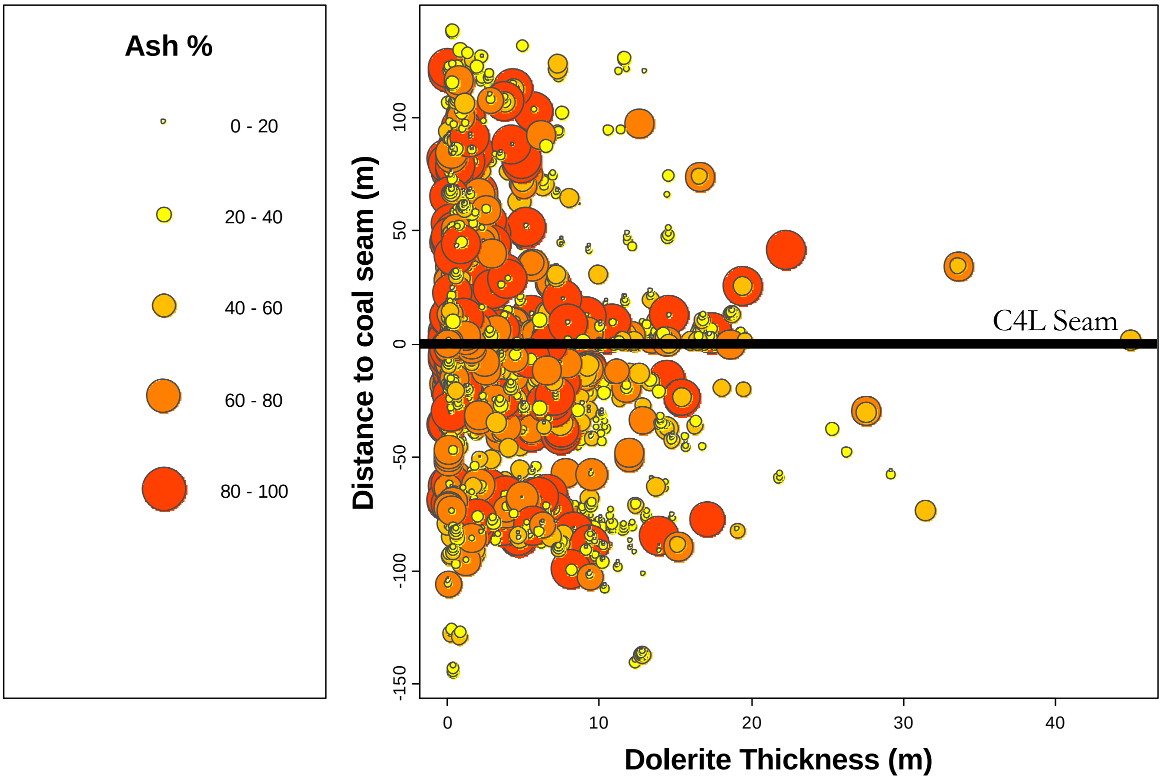


Figure 3: Coal Ash percentage in relation to the thickness of dolerite and the interval between the dolerite and the coal seam for the DO8 dolerite

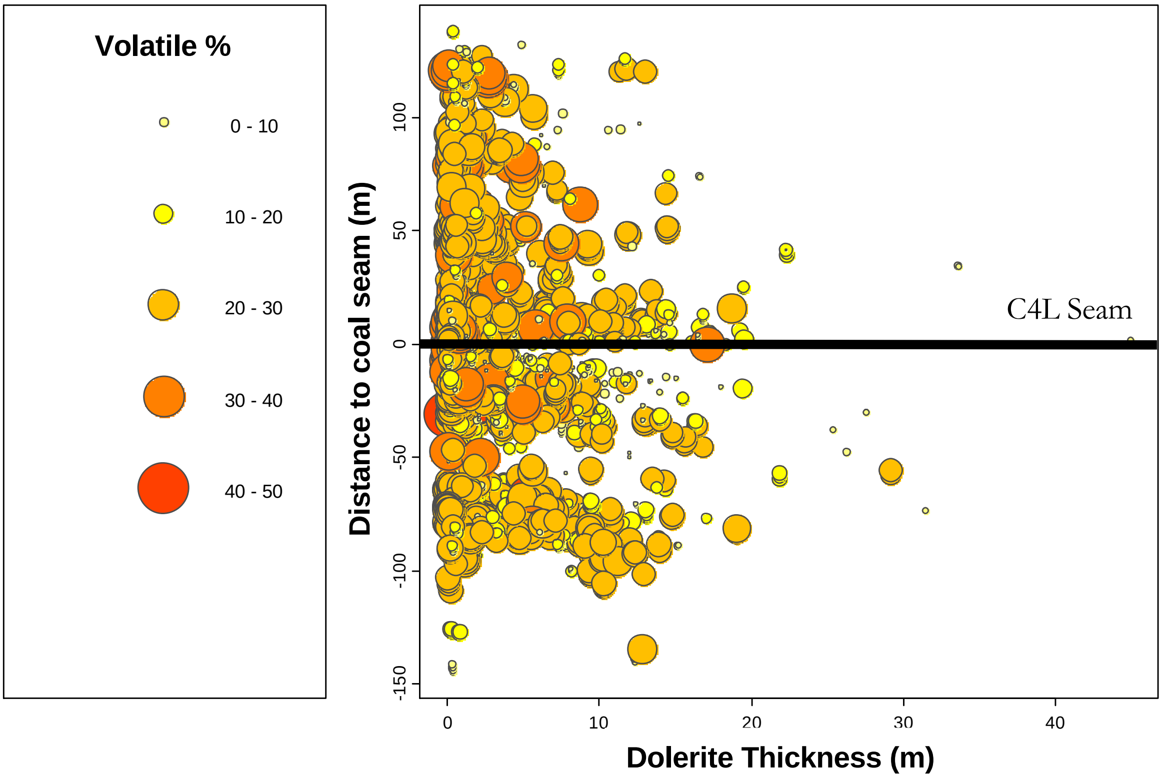


Figure 4: Coal Volatile percentage in relation to the thickness of dolerite and the interval between the dolerite and the coal seam for the DO8 dolerite

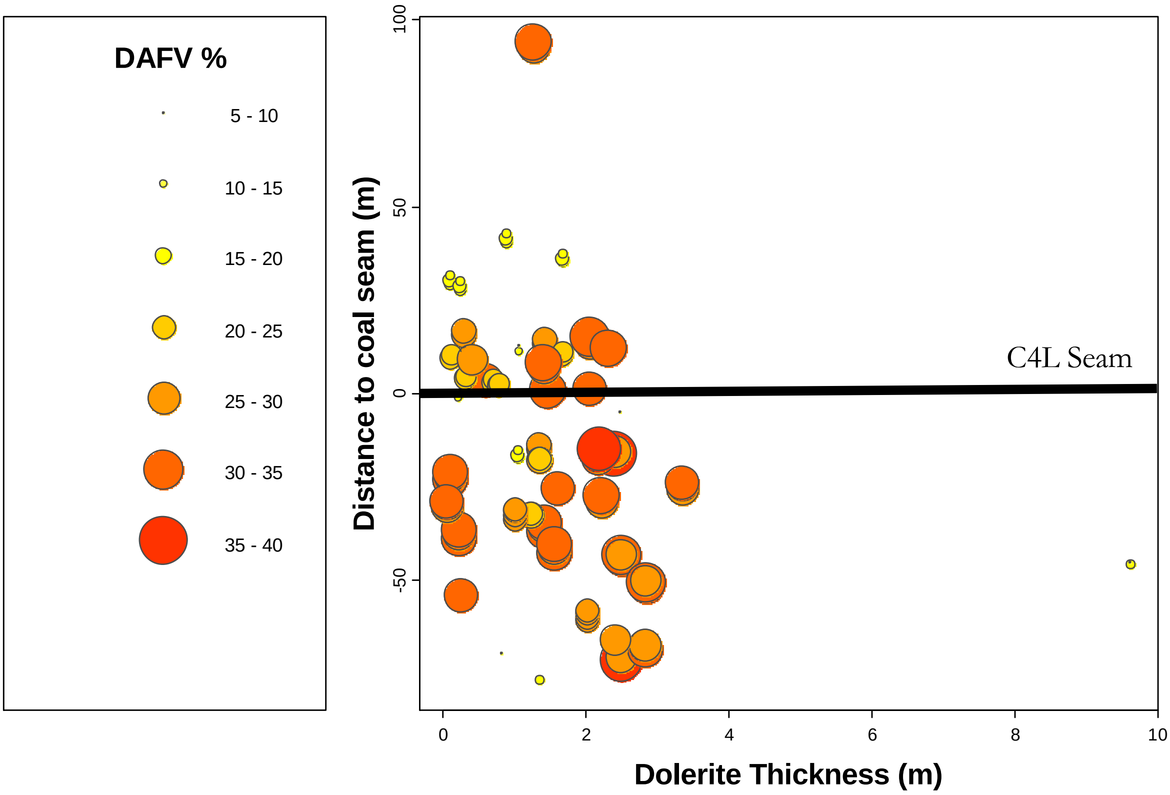


Figure A7: Coal dry ash free volatile percentage in relation to the thickness of dolerite and the interval between the dolerite and the coal seam for the DO10 dolerite

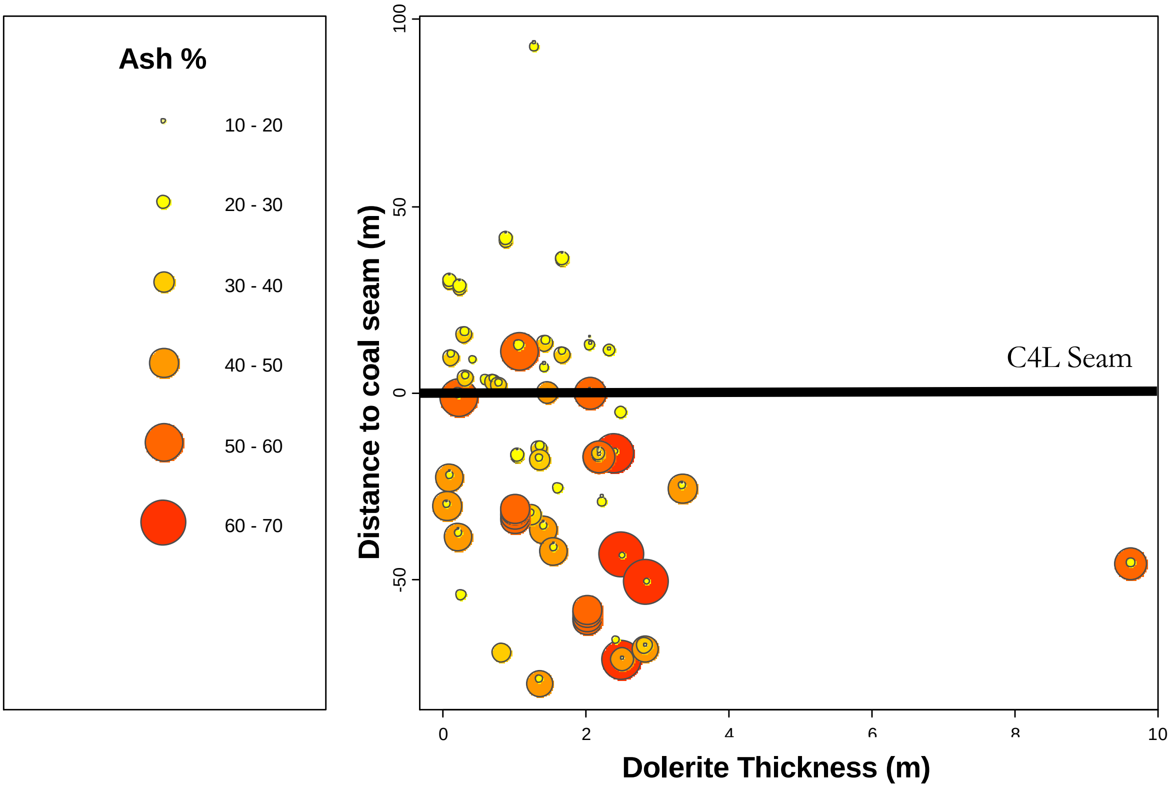


Figure 5: Coal Ash percentage in relation to the thickness of dolerite and the interval between the dolerite and the coal seam for the DO10 dolerite

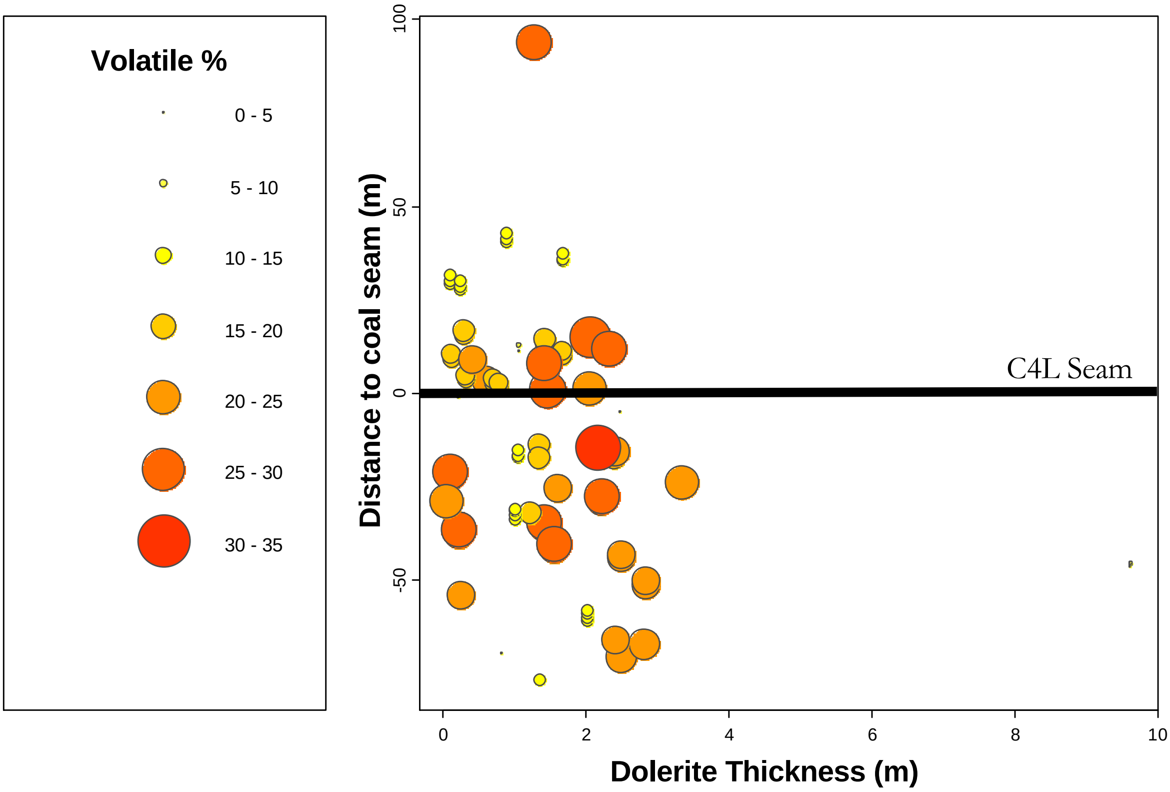
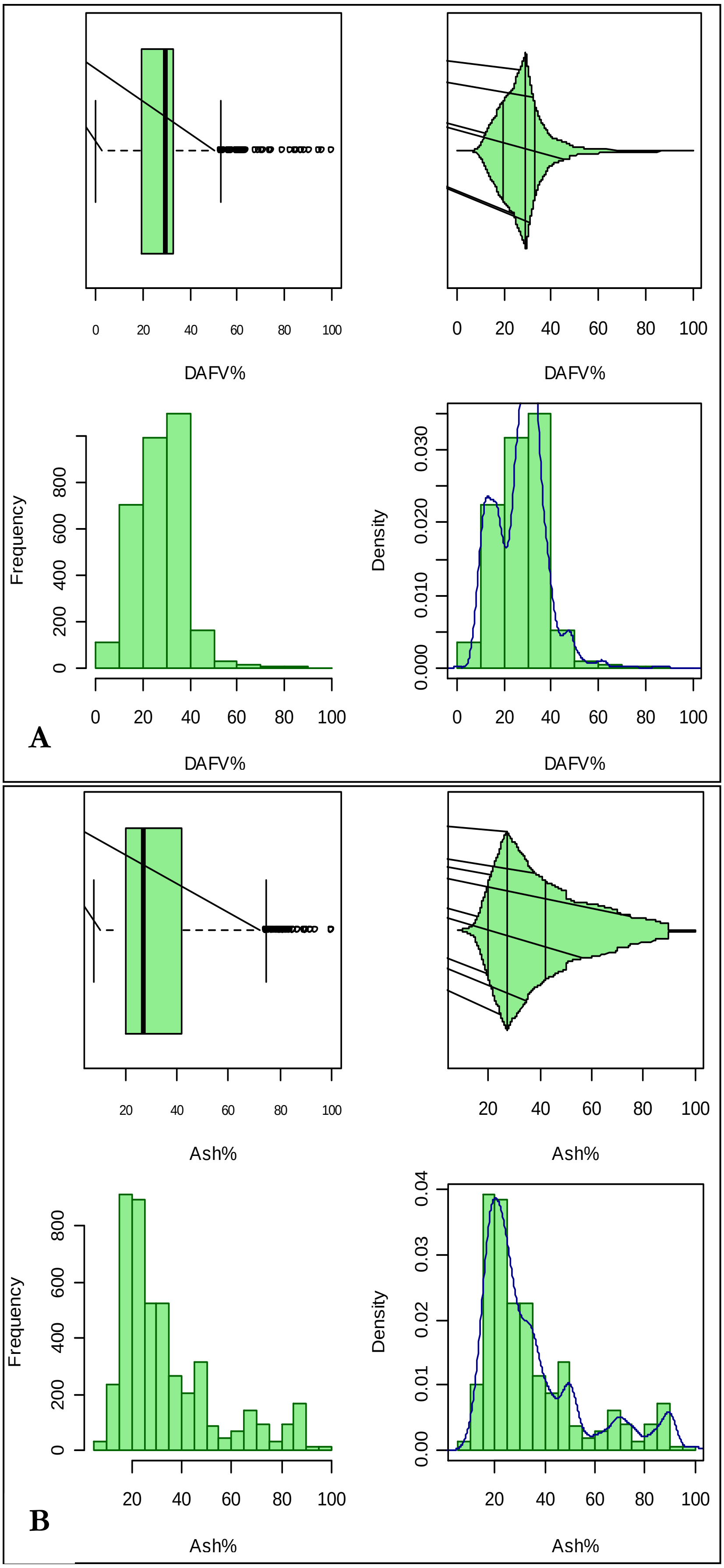


Figure 6: Coal Volatile percentage in relation to the thickness of dolerite and the interval between the dolerite and the coal seam for the DO10 dolerite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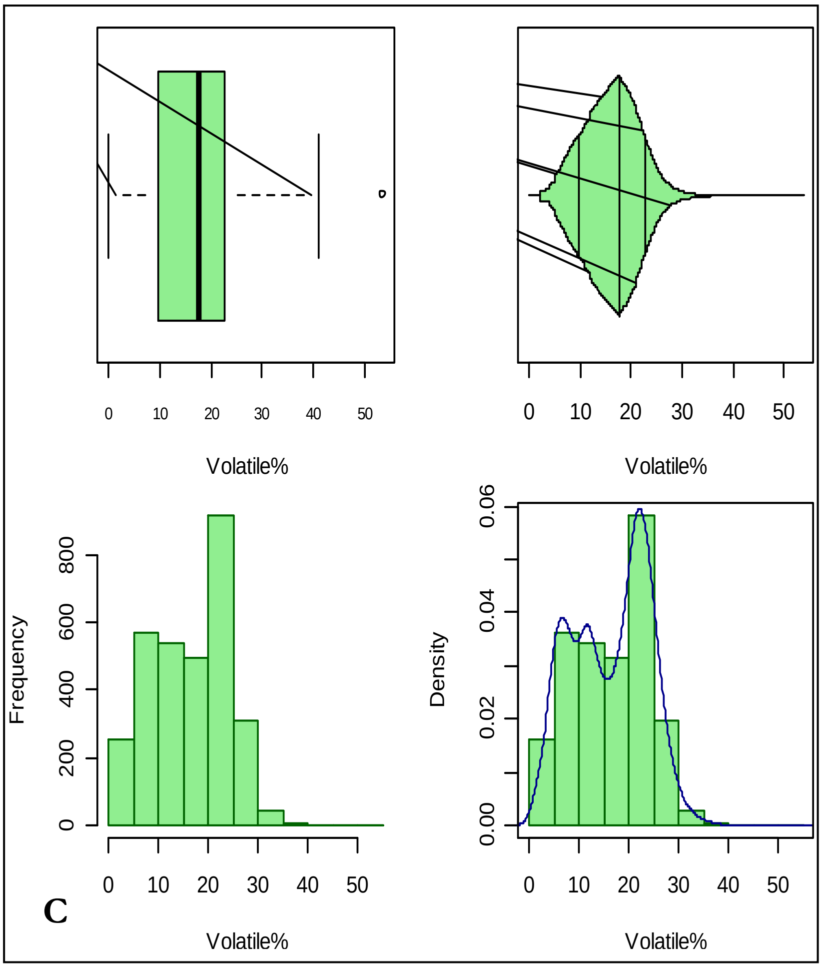
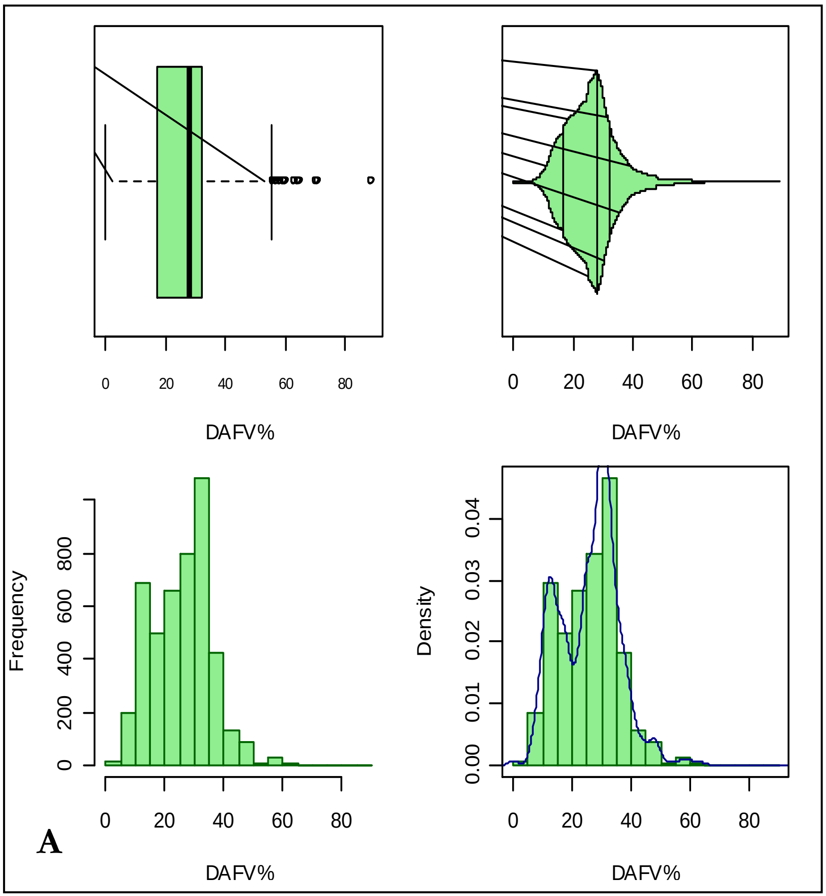


Figure A10: A: Dry ash free volatile percentage % graphical statistics on DO4 dolerite samples. B: Ash % graphical statistics on DO4 dolerite samples. C: Volatile % graphical statistics on DO4 dolerite samples.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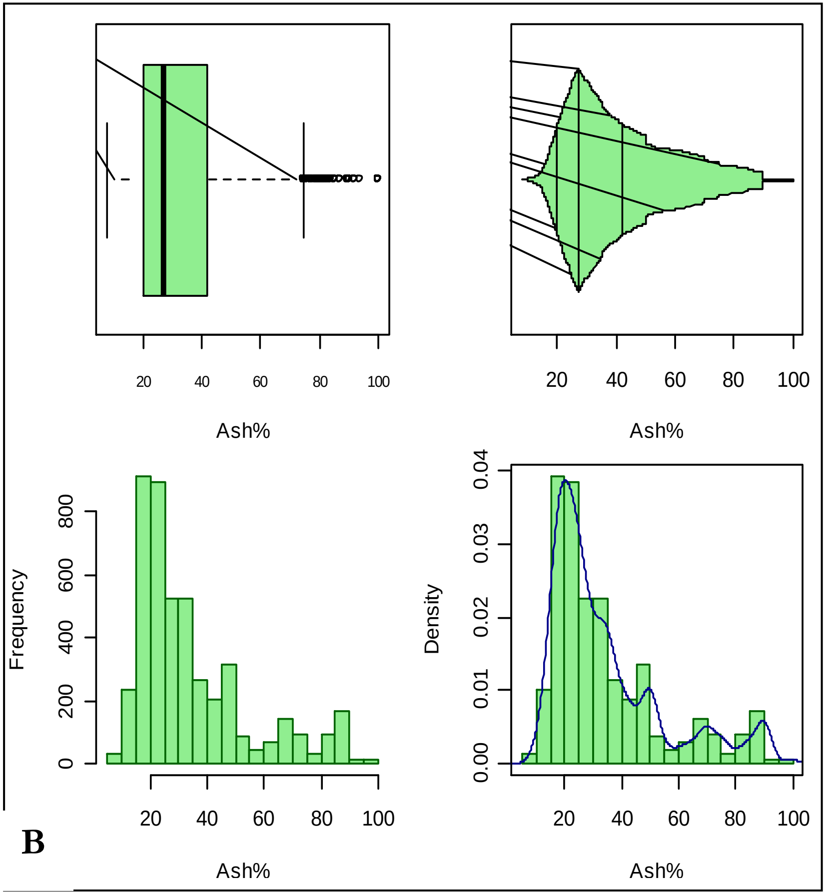
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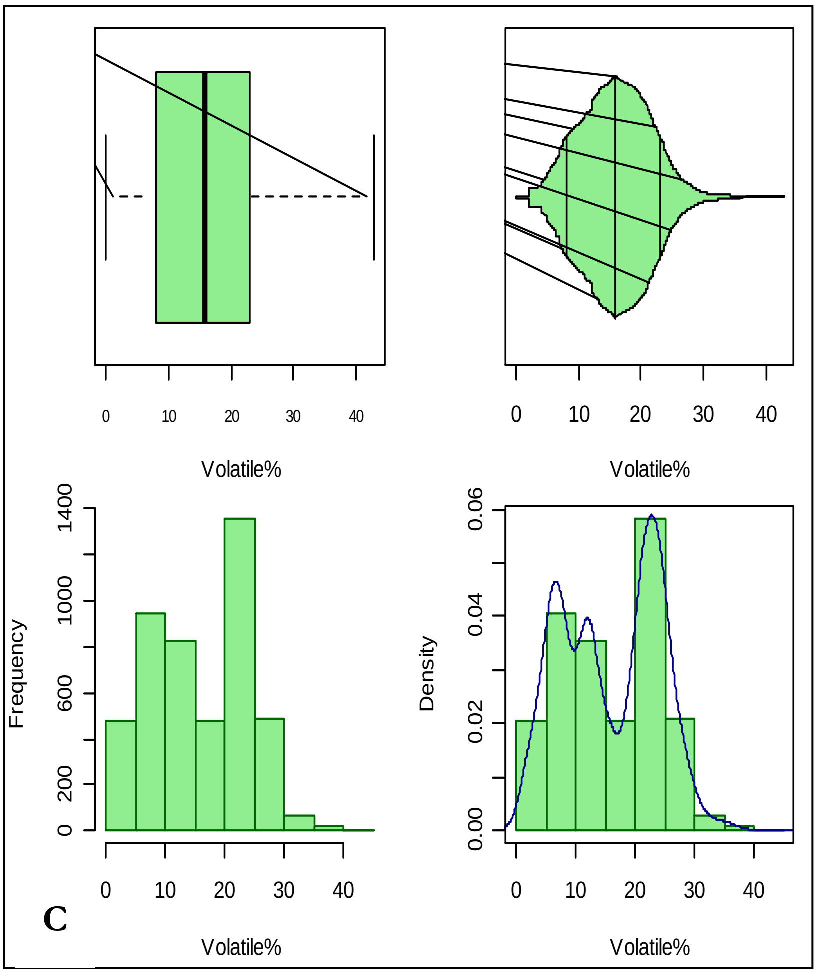
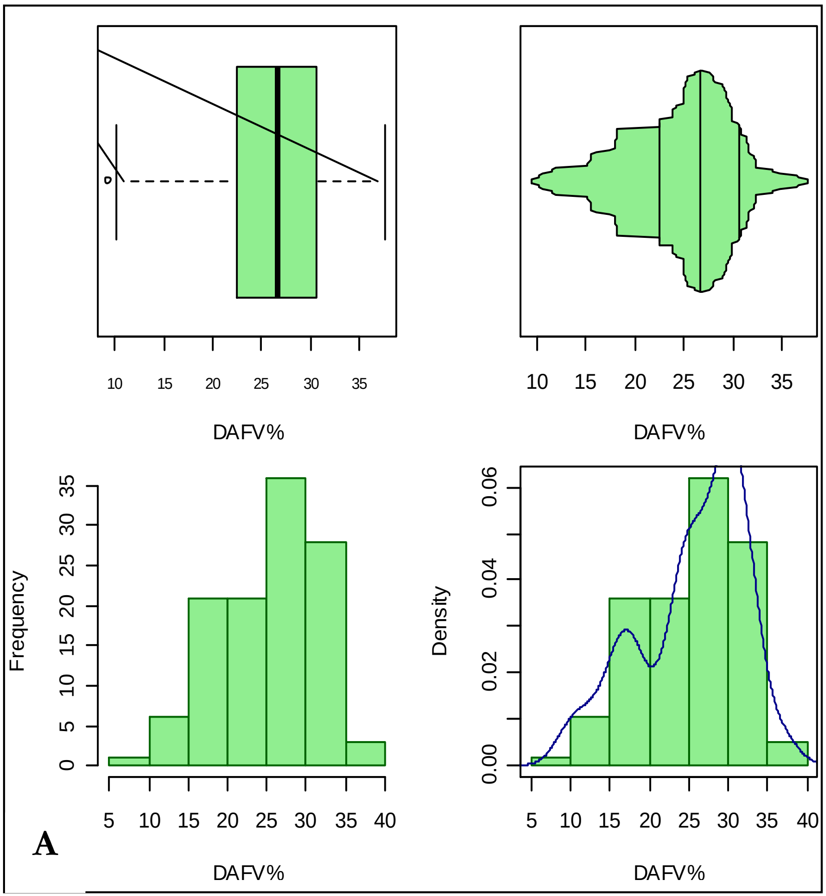


Figure A11: A: Dry ash free volatile percentage % graphical statistics on DO8 dolerite samples. B: Ash % graphical statistics on DO8 dolerite samples. C: Volatile % graphical statistics on DO8 dolerite samples.



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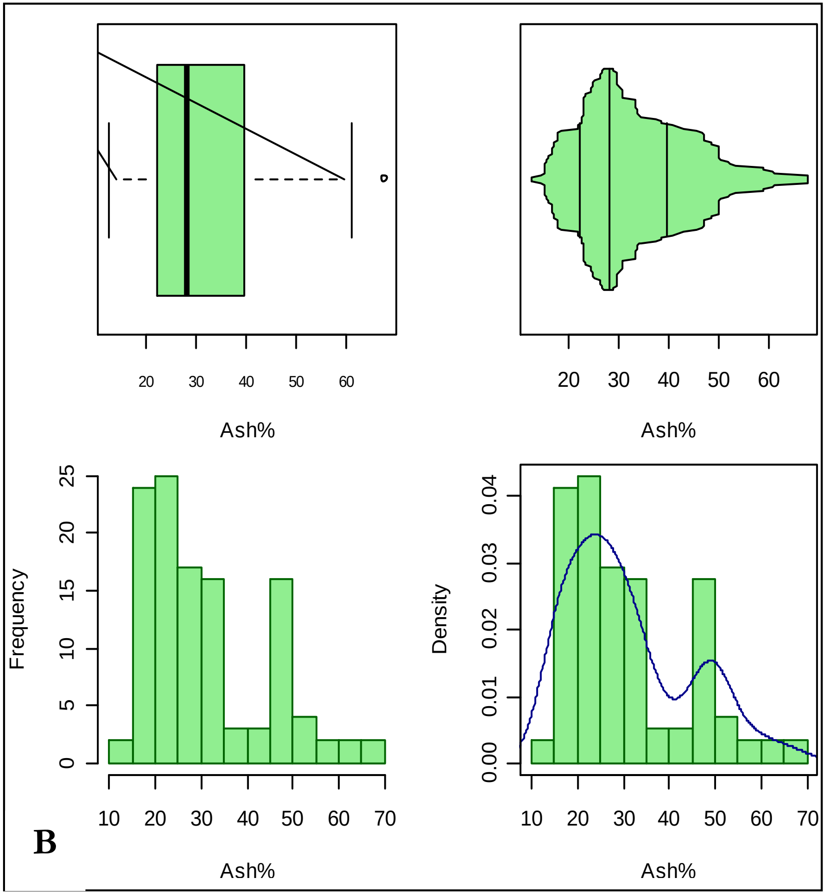

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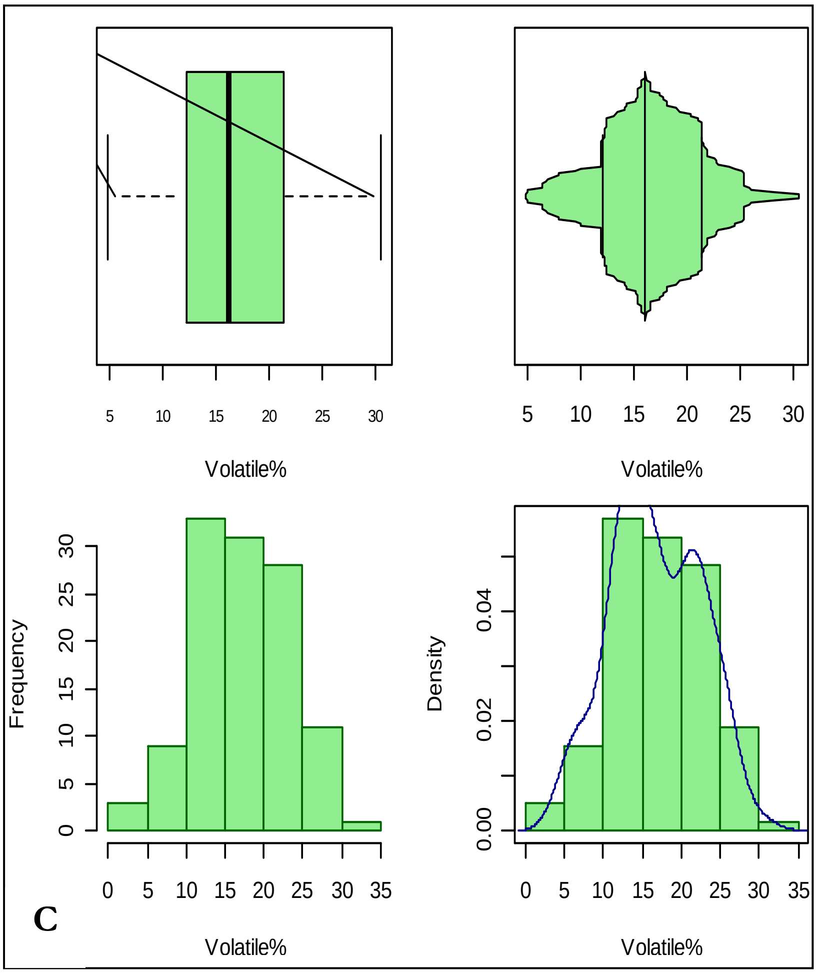

Figure A12: A: Dry ash free volatile percentage % graphical statistics on DO10 dolerite samples. B: Ash % graphical statistics on DO10 dolerite samples. C: Volatile % graphical statistics on DO10 dolerite samples.