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Mineralogical, Microstructural and Physio-Mechanical Characterisation of the Low-Grade Metamorphosed Phyllites: The Chancellor and Galera Formations of Trinidad

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Abstract: *Low-grade metamorphosed sedimentary phyllites represent a characteristic lithological member of the Upper Member of the Chancellor Formation and the Galera Formation of Trinidad. From limited localities, the exposure along the Lady Young Road and at the Keshorn Walcott Lighthouse site has been chosen and subjected to field as well as laboratory study (including x-ray diffraction (XRD), scanning electron microscopy (SEM), physical properties characterisation and compressive strength). This is an attempt at quantitatively characterising the mineralogy as well as determining the elemental distribution within the rocks of the formations. The results are expected to contribute to the existing literature on the petrophysical and microhardness characterisation of the Chancellor and Galera Formations. The following mineral phases were found: quartz+calcite+muscovite+chlorite+orthoclase – Chancellor; and quartz+muscovite+orthoclase - Galera. For samples from both formations, there was a high degree of variability in miscrostructure, and from an elemental perspective a widespread distribution of silicon, aluminium and potassium was unveiled. Physical characteristics such as apparent porosity and water absorption were also determined. The compressive strength parallel to the direction of layering indicate that both formations could be characterised as very weak to weak. The knowledge of the properties of these phyllites of the Chancellor and Galera formations is pertinent to geotechnical design and stability evaluation applications in these areas.*

Keywords: *Electron microanalysis; Lower Cretaceous; Low-grade metamorphosed; Tertiary-Quaternary; X-ray diffraction*

1. Introduction

Geologically, Trinidad is located at the southeastern corner of the Caribbean Plate and the South American Plate (Donovan, 1994). Barr (1963) divided Trinidad into five (5) physiographic regions, one of which, the Northern Range, was the sample location in this research. The Northern portion of Trinidad forms an eastern continuation of the Sierra de la Costa of eastern Venezuela, which Barr (1962) considered as an extreme eastern ramification of the Andean fold mountain system (Cruz et al., 2007). The Northern Range is comprised of a series of ridges parallel to one another with varying metamorphosed sedimentary and igneous rocks. The northern region of the range is steeper than the southern sloping side.

The Northern Range, varying in age from Upper Jurassic to Lower Cretaceous, is made up of a series of low grade metamorphosed sedimentary rocks which were predominantly argillaceous and are now represented by lustrous sericitic phyllites (Barr, 1962). The regions of focus in this study are the Chancellor and Galera Formations. In general, previous studies of the Northern Range have described the rocks in terms of lithostratigraphical, geological, petrological, microscopical and mineralogical characteristics.

For instance, first published and mentioned by Kugler (1959) in the Geological Map of Trinidad, the Chancellor Formation is Lower Cretaceous in age. Potter (1974) used stratigraphic methods to characterise the Chancellor Formation into four (4) members due to the distinct variation of lithology observed. Geologically, the Chancellor Formation consists of an interbedded group of limestones and phyllites. Potter (1974) using thin sections concluded, from his analysis that the limestones from the Chancellor are less pure than those found in the surrounding formations. Frey, Saunders and Schwander (1988) used x-ray powder diffraction to determine the mineralogy of the rock sample, but only qualitatively.

The Galera Formation is the youngest in the eastern part of the Northern Range (Barr, 1963). Using paleontological evidence, the age of the Galera Formation was determined to be Late Cretaceous. Wall and Sawkins (1860) termed the rocks consisting the

Galera Formation as a series of low-grade metamorphic rocks, with sequences of shales, thin limestones and sandstones. This description is notably similar to Barr's (1963). Also, the mineralogy of the rock samples was determined qualitatively using x-ray powder diffraction by Frey, Saunders and Schwander (1988).

In this study, a non-invasive experimental approach which involved a combination of petrophysical techniques to characterise the rock samples was adopted. Some of these included x-ray diffraction (XRD), scanning electron microscopy (SEM) and physical characterisation methods. With the application of these techniques, these outcrop samples can be quantitatively and qualitatively characterised in terms of their mineralogy and elemental composition (Baboolal, 2013). Therefore, the main objective of this research was to give a more detailed mineralogical, microstructural and physio-mechanical characterisation of the metamorphosed sedimentary rocks of the Formations using a combination of advanced analytical techniques that are now available.

2. Materials and Methods

2.1 Sampling and Sampling Technique

In previous studies of the Northern Range, many researchers were unable to examine certain regions due inaccessibility of the area and outcrops; dense forest cover; and the presence of dangerous fauna such as the poisonous *Tripanurgos compressus* snake, more commonly known as the Mapepire. These factors had to be considered in this present study, therefore samples were taken at easily accessible outcrops along the Lady Young Road and at the Keshorn Walcott Lighthouse (See Figures 1 and 2). Fresh, un-weathered samples were taken to avoid probable misleading results should weathered samples be used. The samples were chiselled out of the rock mass beneath the regolith layer.

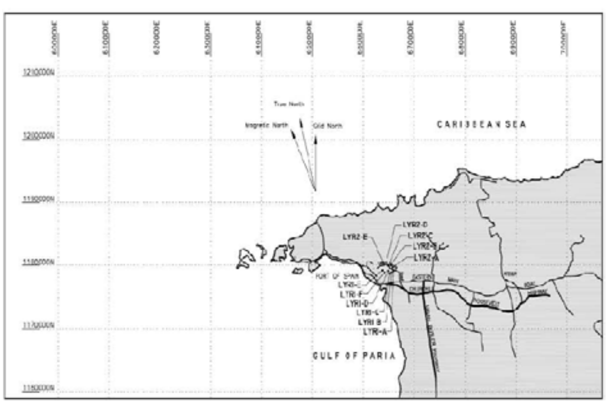


Figure 1. Sampling points for the twelve samples taken from the Chancellor Formation, in the west of the Northern Range, Trinidad

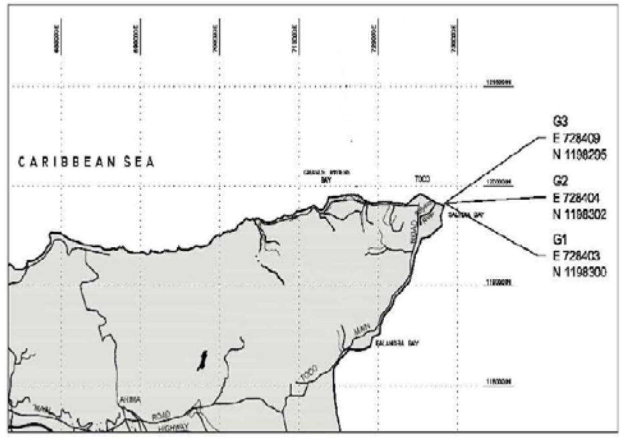


Figure 2. Sampling points for the three samples taken from the Galera Formation, in the east of the Northern Range, Trinidad

2.2 Experimental Methods

2.2.1 X-ray Powder Diffraction

XRD mineralogical characterisation of the rock samples was done using Cu Kα radiation in a Bruker 5005D x-ray diffractometer. Samples from the bulk rocks were ground to a particle size less than 500 µm, and analysed over the 2-theta range 3º to 40º. In conjunction with the qualitative profiles obtained, the TOPAS software based on the Rietveld quantitative phase analysis (Jenkins and Snyder, 1996; Knorr and Bruker, 2008; Pecharsky and Zavalij, 2009; Szponder and Trybalski, 2010) was used to generate quantitative data. This is a widely used and reliable quantitative phase analysis technique employed in both research and industry (University of Cambridge, 2012).

2.2.2 Scanning Electron Microscope

Fractured sections from the bulk rocks were gold coated and imaged in a Philips 500 electron microscope operated at 20 kV. Energy Dispersive X-ray Analysis (EDXA) elemental mapping was also done using the electron microscope together with the EDAX Genesis elemental analyser (Goldstein et. al., 2003).

2.2.3 Physical Characterisation Methods

The water displacement method, based on Archimedes' principle, was used to determine the apparent porosity, bulk density and water absorption of the samples (Yavuz et al., 2010). The method involved obtaining a dry weight W_d, and a wet weight W_w after the open pores were saturated with water under vacuum. Subsequently, a suspended weight W_s was also obtained. These weights were used to calculate the various physical property parameters according to:

$$Apparent\ Porosity = \frac{W_w - W_d}{W_w - W_s} \times 100\% \quad (1),$$

$$Water\ Absorption = \frac{W_w - W_d}{W_d} \times 100\% \quad (2), \text{ and}$$

$$Bulk\ Density = \frac{W_d}{W_w - W_s} \quad gcm^{-3} \quad (3).$$

Table 1. General description of the rock samples analysed from the Chancellor Formation

Rock Classification	Sample	General Description
Phyllite	LYR1-A	Dark grey and orange appearance on the exterior with a pearly lustre and black spots. The structure of the rock was highly laminated.
Quartz phyllite	LYR1-B	Dark brown to red appearance on the exterior. Texturally hard, dense and an angular orientation. Crystallized interior, mostly white with minor orange translucent crystals, and clear translucent crystals infused.
Phyllite	LYR1-C	A mix of red, orange and brown appearance on the outside. Texturally hard, dense and possesses an angular orientation. The interior was white, crystallized and translucent crystals infused throughout the rock.
Quartz phyllite	LYR1-D	Soft and layered texture. Cream, red and brown appearance. Small, dark brown irregular fragments embedded inside the white matrix of the sample.
Phyllite	LYR1-E	Thin, soft layered, exterior and pearly brown in apperance. Adjoined with hard, dense white glassy interior. Brown fragments embedded the white crystallized (non-translucent) matrix.
Schist	LYR1-F	Red to brown in colour. Soft, fine grained, and highly laminated in texture.
Phyllite	LYR2-A	Light grey appearance with pearly lustre. The structure was hard and dense with a layered texture.
Phyllite	LYR2-B	Grey and black appearance with pearly lustre. The structure of the sample was highly laminated.
Quartz phyllite	LYR2-C	Dark, grey and orange appearance on the exterior. The rock had a hard texture. Interior of the sample was made up of a dense white matrix.
Phyllite	LYR2-D	Light grey, with dark grey striations and slight lustre appearance on the outside of the rock. Dull light and dark grey bands on the interior. The sample was dense in nature.
Quartz phyllite	LYR2-E	Dark, grey appearance on the exterior. The structure had a hard texture. Interior of the sample was made up of a dense white matrix.
Quartz phyllite	LYR2-F	White crystallized interior appearance with brown, glassy, fragments embedded on the surface and throughout the rock. Dark grey weathered appearance on the exterior.

From each bulk sample twelve (12) replicates were used to calculate the standard deviation.

2.2.4 Compressive Strength

Cuboid-shaped samples of dimensions 3cm x 3cm x 5cm from the Chancellor Formation were cut from the bulk samples and tested in compression using a Tinius Olsen H20K-W Tensometer. Compressive strength values were determined both parallel and perpendicular to the direction of layering for the rock samples.

3. Results and Discussion

3.1 Chancellor Formation

3.1.1 General Description of Samples

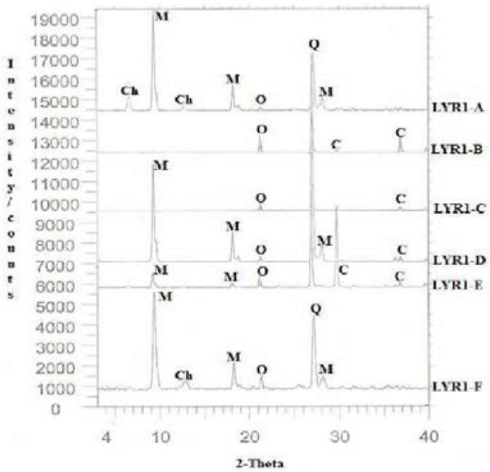
Table 1 shows the general description of the Chancellor samples analysed--labelled LYR1-A to LYR1-F and LYR2-A to LYR2-F. These samples were either friable, highly laminated, hard or dense in nature and varying in colour—grey, orange, brown and red hues (see Figure 3 (a) – (f)).

3.1.2 X-Ray Diffraction (XRD)

All the Chancellor samples are similar, from the viewpoint of mineral composition. They are essentially composed of a mixture of quartz+calcite+muscovite+chlorite+orthoclase in different ratios as shown in Table 2.

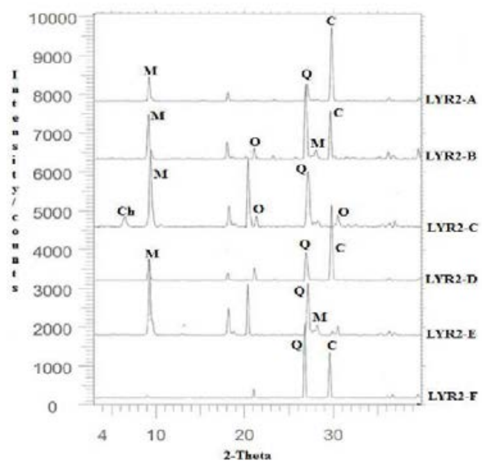
Figures 4(a) and 4(b) show normalised XRD profiles for the LYR1-F and LYR2-A to LYR2-F samples respectively. From previous x-ray diffraction analyses performed by Frey, Saunders and Schwander (1988) the major minerals detected were muscovite, quartz, dolomite and calcite. As can be seen, quartz and muscovite were the most prominent minerals detected in the samples of this study. In LYR1-A to LYR1-F orthoclase was not detected. The mineralogical intermix of some samples varied, for example sample LYR1-D's XRD profile did not display the characteristic 29˚ to 30˚ 2θ diffraction peak for calcite. Hence no quantitative value could have been determined for this sample (Figure 4(a) and Table 2). For the LYR1-E sample the intermix is composed of mainly quartz+calcite+muscovite with no chlorite detected.

Figure 3 (a) – (f). Selected samples from the Chancellor and Galera Formations: (a) LYR1-A, (b) LYR1-D, (c) LYR1-F, (d) LYR2-B, (e) LYR2-D and (f) G2



Explanation: Q = Quartz, Ca = Calcite, M = Muscovite, Ch = Chlorite and O = Orthoclase

Figure 4(a). Normalised XRD profiles for samples LYR1-A to LYR1-F from the Chancellor Formation



Explanation: Ch = Chlorite, M = Muscovite, Q = Quartz, O = Orthoclase and Ca = Calcite

Figure 4(b). Normalised XRD profiles for the samples LYR2-A to LYR2-F from the Chancellor Formation

3.1.3 Scanning Electron Microscopy (SEM)

The secondary electron SEM image of a selected region in the LYR1-A sample, is texturally defined as being both dense and highly layered (Figure 5(a)). The dense nature of the sample, could be due to the intermix of quartz/calcite/chlorite (as indicated by the arrow on the left hand side of Figure 5 (a)) amounting to 93% (Table 1). Notice the highly laminated muscovite region on the top right hand side of the micrograph.

Glassy brown fragments embedded into the white crystallized matrix were located throughout samples LYR1-E, LYR2-C, LYR2-E and LYR2-F, indigenous to the Chancellor Formation (see Table 1). Mineralogically, quartz and muscovite were similarly identified in the samples mentioned. The glassy brown fragments were characterised as discoloured quartz grains.

A selected region of the discoloured quartz grains in sample LYR1-E, and small voids throughout the image are indicated with white arrows (see Figure 5(b)). This region was observed at a higher magnification imaging as shown in Figure 5(c) which clearly highlights the dense, thin laminated structure.

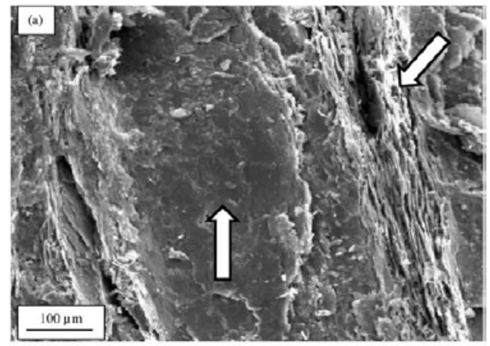


Figure 5(a). Secondary electron SEM image of a selected area of the LYR1-A sample

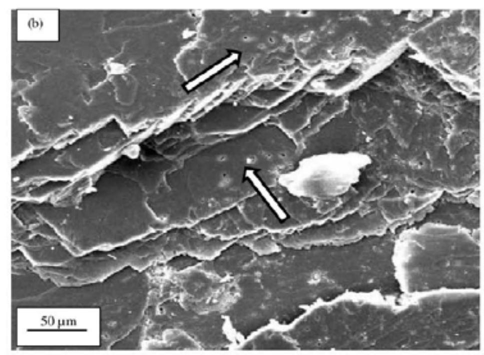


Figure 5(b). Secondary electron SEM image of a selected area of the discoloured quartz grains in sample LYR1-E

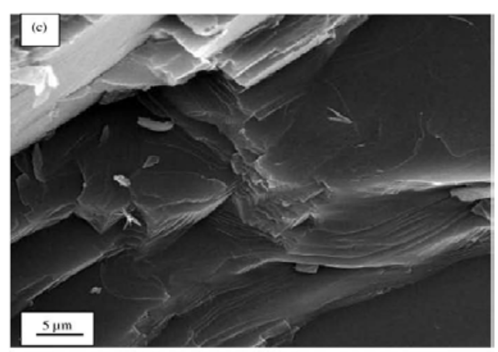


Figure 5(c). Secondary electron SEM image of a selected region of the area seen in (b), sample LYR1-E at higher magnification (x2300)

Meaningful microstructural investigation was possible using the SEM micrograph of a selected region of the LYR1-A sample (see Figure 6) with the corresponding elemental maps shown in Figure 7.

Table 2. Quantitative mineralogical percentages for the samples collected from Chancellor Formation

Sample	Quartz/ %	Calcite/ %	Muscovite/ %	Chlorite/ %	Orthoclase/ %
LYR1-A	69.07	2.61	7.67	20.65	---
LYR1-B	96.89	1.57	0.72	0.83	---
LYR1-C	98.90	0.31	0.67	0.12	---
LYR1-D	90.00	---	2.22	7.78	---
LYR1-E	56.52	36.15	7.33	---	---
LYR1-F	56.60	0.65	6.49	36.26	---
LYR2-A	18.94	71.72	9.34	---	---
LYR2-B	65.09	---	17.84	1.36	15.71
LYR2-C	62.21	---	12.34	6.48	18.97
LYR2-D	31.78	57.22	9.99	1.01	---
LYR2-E	10.52	---	4.89	4.48	80.11
LYR2-F	75.23	21.11	2.20	1.46	---

Consistent with quartz, calcite, chlorite and muscovite being the major constituents (see Table 2), areas rich in, for example, Al (Figure 7(a)), Fe (Figure 7(b)), Si (Figure 7(c) and K (Figure 7(d)) are clearly identifiable. Trace amounts of Ba, Zn and O were also detected and confirmed on the basis of the EDXA spectrum (Figure 8) obtained from the same field of view of the sample.

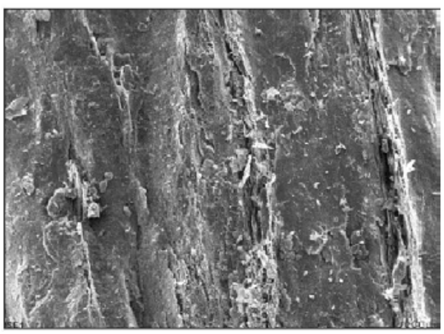


Figure 6. Scanning Electron Micrograph showing a selected field view of sample LYR1-A

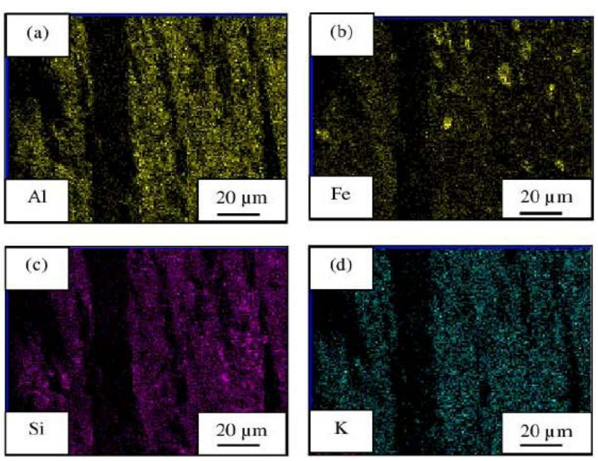
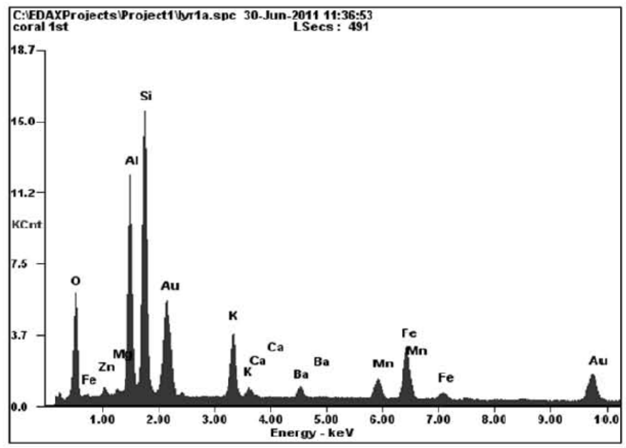


Figure 7. Significant EDXA elemental maps obtained for Sample LYR1-A indicating areas rich in (a) aluminium, (b) iron, (c) silicon and (d) potassium



Note: Au derived from coating used during preparation

Figure 8. The EDXA Spectra obtained from the same field of view of the sample LYR1-A

3.1.4 Physical and Mechanical Properties

Table 3 shows the apparent porosity, bulk density and water absorption of the Chancellor samples. For all of the samples, the apparent porosity and the water absorption were in the range 1-16%. Figures 5(a), (b) and (c) show the porous nature of the sample, which is consistent with the values determined for apparent porosity and water absorption.

3.1.5 Compressive Strength

The compressive strength, perpendicular and parallel to the direction of layering were 4.04 MPa and 7.42 MPa respectively, for the Chancellor Formation. In this case, the compressive strength parallel to the direction of layering is approximately twice the compressive strength perpendicular to the direction of layering. From the compressive strength parameters, the Chancellor Formation can be characterised as a very weak region based on Brown (1981).

3.2 Galera Formation

3.2.1 General Description of Samples

Table 4 shows the general description of the Galera samples analysed labelled G1, G2 and G3 which were

Table 3. Physical Properties of the Chancellor samples

Sample Name	Apparent Porosity/ %	Bulk Density/ g cm^{-3}	Water Absorption/ %
LYR1-A	7.03 ± 2.24	1.61 ± 0.05	4.37 ± 0.92
LYR1-B	2.10 ± 0.48	1.80 ± 0.08	1.21 ± 0.14
LYR1-C	2.55 ± 0.81	1.52 ± 0.03	1.53 ± 0.24
LYR1-D	13.12 ± 2.75	1.81 ± 0.08	8.21 ± 0.65
LYR1-E	1.90 ± 0.39	1.61 ± 0.05	1.16 ± 0.08
LYR1-F	10.85 ± 2.42	1.58 ± 0.04	7.49 ± 1.16
LYR2-A	2.18 ± 0.52	1.65 ± 0.05	1.28 ±0.22
LYR2-B	16.65 ± 3.87	1.61 ± 0.05	10.05 ± 1.84
LYR2-C	2.67 ± 0.78	1.53 ± 0.03	1.63 ± 0.35
LYR2-D	5.31 ± 1.51	1.41 ± 0.03	3.36 ± 0.95
LYR2-E	4.02 ± 1.35	1.66 ± 0.05	2.51 ± 0.68
LYR2-F	2.28 ± 0.62	1.64 ± 0.04	1.36 ± 0.35

Table 4. General description of the rock samples analysed from the Galera Formation

Rock Classification	Sample	General Description
Phyllite	G1	Cream, purple and green hues on the exterior of the rock sample. Quartz veins less than 1 cm in thickness criss cross the rock. The sample was dense and hard.
Chloritoid phyllite	G2	Cream and puple hues on the exterior of the rock sample. Quartz veins of 1-2 cm in thickness traversed the rock. The structure waas also hard and dense.
Calcareous phyllite	G3	Red appearence, angular texture on the outside, and white rounded translucent fragments with air pockets on the inside (causing the rock to break apart easily).

Table 5. Quantitative mineralogical percentages obtained for the type locality for the Galera Formation

Sample	Quartz / %	Muscovite / %	Orthoclase / %
G1	67.63	24.52	7.85
G2	72.01	21.56	6.43
G3	60.94	26.14	12.92

Table 6. Physical properties of the Galera samples

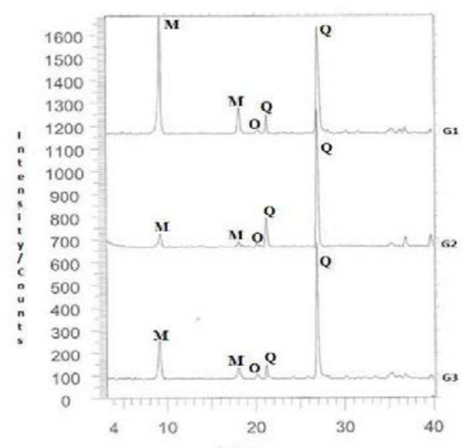
Sample Name	Apparent Porosity/ %	Bulk Density/ g cm^{-3}	Water Absorption/ %
G1	4.40 ± 1.16	1.68 ± 0.05	2.67 ± 0.72
G2	3.21 ± 1.09	1.22 ± 0.02	2.37 ± 0.34
G3	3.89 ± 1.12	1.52 ± 0.03	2.16 ± 0.46

mostly hard or dense in nature, and varying in hue – largely cream and purple, traversed with approximately 1cm quartz veins (see Figure 3(a)-(f)).

3.2.2 X-Ray Diffraction

Maximum intensity peaks for quartz for the three rock samples from the Galera Formation can be seen in the normalised XRD profiles (see Figure 9). Orthoclase was identified here as opposed to the minerals paragonite and pyrophyllite identified by Frey, Saunders and Schwander (1988). The quantative analysis revealed that in fact, samples G1, G2 and G3 were comprised of quartz, muscovite and orthoclase (also known as potassium feldspar) (see Table 5).

X-ray diffraction analyses performed by Frey, Saunders and Schwander (1988) identified the minerals muscovite, dolomite and quartz as being present in the samples tested from the area. The variation in the mineralogy, as obtained by Frey, Saunders and Schwander (1988) and in this present study, may be due to the difference in the sampling locality.



M= Muscovite, O= Orthoclase, Q= Quartz

Figure 9. Normalised XRD profiles of samples G1, G2 and G3 from the Galera Formation

3.2.2 Scanning Electron Microscopy

The intermix quartz/muscovite/orthoclase percentage ratio of 67:24:9 for samples G1, G2 and G3 is shown in

Table 6. Figure 10 shows a region for sample G1 consisting of quartz, as indicated by an arrow, embedded into the major muscovite/orthoclase matrix of the micrograph.

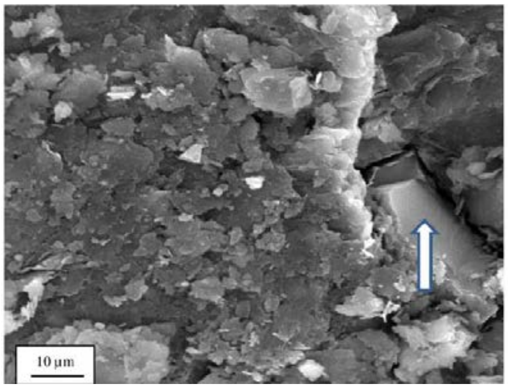


Figure 10. SEM micrograph of a selected region of the sample G1

3.2.3 Physical and Mechanical Properties

The rocks collected from the Galera Formation have a higher degree of metamorphism when compared with the Chancellor Formation. Texturally, the rocks can be described as hard and dense, as seen from the micrograph in Figure 10. This accounts for the low apparent porosity and water absorption values.

3.2.4 Compressive Strength

Compressive strength analysis was performed for the Galera Formation, where, values 12.61 MPa and 22.18 MPa were the compressive strengths perpendicular and parallel to the direction of layering, respectively. From the compressive strength parameters, the Galera Formation can be characterised as a weak region (Brown, 1981).

4. Conclusion

Physically, the phyllites of the Galera Formations have low porosity and water absorption compared to the Chancellor Formation. The mineralogical analysis established additional minerals as compared with previous studies (Frey et al., 1988) which may be attributed to differing sampling localities. Both formations showed some similarity in the mineral phases all having quartz, muscovite and orthoclase, with Chancellor having calcite and chlorite also. This study provides a quantitative description of the mineralogy. Significant to note is that there was a high degree of variability in the microstructure of the samples. Mechanically, both regions can be characterised as low strength based on the compressive strength test. The results of this work have implications for geotechnical designs and stability evaluations. Knowledge of the properties of the phyllites is useful in determining whether they would be used as decorative stones in countertops and building facades.

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