ABSTRACT

The granulometric characteristics of sandstones from Cretaceous Knysna and Robberg Formations were studied to determine sandstone types, depositional environments and their possible sources. This research was carried out by measuring the grainsizes of samples in this section using a petrographic microscope. Textural characteristics were determined from grain size properties such as the mean grain size, sorting, skewness and kurtosis all showed the sediment sources as well as sedimentary process the sediments were subjected to. Unimodal to Polymodal grain-size distributions were observed and it is evident that sediments from Robberg Formation are well-sorted to moderately well-sorted, deposited in a beach environment, while sediments from Knysna Formation are moderately well-sorted to moderately-sorted from a fluvial depositional environment. The most possible source of sediments are from weathered underlying Cape Supergroup rocks in the area. Also, the granulometric properties of the robberg sandstones indicate its potential as a reservoir rock, especially for water.

Keywords: granulometric, depositional environment, textural characteristics, robberg formation, knysna formation.

INTRODUCTION

Cretaceous rocks in South Africa were deposited in several basins such as the Pletmos Basin which hosts the Knysna and Robberg Formations. These two rock formations comprise mostly of conglomerates and sandstones which unconformably overly metamorphosed rocks of the Cape Supergroup. These Cape Supergroup rocks were formed during the breakup of Gondwana (Reddering, 2000). This study aims to present the granulometric analysis of sandstones from the study area. We analysed the textural properties of sandstones from these formations and also discuss possible sediment source and depositional environments where the sediments were accumulated.

Several authors have emphasized the importance of textures and mineral composition in the study of sediment types, source and depositional environments (Folk, 1966; Pettijohn, 1975; Datta, 2005; Okeyode and Jibiri, 2013), because “each grain preserves imprints of its geological story” (Garzanti et al., 2008). According to Boggs (2009) and Okeyode and Jibiri (2013), one way to characterize a sediment is by analysis of the grain sizes and mineral types present in the sediment. Textural characteristics include grain-size, shape, sorting which are dependent on statistical parameters such as mean grain size distribution, standard deviation, skewness and kurtosis. Sedimentary rock textures also affect porosity, permeability, density and many other rock properties (Folk, 1966; Qinghai et al., 2005; Boggs 2009). This study was carried out on representative sandstone samples from Knysna and Robberg Formations. The sediments of this formation represents some of the early cretaceous deposits in the south-east coasts of South Africa.

The study area

The study areas Knysna and Robberg Formations lie between latitudes 23°03’34” and 23°21’38” and longitudes 34°02’36” and 34°04’07”. Cretaceous sediments were deposited along the South African coast line, near the boundary between KwaZulu-Natal and the Eastern Cape, with scattered outcrops from Port Elizabeth to George in the south (Reddering, 2000; Norman and Whitefield, 2006). Knysna town generally has a temperate climatic condition with warm summers and cool winters while the area of Plettenberg, most of the time has a mild temperate climatic condition with few rainfalls and temperature extremes.

MATERIALS and METHODS

The most widely used methods for textural analysis are sieving and thin sections granulometric measurements (Folk, 1980). Other methods include Laser Diffractionometry, Settling-tube techniques, Pipette method, Photo-sieving and Photon Correlation Spectroscopy (Kench, 1997; Beuselinck et al., 1998; Donghuai, 2004; Lamorski et al., 2014). In this study, we used thin section granulometric measurements to determine the textural characteristics of sandstones from the study area.

Samples of sandstones were collected systematically from both formations. At each sampling point, about 200 g of the samples were collected and each sample was packed in well labelled zip lock bags. The samples were then sent out to the Council for Geoscience, Pretoria, South Africa, to make thin sections which were brought back to our laboratory where the thin sections were observed using an Olympus BX51 Petrographic microscope at the Department of Geology, University of Fort Hare, South Africa.

For the granulometric analysis, at least 450 grains were measured for each thin section that was studied. This
was done according to the methods of (Folk, 1966; Le Roux and Rojas, 2007). The longest axis of each grain was measured and recorded in millimetres (mm). The values in mm were later converted to their equivalent Phi (ф) values. The grainsizes observed in each thin section were classified using the standard grainsize categories by (Udden Wentworth, 1922). The statistical parameters such as mean grainsize; sorting, skewness and kurtosis for each thin section were also calculated. Various values of sorting and their verbal terms are: <0.35 = very well sorted, 0.35 - 0.50 = well sorted, 0.50 - 0.71 = moderately well sorted, 0.71 - 1.00 = moderately sorted, 1.00 - 2.00 = poorly sorted 2.0 - 4.00 = very poorly sorted and >4.00 = extremely poorly sorted. Sorting has the same value as the graphic standard deviation of the grain-size data which can be calculated using Equation (1). For skewness, the values and verbal terms are: 1.00 – 0.30 = Very negative, -0.30 - -0.10 = Negative, -0.10 - +0.10 = Near symmetric, +0.10 - +0.30 = Positive and +0.30 - +1.00 = Very positive, skewness can be calculated using Equation 2. While Kurtosis values and their verbal interpretations are: 0.67 - 0.90 = wide, 0.90 - 1.11 = medium, 1.11 - 1.50= narrow, 1.50 – 3.00 = very narrow and >3 = extremely narrow.

Bivariate plots of the textural parameters were also constructed so as to emphasise depositional environments. Over the past years sedimentologists have used bivariate analysis to interpret depositional energy, environment and transportation mode (Essien et al., 2016), because it is believed that differences in fluid-flow mechanisms can be reflected in statistical parameters (Alsharhan and El-Sammak, 2004).

\[ S_1 = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_{5}}{6.6} \]

**Equation 1:** Formula for calculating sorting in grain-size analysis (ϕN = ϕ value at Nth percentile).

\[ S_{kl} = \frac{\phi_{84} + \phi_{16} - 2(\phi_{50})}{2 (\phi_{84} - \phi_{16})} + \frac{\phi_{95} + \phi_{5} - 2(\phi_{50})}{2 (\phi_{95} - \phi_{5})} \]

**Equation 2:** Formula for calculating skewness in grain-size analysis (ϕN = ϕ value at Nth percentile).

\[ K_g = \frac{\phi_{95} - \phi_{5}}{2.44 (\phi_{75} - \phi_{25})} \]

**Equation 3:** Formula for calculating kurtosis in grain-size analysis (ϕN = ϕ value at Nth percentile).

**RESULTS**

**Textural characteristics**

Textural parameters were measured according to the procedure in the methods section and the results are reported in Table-1. The mean grain size observed for Robberg Formation is 1.69ф (Table-1). This means that the most of the Robberg Formation Sandstones are medium grained, while the mean grain size for the sandstones of Knysna Formation Sandstones is 2.02ф, meaning that Knysna sediments are mostly fine grained (Table-1). Histograms and cumulative frequency curves were generated for both formations (Figure-1 and Figure-2); the other statistical parameters were generated from these.

**Figure-1.** Representative histogram and cumulative frequency curve for the grain-size distribution in sandstone samples from Robberg formation, showing medium to fine grained sandstone. Sample has a polymodal distribution.
Figure-2. Representative histogram and cumulative frequency curve for the grain-size distribution in Sandstone samples from Knysna formation showing medium to fine grained sandstone.

Table-1. Derived values for sorting, mean, skewness and kurtosis for grain-sizes of Robberg and Knysna formation sandstones.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mean (M)</th>
<th>Sorting ($S_1$)</th>
<th>Skewness ($S_{sk}$)</th>
<th>Kurtosis ($K_g$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Robberg formation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R 1</td>
<td>1.37</td>
<td>0.45</td>
<td>0.21</td>
<td>1.21</td>
</tr>
<tr>
<td>R 2</td>
<td>2.20</td>
<td>0.64</td>
<td>-0.35</td>
<td>0.81</td>
</tr>
<tr>
<td>R 3</td>
<td>2.10</td>
<td>0.59</td>
<td>-0.20</td>
<td>1.14</td>
</tr>
<tr>
<td>R 4</td>
<td>1.31</td>
<td>0.49</td>
<td>-0.01</td>
<td>1.74</td>
</tr>
<tr>
<td>R 5</td>
<td>1.35</td>
<td>0.59</td>
<td>-0.01</td>
<td>1.29</td>
</tr>
<tr>
<td>R 6</td>
<td>1.84</td>
<td>0.45</td>
<td>-0.05</td>
<td>0.78</td>
</tr>
<tr>
<td>R 7</td>
<td>1.73</td>
<td>0.53</td>
<td>0.00</td>
<td>0.70</td>
</tr>
<tr>
<td>R 8</td>
<td>1.70</td>
<td>0.49</td>
<td>0.00</td>
<td>0.76</td>
</tr>
<tr>
<td>R 9</td>
<td>1.58</td>
<td>0.47</td>
<td>0.14</td>
<td>0.99</td>
</tr>
<tr>
<td>Average</td>
<td>1.69</td>
<td>0.52</td>
<td>-0.03</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>Knysna formation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K4</td>
<td>2.02</td>
<td>0.52</td>
<td>0.00</td>
<td>0.82</td>
</tr>
<tr>
<td>K6</td>
<td>1.98</td>
<td>0.92</td>
<td>-0.10</td>
<td>0.79</td>
</tr>
<tr>
<td>K7</td>
<td>2.47</td>
<td>0.66</td>
<td>-0.21</td>
<td>0.71</td>
</tr>
<tr>
<td>K8</td>
<td>1.42</td>
<td>0.43</td>
<td>0.14</td>
<td>1.27</td>
</tr>
<tr>
<td>K9</td>
<td>2.23</td>
<td>0.59</td>
<td>-0.33</td>
<td>0.82</td>
</tr>
<tr>
<td>Average</td>
<td>2.02</td>
<td>0.62</td>
<td>-0.10</td>
<td>0.88</td>
</tr>
</tbody>
</table>

The dominant medium sized grains of Robberg Formation indicate that the depositional energy was moderate, while the depositional energy for Knysna was relatively lower than that of Robberg Formation. Most of the sandstones from both formations are polymodal and this indicates different transportation and depositional processes. Knysna has more polymodal sediments which may indicate a possible aeolian sediment source for some of the sediments (Sun et al., 2002).
Robberg Formation sandstones have sorting values ranging from 0.45 to 0.69, indicating that this formation is composed of well sorted to moderately well sorted grains. Knysna Formation on the other hand has sorting values ranging from 0.43 to 0.92, although only one sample had sorting less than 0.50, this means that Knysna Formation sandstones are composed mostly of moderately well sorted to moderately sorted grains. Sorting is often used to characterise the kinetic energy within the deposition environment (Folk, 1966; Le Roux and Rojas, 2007). The sorting values obtained indicate that deposition energy was moderate to high. Knysna sandstones show less sorting than those of Robberg Formation indicating there was a lower deposition energy for knysna sediments, this prevented the complete sorting of the sediments.

The skewness values observed for Robberg Formation ranged from strongly coarse to coarse to fine or very negative to positive with values ranging from -0.35 to 0.21 (Table-1). Knysna Formation sediments on the other hand had very negative, negative and near symmetric skewness or strongly coarse to coarse with values ranging from -0.33 to 0.14 (Table-1). Skewness is mostly affected by depositional environments (Sharma et al., 2017), the positive values indicates the presence of finer grained sediments while the negative values are associated with more coarse grains (Okeyode and Jibiri, 2012). The average skewness values for Robberg Formation is -0.30 and -0.10 for knysna, the negative values indicate that there was turbulence at some point in time during deposition which resulted in the deposition of relatively coarse sediments. The Kurtosis observed for Robberg formation ranged from wide (platykurtic) to narrow (leptokurtic) while in Knysna, the major kurtosis is wide (platykurtic) with only one sample having a narrow kurtosis. This means the distributions have thinner tails. There were no negative kurtosis values observed for any of the sample distributions. The average values of kurtosis 1.05 for Robberg Formation and 0.88 for Knysna Formation indicate the sediments are not well sorted, meaning they were transported in a relatively low energy environment and deposition also took place in the same environment. Knysna sediments were deposited in an even lower energy environment as compared to Robberg.

Bivariate analysis

Bivariate plots of the textural parameters were also constructed to link and apply the depositional environments. Over the past years sedimentologists have used bivariate analysis to interpret depositional energy, environment and transportation mode (Essien et al., 2016) as it is believed that differences in fluid-flow mechanisms can be reflected in statistical parameters of grain distribution (Alsharhan and El-Sammak, 2004). The sections below describe the bivariate characteristics of the grain size of the Knysna and Robberg Formation Sandstones.

Kurtosis versus skewness

According to Watson et al. (2013), the trend in the kurtosis versus skewness plot could be used to determine the type of a deposition setting, i.e. shallow marine, fluvial or basin environment. Wide or platykurtic kurtosis were observed throughout most of the sandstone samples (Figure-3) of both Robberg and Knysna Formations. According to Friedman (1961), extremely high or low values of kurtosis indicate that the sediments were already sorted in a high energy environment before they were deposited in their current environment. In this study, the skewness values ranged from very negative to near symmetric. The negative skewness values are indicative of a beach environment (Essien et al., 2016). As skewness increases in value, kurtosis gets wider, indicating the samples of both Robberg and Knysna Formations show a positive relationship between kurtosis and skewness.

![Figure-3. Bivariate scatter plot showing kurtosis versus skewness.](image-url)
Kurtosis versus sorting
Wide or platykurtic kurtoses are observed for most of the samples. Only one sample from Knysna Formation was not platykurtic. From the samples distribution in Figure-4, it is observed that as the extent of sorting reduces, kurtosis gets wider, indicating that the samples from both Robberg and Knysna Formations show a negative relationship between kurtosis and sorting. The wider the kurtosis, the higher the sorting.

![Figure-4. Bivariate scatter plot showing Kurtosis versus sorting.](image)

Kurtosis versus mean
The relationship between kurtosis and mean grain size is complicated, but shows a negative relationship, i.e. the coarser the grain size, the narrower the Kurtosis. Figure-5 shows that as the grain size decreases, the kurtosis become more widely distributed. This may be due to the fact that there is relatively more sorting in the coarse sediments but they get finer and less sorted with a change in depositional environment.

![Figure-5. Bivariate scatter plot showing kurtosis versus mean.](image)
Sorting versus mean

The plot of mean versus sorting indicates that the sediments are medium to fine grained and are all well sorted to moderately well sorted except for one sample from Knysna Formation which is just moderately sorted and medium grained. The relationship between the mean and sorting shown in Figure-6 indicates a positive relationship, which means that, coarse grain sized sediments were more well sorted compared to fine grain-sediments. The mixture of well sorted to moderately well sorted grains indicate a continuous reworking process by waves and currents (Baiyegunhi et al., 2017a). The change in the sediment grain size and sorting points to a change in hydrodynamic energy of the depositional medium.

**Figure-6.** Bivariate scatter plot showing sorting versus mean (After Folk, 1974).

Skewness versus sorting

The plotting of skewness versus sorting provides an effective means to differentiate among river and beach sands (Boggs 2009; Okeyode and Jibiri, 2012). From the plot of skewness versus sorting (Figure-7), it can be deduced that as the skewness increases, the sorting of grains also increases.

**Figure-7.** Bivariate scatter plot showing skewness versus sorting.
Only one sample from Knysna Formation falls outside the moderately well sorted class, all others ranged from well sorted to moderately well sorted. Most of the samples fall within the fine skewed range, the presence of shells and other fragments may be responsible for the few coarse skewed samples. The well sorted grains are indicative of a beach deposition environment, which is the majority of the sediment distribution (Mukherjee et al., 2015); while the moderately well sorted indicate a fluvial environment. As sorting increases, skewness becomes more positive, most of Knysna Formation sediments fall within the moderately sorted range and according to Friedman (1967), river sediments fall in the right hand side in the plot of skewness versus sorting.

**Depositional settings derived from bivariate plots**

The plots of sediment grain size distribution, skewness and sorting have often been used to classify depositional environments and the processes of sedimentation. In this section, bivariate plots of skewness versus mean and mean versus sorting were used to distinguish depositional environments.

Bivariate plots are common methods employed to determine the possible environments of sediment deposition. Researchers since the 1960s (Friedman, 1967; Moiola and Weiser, 1968; Tanner, 1991) have developed boundary lines for differentiating environments within specific bivariate plots. These plots have been used to differentiate between shallow marine (beach) and fluvial depositional environments for sediments. Figure-5.20 shows the plot of skewness versus mean grain size. From this result, we realize that most of Knysna Formation sediments (about 80%) fall within the river depositional environment with only one sample found in the beach environment. According to Friedman (1979), fluvial sediments are clustered towards the right hand side in the plot of skewness versus mean. This agrees with our observations for most of Knysna Formation sandstones. Most of the river sediments are very close to the beach-river marginal line (Figure-8); this is probably due to deposition in the lower reaches of a fluvial system. Robberg Formation sediments on the other hand were mostly located on the beach side, only 11% of the distribution falls within the river environment.

The relationship between mean and sorting was also used to discriminate depositional environments by Moiola and Weiser (1968). This indicated a river environment for most of Knysna sediments and a beach environment for most of Robberg Formation (Figure-9).

![Figure-8. Bivariate scatter plot showing skewness versus mean (boundary after Friedman, 1967; Tanner, 1991).](image-url)
Figure-9. Bivariate scatter plot showing mean versus sorting (boundary after Moiola and Weiser, 1968; Tanner, 1991).

From the bivariate scatter plots, beach and river sediments have been identified for both formations and the changes observed in the sediment environment distribution may be due to mixing activities between marine and fluvial environments as most of the samples were found very close to the beach-river boundary of coastline environments. The plot of skewness versus mean is important for the differentiation between beach and river environments (Tanner, 1991).

DISCUSSION AND CONCLUSIONS

Based on the average values of the statistical grain size parameters for Robberg and Knysna Formations, the mean grain size value for Robberg Formation is 1.69 Ø indicating medium grained sandstones are present and for Knysna Formation, a mean grain size value of 2.02 Ø indicates fine grained sandstones are dominant. Robberg formation sandstones were mostly well sorted, negatively skewed and have medium kurtosis while Knysna Formation sandstones were moderately well sorted, positively skewed with a wide kurtosis. The histograms and cumulative frequency curves show a unimodal grain size distribution for most of Robberg Formation, while Knysna Formation has mostly bimodal grain size distribution. Based on the depositional settings derived from the bivariate plots of skewness vs mean and mean vs sorting, a beach environment was indicated for Robberg Formation and river environment for Knysna Formation. The samples from Robberg Formation which fall within the river area on the plots were most likely due to the fact that the beach sands still have the characteristics of river sands as they have not yet come to equilibrium with their new environment (Essien et al., 2016). The results obtained from the bivariate plots also confirmed that the sediments of the study area have been mainly controlled by marine and fluvial processes.

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