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The Physical Properties of Aggregate Rocks of Botswana

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ABSTRACT

Aggregate materials are essential for the building and construction industry, and hence it is important that sufficient, good-quality material is available close to centres of population at a reasonable price. Therefore, this report aims at closing the gap in aggregates information by reviewing all relevant information on prospects and deposits investigated, including data on geographical location, geological settings, mineralogical composition and physical test results. Part of the report is an aggregate compilation/database, which is used to inform aggregate exploration companies to locate areas with known or potential resource. Industrial minerals assessment will not only guide the construction industry; it will also guide land use planning which could help to avoid resource sterilization in the future.

Mineralogy, water absorption and three approved fundamental laboratory physical tests (Aggregate impact value (AIV), Los Angeles test (LA) and Aggregate crushing value (ACV)) were used to characterize rocks in Botswana for potential aggregate purposes. Kgalagadi and Gantsi Districts comprise quartzitic rocks that fall within aggregate test limits. Southern, Central and North East Districts generally comprise granite, dolerite and metamorphosed granite, with good physical strength and low in water absorption. Most of these rocks qualify as aggregate material for road and building construction. The strength of sedimentary rocks ranges from (AIV: 8.7 % - 25%, LA: 14.3 % - 40.3 %), which is significantly lower than those of igneous are (AIV: 7.9 % - 28.5 % LA: 7.9 % - 34.4 %) and metamorphic rocks (AIV: 9.5 % - 31.6 % LA: 7.9 % - 34.6 %). This phenomenon is caused by high porosity in sedimentary rocks, hence high water absorption rate and poor compressive strength. The results are presented by describing the distribution of aggregate occurrences at regional level, with each region reflecting the type of available aggregate source rock and its physical strength.

Industrial Minerals Occurrence Map of Botswana on the other hand was compiled from both historical and new data collected during the project life. The main objective for the production of this map, is to show the distribution of industrial minerals in Botswana. This product is intended to guide prospectors and the community on areas that can be considered suitable for any further work or mining. This work has shown that Botswana has a wide distribution of industrial minerals. Even though aggregates seem to be deficient in some regions, analysis has revealed that there are occurrences that can be evaluated for production. This can reduce transportation costs associated with aggregate material which is currently being ferried from long distances. It can also address employment challenges that the country is currently facing.

1. INTRODUCTION

Construction aggregate is normally defined as hard, granular materials usually suitable for use either on their own or with the addition of cement, lime or a bituminous binder in construction (Ademila, 2019). Its important applications include concrete, mortar, road stone, asphalt, railway ballast, drainage courses and bulk fill. To ensure that construction aggregates are fit for purpose and meet the requirements of the end uses, it is important to have an understanding of the mineralogy of the source rocks, production processes, the different standards for different uses and test methods used to evaluate their suitability. Aggregates are expected to be durable and resistant from both environmental and man-made degradation.

There are three main types of aggregates namely: i) natural aggregate often referred to as 'primary aggregate' (from mineral sources with nothing more than physical processing), ii) manufactured aggregate often referred to as 'secondary aggregate', (derived from industrial processes as a by-product) and iii) recycled aggregate which is recovered from material previously used in construction (Hamilton, 1984).

Compilation of aggregate resources in Botswana was initiated by the Department of Geological Survey (DGS) (Ntsimanyana, 1995; Kreimer et al., 1990; Lekula, et al., 2015). The Department focused its efforts in the Eastern part (Southern, Central, Kgatleng and North Eastern Districts) of the country where the demand for aggregates was high (Kreimer et al., 1990). Other parts including the Kgalagadi District, Gantsi District, Ngamiland, Boteti and Chobe District were however, excluded. The previous attempt to compile aggregate information also lacked information on aggregate quality in relation to their suitability for different applications (Kreimer et al., 1990). Therefore, the main aim of this report is to explore for aggregate source rocks in Botswana, compile a database for all aggregate deposits, review different geological settings in which aggregate source rocks occur and produce an industrial minerals map to show the distribution of industrial minerals around the country. The assessment will not only guide the construction industry and aggregate exploration companies; it will also guide land use planning which could help avoid resource sterilization in the future.

The report focuses on the natural (primary) aggregates of Botswana. It reconfirms all past aggregates sites which have been captured in a map for ease of reference. Most of the data was compiled from existing Geological Survey Bulletins, District memoirs, unpublished DGS reports, Government Departments and relinquished exploration reports to produce an industrial minerals database. In addition, new data was generated from sites that were excluded from the early campaigns.

It is observed from this project that aggregate source rocks are in abundance in the Eastern part of the country where there are occurrences of outcrops (Kreimer et al., 1990; Lekula, et al., 2015), while in the Western part, aggregates source rocks are sometimes found at depth. The target of this work is to assess the physical and mechanical properties of rocks in Botswana through laboratory tests that include Aggregate Impact Value (AIV), Los Angeles Abrasion test (LAA) and Water Absorption.

2. Methodology

The following steps were followed to compile the aggregate report of Botswana:

1. Historical data from Geological Survey Bulletins, district memoirs, other government departments and relinquished exploration reports, and unpublished DGS reports was gathered, reviewed and used to produce a database.
2. Study of geological maps and surface geology for potential aggregate sources.
3. Processing of landsat imageries of Kgalagadi District, Gantsi District, Ngamiland District, Chobe District and Boteti area, and mapping of major rock exposures in the areas.
4. Verification of data collected from the literature, through field assessment followed by rock sampling in areas with gaps of data or analysis in Kgalagadi, Gantsi, Ngamiland, Chobe Districts and Boteti area.
5. Performance of three standard aggregate physical tests namely; water absorption, resistance to abrasion and aggregate impact value on rock samples obtained from the areas under consideration. The three physical tests were performed because they are regarded as the fundamental tests for a potential source rock of aggregate (Yılmaz & Tuğrul 2012).
6. Mineralogical analysis to identify unknown crystalline compounds within rock samples and mineral quantification through X-Ray Diffraction (XRD) technique.

3. Outline of Geology of Botswana

The eastern part of Botswana is mainly underlain by the Archean (4000 - 2500 Ma) and Paleoproterozoic (2500 - 1600 Ma) rocks of the Kaapvaal craton, Zimbabwe craton, and metamorphosed rocks of the Limpopo mobile belt (Chisenga et al., 2016; Key & Ayres., 2000) (Figure 1). The southeast part is partially covered by Archean supracrustal rocks. A sequence of Mesoproterozoic and Neoproterozoic rocks predominate in north-western Botswana and belong to the Damara Belt (Ramokate et al., 2000) (Figure 1). The Gantsi Group along northeast strike are a continuation of Proterozoic rocks of Namibia, which forms part of the Damara Belt (Hall, 2007). The Karoo sediments predominate the central part of Botswana within the Kalahari basin, which covers about 60% of the country (Diskin et al., 2010). In the eastern part of the country, Karoo strata and thick basaltic lavas superimpose Precambrian rocks (Key & Ayres, 2000). Generally, the geology of Botswana is buried by cretaceous to recent Kalahari beds, which comprise mainly of aeolian sand (Key & Ayres., 2000; Hall, 2007).

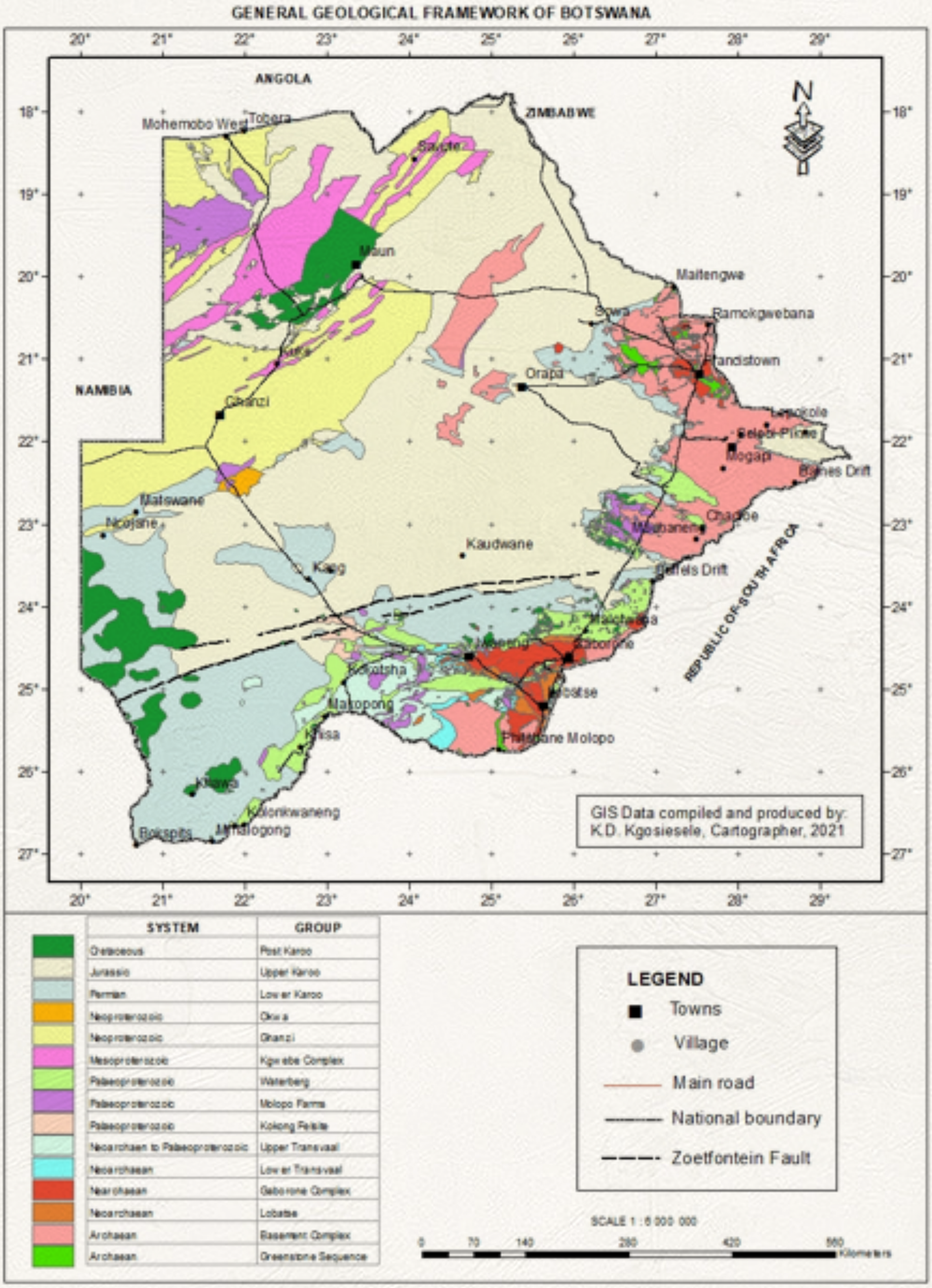

Figure 1: General overview of the geological framework of Botswana (After key., et al 2000).

4 Aggregates Source Geology

Aggregate is crushed rock produced from hard, strong rock formations including igneous (andesite, basalt, diorite, dolerite, gabbro, granite and rhyolite), metamorphic (hornfels, gneiss, quartzite, schist) and sedimentary (sandstone, limestone, arkose, subarkose and greywacke) rocks (Smith & Collis, 1993). Therefore, locating or assessing suitable aggregate deposits starts with understanding the geologic setting and geologic processes that form these rocks.

4.1 Sedimentary rocks

Sedimentary rocks are generally classified into three groups namely: clastic (detrital), chemical and biochemical rocks (see Table 1 after Smith & Collis, 1993). In Botswana, aggregate from sedimentary rocks is predominantly sourced from the Proterozoic siliciclastic strata along the Gantsi-Chobe ridge (Litherland, 1982) and Karoo sediments (Bordy et al., 2010). In Botswana, sandstone, arkose and chert are used as aggregates but sandstone is the most frequent source rock. Chert/flint is the only siliceous precipitation rock used for aggregate purposes in Central District around Letlhakane/Orapa area.

Table 1: Types of sedimentary rocks normally used as crushed rock aggregates worldwide. (After Smith et al, 1993).

Source material (unconsolidated)	Equivalent rocks (consolidated)
Clastic rocks Angular course fragments Gravel Sand Silt and clay	Breccia© Conglomerate© Quartzite©, sandstone with varieties according to cement (silicious, calcareous, clayey, ferruginous). Constituents other than quartz (arkose©, greywacke© and tuff©) Argillite, siltstone, claystone, shale
Chemical and Biochemical **Calcareous rocks** Shales, coral, criniods $CaCO_3$ precipitated $CaMg(CO_3)$ precipitated Silicious precipitation, fossil	 Limestone©, chalk Oolitic limestone Dolomite©, dolomitic limestone© Flint©, chert©, diatomite

©Rocks commonly used as aggregates, May be reactive with alkali in Portland-cement paste

4.1.1 Western Botswana

In Western Botswana, some of the clastic sedimentary rocks which are used as aggregate form part of the Ghanzi ridge (Figure 2). The Ghanzi ridge is a Northeast –Southwest trending topographic structure covered by comparatively recent Kalahari beds (Litherland, 1982). This ridge is also known as the Mamuno Formation. It consists of a thick package of purple oxidised siliciclastic facies, which are slightly metamorphosed (Figure 6 B), with some distinctly alternated layers of limestone near the top (Hall, 2007; Modie, 1996; Ramokate et al., 2000). The formation has a thickness of about 6000 m towards the West (Ramokate et al., 2000), where it outcrops near Mamuno, Karakubis and is covered partly by calcareous material around Gantsi village (Litherland, 1982). Mamuno Formation consists of a thick package of purple siliciclastic facies, which are slightly metamorphosed and is used as an aggregate rock. (Modie B. , 1996)

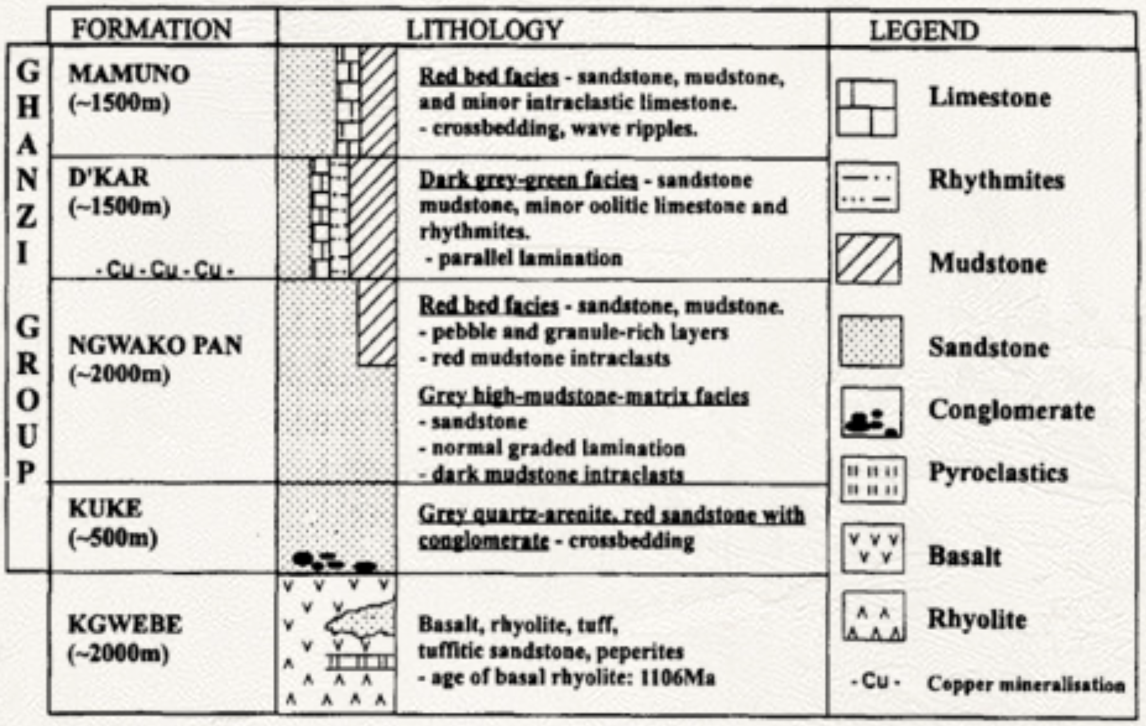

Figure 2: The stratigraphic sequence of Ghanzi Ridge with Kgwebe Formation at the base, and directly overlain by Ghanzi Group (Modie B. , 1996)

4.1.2 South West Botswana

In Southwestern Botswana, aggregate source rocks are orange sandstones belonging to the Lebung Group (Figure 3). The deposit is a concealed clastic sedimentary rock of the late Triassic to early Jurassic upper Karoo sediments (Bordy et al., 2010). These sandstones are generally orange-red medium to coarse grained with local calcareous reddish siltstone increasing downwards (Segwabe, 2008). The sandstone appearance is fibrous from multiple quartz veins (Figure 6 B), which are milky to white in colour and contain sand grains with frosted surfaces, indicating accumulation under aeolian conditions (Smith, 1984). The Lebung Group marks the start of the upper Karoo deposit and it comprises of orange-red medium to coarse grained sandstone, locally calcareous with reddish siltstone increasingly common downwards (Bordy et al., 2010).

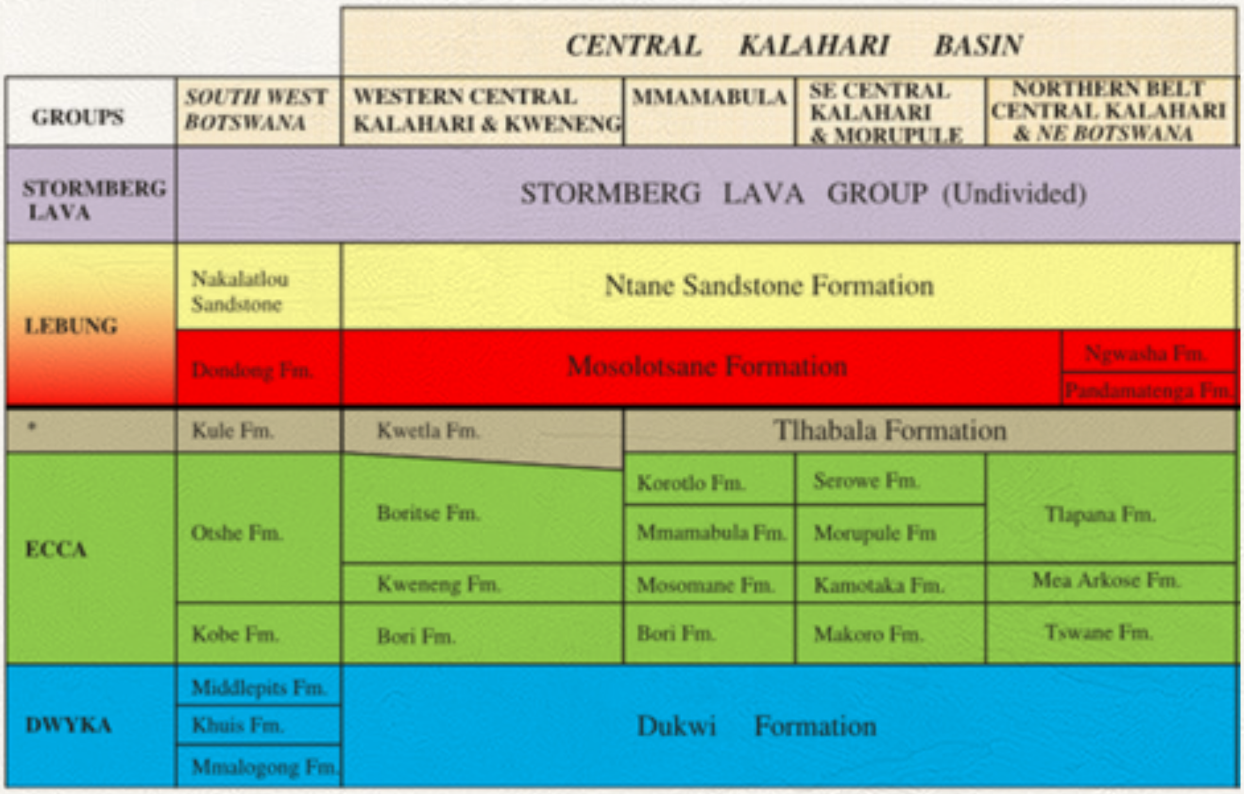

Figure 3: Lithostratigraphy of the Karoo Supergroup in Kalahari Karoo Basin of Botswana (After Bordy et al., 2010).

4.1.3 Central Botswana

In central Botswana (Boteti area), aggregate material is sourced from chert or flint deposits, which occur along the Boteti river.

4.1.4 North West Botswana

In Northwest Botswana, conglomerates are mined for aggregate purposes in the Talpan area. The area comprises of the Toteng diabase, Kgwebe meta-rhyolite, feldspathic sandstone with chert, quartzitic sandstone and silicified sandstone (Appendix 1). The Talpan boulders and cobbles are cemented by calcareous sediments, which are more likely post Karoo age (Thomas, 1969) and belong to the Kalahari system (Hall, 2007).

4.2 Igneous rocks

Igneous rocks generally are a good source rocks for aggregate deposit, because they are hard, dense and have good strength. Table 2 shows igneous rocks classification according to mineral composition (acidic, intermediate and basic), texture and grain size (Smith & Collins 1993). Igneous rocks are mostly exposed in the Southern and Northeast parts of Botswana. They mostly belong to the Archean Kaapval and Zimbabwe Cratons (Figure 4).

Table 2: Different types of igneous rocks, which normally qualify to be used as crushed aggregates. Some of these rocks are readily available in Botswana as crushed aggregate. (After Smith & Collis, 1993).

<table>
<tr><th>ACIDIC (Silicic)</th><th>INTERMEDIATE</th><th>BASIC (Mafic)</th></tr>
<tr><td colspan="3">Coarse grained (plutonic) rocks (grain size larger than about 5 mm). May be brittle from presence of large crystals</td></tr>
<tr><td>Granite
Granodiorite
Quartz monzonite</td><td>Syenite
Diorite
Quartz Diorite</td><td>Gabbro
Peridotite
Dunite</td></tr>
<tr><td colspan="3">Medium grained (hypa-byssal) rocks (grain size between 1 and 5 mm); crystals commonly intergrown. Commonly good aggregate</td></tr>
<tr><td>Granophyre</td><td>Porphyry
porhyrite</td><td>Diabase</td></tr>
<tr><td colspan="3">Fine grained (extrusive) rocks (grains less than 1 mm, i.e beyond the range of unaided eye) some rocks may be brittle and splintery; some may be alkali-silica reactive; otherwise good aggregate</td></tr>
<tr><td>Rhyolite</td><td>Dacite</td><td>Basalt
Andesite[p]</td></tr>
<tr><td colspan="3">Medium grained (hypa-byssal) rocks (grain size between 1 and 5 mm); crystals commonly intergrown. Commonly good aggregate</td></tr>
<tr><td colspan="3">Continuous variation in properties and composition</td></tr>
<tr><td>Light color
Low relative density
High silica percentage
(66% +) potassium feldspar</td><td></td><td></td></tr>
</table>

[p] May be reactive with alkali in portland-cement paste

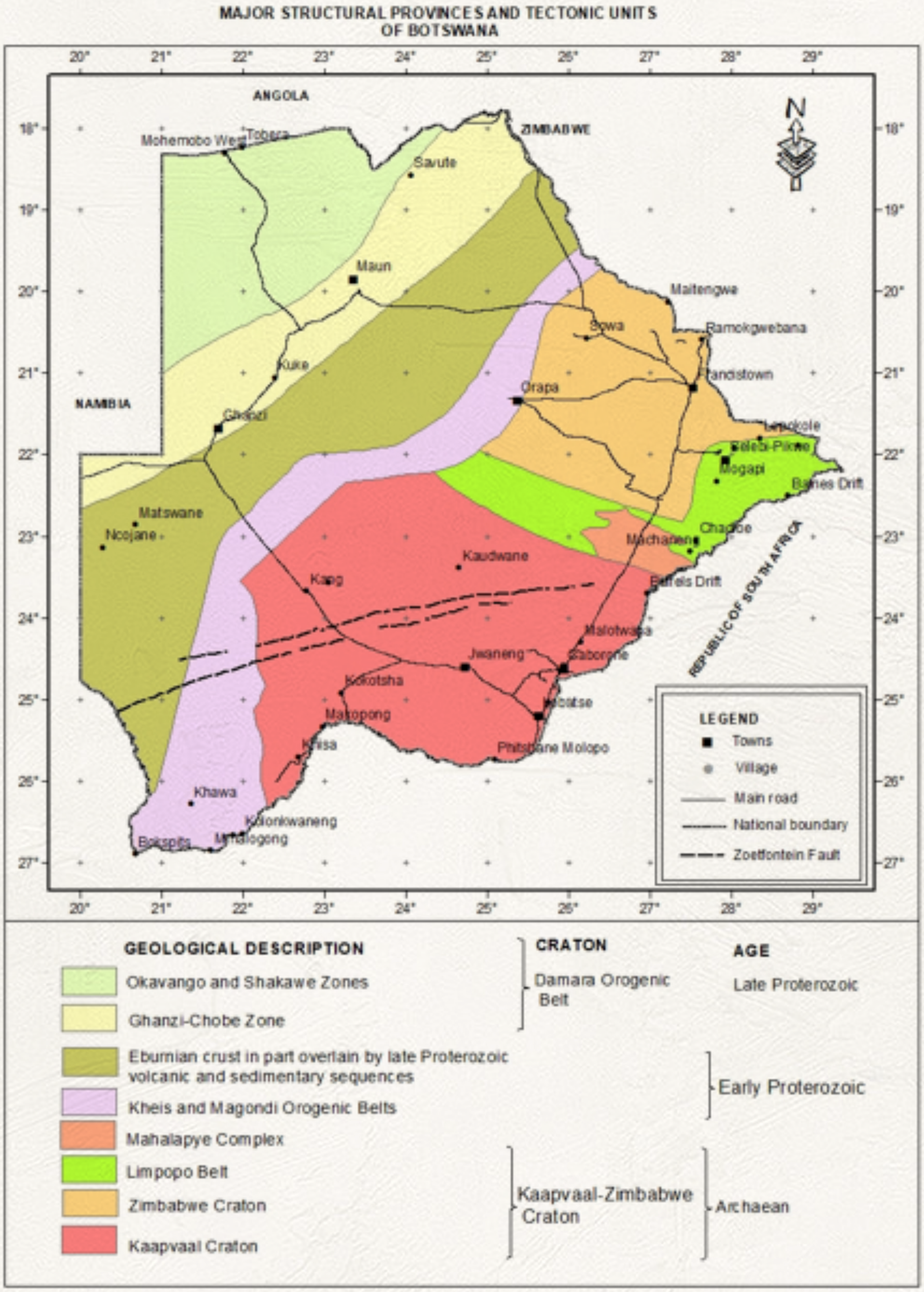

Figure 4: A map showing major structural provinces and tectonic units of Botswana (After Carney.,at el 1994).

4.2.1 Southern Botswana

Southern Botswana belongs to the Kaapvaal Craton and is dominated by the oldest supracrustal sequence of the Lobatse Volcanic Group (Key & Ayres 2000). The Lobatse Volcanic Group is dominated by felsic volcanic rocks of the Kanye Volcanic Formation (Walraven et al., 1996). Kanye Volcanic Formation is intruded by the Gaborone granite suite (Key & Ayres 2000). The Gaborone granite suite is restricted to the area south of a prominent Zoetfontein Fault (Kampunzu et al., 2004), and it encompass two types of granitic textures and colours (Lekula, et al., 2015). In the centre, it comprises of a coarse granite (Thamaga granite type), surrounded by an equigranular, medium-grained Kgale granite (Key & Wright 1982). The Ntlhantlhe porphyritic granophyre and micro granite sits between the Gaborone granite suite and the Kanye Volcanic Formation (Key, 1983; Key & Ayres 2000; Lekula, et al., 2015).

4.2.2 North East Botswana

The Achaean rocks of northeast Botswana belong to the Zimbabwe craton (Figure 4) and was mapped as the Tati-Vumba, Maitengwe and Matsitama granitoid-greenstone terrains (Litherland, 1975; Carney et al., 1994) contained within the Francistown Complex (Kampunzu et al., 2004). The rocks are mafic and ultramafic volcanic, comprising tonalite and trondhjemite-granite, monzonite, granodiorite and granite (Kampunzu et al., 2004; Bagai et al., 2002).

Matsitama granitoid rocks and the granitoids near Mosetse village are contained within the Mosetse Complex (Majaule & Davis, 1998) which are divided into granodioritic orthogneisses, leucocratic gneisses and coarse granitic gneiss (Carney et al., 1994). Mosetse complex and Motloutse complex form a steeply dipping boundary zone with similar compositional characteristics (Aldiss 1991; Carney et al., 1994). Majaule & Davis (1998) divided the Motloutse complex rocks into granite, granitic gneiss, megacrystic granitic gneiss, foliated tonalite, grey orthogneisses and migmatitic gneisses categories.

4.3 Metamorphic rocks

Table 3 shows the classification of metamorphic rocks and the original rocks from which they are derived. Granitic gneiss, quartzitic sandstones, quartz and marble are among valuable aggregate deposits that are commonly used in Botswana. Granitic gneisses are the oldest metamorphic rocks that are found in the Kaapvaal Craton (Kampunzu et al., 2004), and the youngest metamorphic rocks in the Limpopo Mobile Belt (Key & Ayres 2000).

Table 3: Different types of metamorphic rocks, which are normally used as crushed aggregates. (After Smith & Collis, 1993).

Metamorphic Environment (temperature and pressure)		
Original rock	**Low grade shallow burial**	**Medium and high grade burial** Deep burial
Argillite, Siltstone, Claystone, Shale Clayey sandstone	**Foliated platy rocks (effects of pressure paramount)**	
Clayey limestone Granite	Slate Graywacke	
Basalt	Slaty marble[p] Sheared granite	Calcareous schist Granite-gneiss[p]
	Green (chlorite) schist	Amphibolite, Hornblende gneiss[p]
	Non-foliated, massive rocks (effects of temperature paramount	
Any parent rock Quartzose sandstone	Quartzitic sandstone	Hornfels[p] (some crystallization but original features my be present) Quartzite[p]
Limestone and dolomite		Marble[p]

[p]Metamorphic rocks commonly used as aggregate

4.3.1 North East Botswana

Metamorphic rocks are consigned to two distinct crustal terranes in the Northeastern part of Botswana. The supracrustal metamorphic rocks of Francistown granite-greenstone on the South-western margin of the Zimbabwe Craton (Bagai et al., 2002), comprise of variably foliated granitic gneiss and tonalite trondhjemite-granite (TTG), gneisses (Key & Ayres, 2000; Kampunzu et al., 2004).

Neighbouring the Francistown granite-greenstone terrane to the south, are the metamorphic rocks of the Matsitama-Motloutse Complex. The two terranes are separated by a thrust Shashe shear zone. The Matsitama complex rocks are dominated by quartzite, marble and calc-silicate metamorphosed rocks (Kampunzu et al., 2004; Aldiss , 1991). The metamorphosed granites within this terrane are divided as tonalitic to granodioritic (TTG) orthogneisses and coarse granitic gneiss sheets (Kampunzu et al., 2004).

4.3.2 East Botswana

The central zone of the Limpopo Mobile belt forms part of the metamorphic rocks in Eastern Botswana. The belt is an East-Northeast trending gneissic terrane, which is situated between the two Archean cratons (Kaapvaal and Zimbabwe cratons). The central zone of Limpopo Mobile Belt has been separated into Mahalapye and Phikwe Complexes (Key & Ayres, 2000). Metamorphic rocks within Phikwe Complex are dominated by granitic gneiss, quartzo-feldspathic gneisses and paragneisses with an assemblage of carbonate-pelite (Aldiss., 1991). Phikwe Complex is bounded on the North and Western side by Magogaphate shear zone (Aldiss D. , 1991; Key & Ayres., 2000).

Metamorphic rocks belonging to Mahalapye Complex form part of the basement rocks, which encompass an assemblage of granitic gneisses, migmatites and some variably foliated plutonic rocks (Ermanovics, 1980). The western margin of the Mahalapye Complex lies beneath younger sedimentary cover, the eastern edge is demarcated by the Mahalapye Migmatite (Ermanovics, 1980; Key & Ayres, 2000). The Mahalapye Complex comprises various rock units that are not genetically related to each other (Ermanovics, 1980). Migmatite within the complex belongs to a tectono-magmatic activity between 2700 Ma and 2600 Ma (Ermanovics, 1980), while the Mahalapye Granite is the youngest component of the Mahalapye Complex (Carney at el., 1994). The complex is divided into Mahalapye Migmatite, Mokgware Granite and the Mahalapye Granite (Carney et al., 1994).

4.3.3 North West Botswana

Northwest Botswana comprises Kgwebe volcanic complex, which forms a projecting NE/SW striking hill track (Huch et al., 1992). The Kgwebe Formation represent the initial stage of the Damara belt formation in the north western Botswana (Modie, 1996). The anticline structure (Mabele-a-pudi Hills) near Kuke village, comprises metamorphosed rhyolites (Appendix 2). Black to dark grey meta-rhyolites have a porphyritic texture and flow banding is some places, probably due to metamorphism or different lava flow (Carney et al., 1994; Key & Ayres, 2000; Hall, 2007).

4.3.4 South West Botswana

In Southwest Botswana, Quartz-rich sandstones and quartzites belonging to the Olifantshoek Sequence form low lying hills around Khuis, Kolonkwaneng, Tsabong and Maralaleng areas (Carney et al., 1994). Around Khuis area, (Key & Ayres, 2000) observed folded schists and metamorphosed quartz sandstones into east-ward reclined structures. Recrystallization of quartzites instigated by dynamo-thermal metamorphism has resulted into elongated quartz grains, parallel to tectonic foliation (Carney et al., 1994).

4.3.5 West Botswana

In the western part of Botswana, lithostratigraphic assemblage of metamorphosed rocks are situated in Okwa inlier (Aldiss & Carney, 1992; Key & Ayres, 2000). The Okwa inlier is located west of Botswana, between Archean Kaapvaal-Zimbabwe craton and Damara Orogenic Belt (Aldiss & Carney, 1992). It comprises metamorphosed granitic rocks, which are exposed sporadically along a 40 km length in the dry Okwa valley (Aldiss & Carney, 1992; Carney, et al., 1994). Predominant metamorphic rocks within this complex zone include augen gneiss, foliated megacrystic granites and the most widely spread granitic gneiss (Aldiss & Carney, 1992).

5. Results and Discussion

The laboratory physical strength tests of the rocks are used to assess the suitability of aggregates for use as road stone and in the concrete industry. They are indicator tests used to measure the likely rather than the actual performance of aggregate material. Three approved fundamental tests results of Aggregate impact value (AIV), Los Angeles Abrasion test (LAA) and Aggregate crushing value (ACV) were used to characterize the potential aggregate source rocks. Table 4 shows the minimum physical laboratory tests which were taken into account and their limits.

Table 4: The three physical strength tests and strength categories) used as aggregate test limits, describing the suitability of the rocks as aggregate material for construction purposes

Aggregate Test	Limits	Very good strength	Good strength
Aggregate impact value (AIV)	<= 30 %	< 20 %	20 % - 30 %
Los Angeles test	<= 30 %	< 20 %	20 % - 30 %
(LA)			
Aggregate crushing value (ACV)	<= 30 %	< 20 %	20 % - 30 %

Mineralogical identification was performed on rock samples from Gantsi District, Kgalagadi District and Ngamiland District. Powder XRD was done to define the proportions of minerals in the rock samples (Figure 5) for naming the rocks and identifying their properties. Appendices 2, 3 and 4 shows mineralogical proportion of different rock forming minerals from Gantsi, Kgalagadi and Ngamiland Districts respectively. The rock types that were analysed from Gantsi District were arkose, rhyolite and granitic gneiss (Appendix 2); Kgalagadi District comprise quartzite and sandstone (Appendix 3) while Ngamiland District comprise quartzite, rhyolite and conglomerate and basalt from Chobe District (Appendix 4).

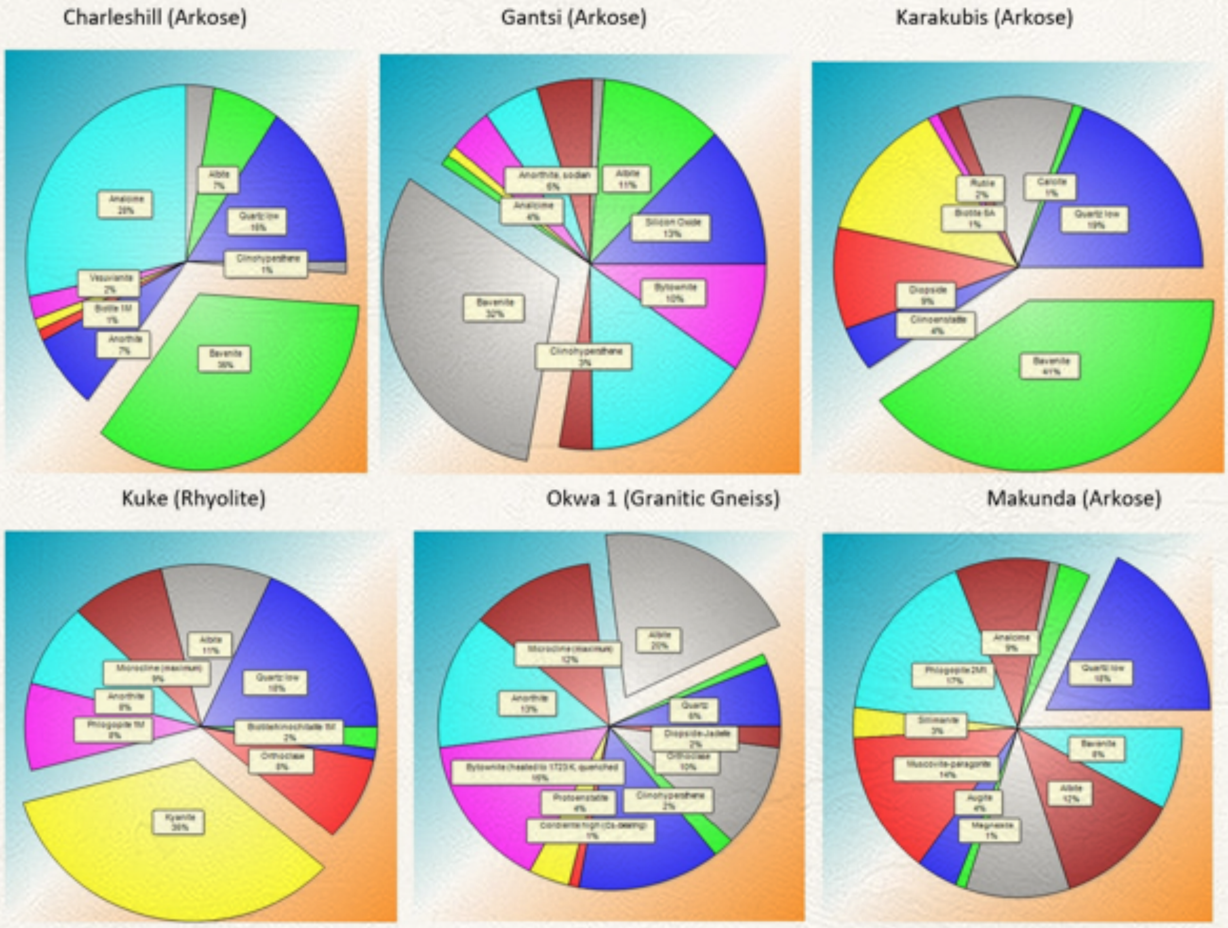

Figure 5: XRD results for different rock types found in different districts

To appropriately interpret the results from the physical tests, petrographic studies were carried out on hand specimens of the rock samples. The petrographic studies enabled the acquisition of information on the mineralogical composition, grain-size distribution, grain shape, micro jointing and alteration status, which are important characteristics for durability and rock strength during technical testing.

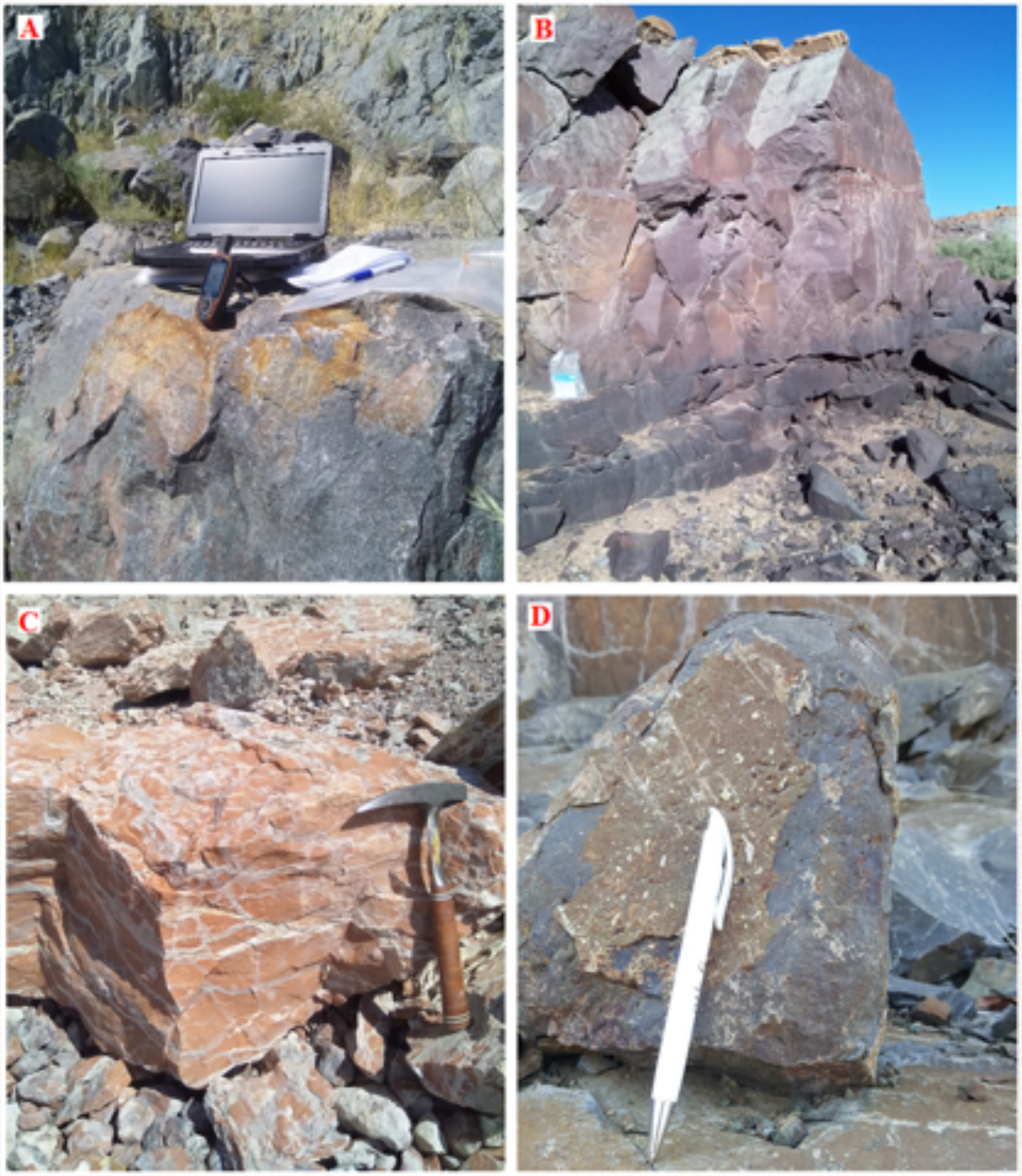

Figure 6: A) Kgwebe metamorphosed rhyolites forming Mabeleapudi hills, which comprise phenocrysts of quartz/calcite and feldspar minerals. B) Metamorphosed, , with vertical joints. C) Orange, red sandstone, locally calcareous with reddish siltstone increasingly common downwards. D) Lesoma basaltic rock, which is dark grey in color.

5.1 Central Region

Central region is dominated by igneous rocks from the Kaapvaal Craton and metamorphosed rocks found adjacent to the Limpopo Mobile Belt. For this work, information on forty-five sampled areas was collected from Geological Survey's Bulletins and District memoirs (Table 5).

AIV for igneous rocks range from 7.69 % to 21.04 %, metamorphic rocks range from 10.08 % to 29.00 %. One sedimentary rock sample from Shapane Hills was analysed for AIV and the value is 23.00 %. LA analysis was only done on igneous rocks and the values range from 6.29 % to 22.93 %. ACV for igneous rocks range from 6.89 % to 30.00 %, metamorphic rocks range from 9.81 % to 30.00 % and 24.00 % for the only one sedimentary rock sample. Water absorption was done on igneous rocks only and the values range from 0.13 % to 2.18 %. Generally, all rock samples from Central region falls within the aggregate strength limits.

Table 5: Shows physical strength test results for rock samples in Central Region (Data collected from Botswana Geological Survey's Bulletins and District memoirs)

Igneous					
Place	Rock Description	LA	AIV	ACV	Water Absp
Tshokwe Drought relief road	Dolerite		12.00	11.00	
Tobane	Gabbro		13.00	12.00	
Manatswele Hills	Dolerite		13.00	12.00	
Palapye	Dolerite	7.45	7.77	6.89	0.34
Mokgware	Granite	11.76	21.04	21.3	0.63
Bonwapitse	Granite to quartz diorite	17.43	19.00	12.80	1.29
Tobela	Granite	16.63	18.58	13.10	2.18
Morale	Granite	15.83	18.77	15	1.07
Shoshong	Granite	7.61	7.98	9.9	0.13
Mahalapye	Granite	22.93	17.93	17	0.48
Patayamatebele	Granite	9.39	8.16	13.2	0.16
Mmutlane	Granite	7.89	7.69	11.2	0.14
PNDGR2	Granite	6.29	8.22	13.6	0.34
Kalamare	Granite	12.48	10.97	15.5	0.36
Mahalapye	Granite	22.93	17.93	17.00	0.48
Topisi	Dolerite	10.08	9.81	9.2	0.21

Table 5: Shows physical strength test results for rock samples in Central Region (Data collected from Botswana Geological Survey's Bulletins and District memoirs) (Continued)

Metamorphic				
Place	**Rock Description**	**AIV**	**ACV**	**Water Absp**
Molomowapudi	Granitic Gneiss	20.00	22.00	
Mashambi Hill	Porphyritic granitic gneiss	19.00	21.00	
Magogaphate	Gray banded gneiss	18.00	21.00	
Thobolotona Hill	Banded gneiss	25.00	26.00	
Tshutshumane Hills	Banded gneiss	16.00	18.00	
Romane Hills	Granitic Gneiss	18.00	20.00	
Lepokole Hills	Red augen gneiss (granitoid)	26.00	26.00	
Majeaditshwene Hills, BPT 163	Granitic Gneiss	18.00	20.00	
Mowana Lands, Trig. BPT 168	Granitic Gneiss	19.00	21.00	
Lekgawe, NE Dibokolodi	Red granitic gneiss	19.00	21.00	
Makgwaphe Hills	Granitic Gneiss	18.00	20.00	
SE Makgwaphe Hills, BPT 167	Red Banded Gneiss	23.00	24.00	
Mosatse Hill	Banded gneiss	20.00	22.00	
Maore Hills	Granitic Gneiss	21.00	23.00	
Matale Hills	Banded gneiss	21.00	23.00	
Marutujwe Hills	Red granitic gneiss	16.00	18.00	
Mabalelo Hills	Leucocratic granitic gneiss	20.00	22.00	
Tloupye Hill, BPS 31	Leucocratic granitic gneiss	21.00	23.00	
Setshweu Hills	Banded gneiss	21.00	23.00	
Thune #2/Sefophe-Bobonong road	Banded quartzo-feldspathic gneiss	26.00	26.00	
Ntswaneng Hill, BPS 42	Granitic Augen Gneiss	27.00	26.00	
Dikanti Hill, BPS 71	Banded gneiss	19.00	21.00	
Matsatsa Lands	Banded gnesis and magmatite	22.00	24.00	
Tsetsebjwe Hill,Tsetsebjwe Village	Paragneiss	19.00	21.00	
Mmalogong Hills	Paragneiss	24.00	25.00	
Lesenapole Hills	Foliated adamellite	29.00	30.00	
Mmasehumana Hills	Banded gnesis(agmatite)	23.00	24.00	
Lecha	Gneiss	10.08	9.81	0.08
Sedimentary				
Shapane Hills	Siliceous breccia	23.00	24.00	

5.2 North East Region

The North East region comprise igneous rocks of the Zimbabwe craton and metamorphic rocks forming part of the Limpopo mobile belt. For this work, 11 igneous rock samples and 11 metamorphic rocks were compiled from Geological Survey's Bulletins and District memoirs (Table 6).

AIV for igneous rocks range from 9.9 % to 32 % and metamorphic rock values range from 9.5 % to 32 %. LA was done on two igneous rock samples from Siviya, and the values were 10.1 % and 14.4 %, metamorphic rock values range from 7.9 % to 34.6 %. ACV for igneous rocks range from 8.2 % to 28.9 % and metamorphic rocks range from 10.6 % to 29.4%. Generally, rock samples from the North East region show three subdivisions; rock samples with very good strength (AIV and ACV less than 20 %) while Siviya granitic gneiss, Domboshaba granite and Mafungo/Mberikama granitic gneiss fall outside the aggregate strength limit. LA and AIV for Mafungo/Mberikama granitic gneiss is 32.5 % and 32 % respectively, LA for Siviya granitic gneiss is 34.6 %, AIV is 31.6 % and ACV is 31.1 % while AIV for Domboshaba granite is 32% (see Appendix 5). Dolerite and gabbro show the best results, with ACV of less than 15 %.

Table 6: Shows physical strength test results for rock samples in North east Region (Data collected from Botswana Geological Survey's Bulletins and District memoirs)

Igneous					
District	**Place**	**Rock Description**	**LA**	**AIV**	**ACV**
North East District	Siviya	Dolerite	27.6	24.3	18.3
North East District	Siviya	Dolerite	34.6	31.6	31.1
Central District	Changate Hills	Coarse grained K-granite	24.5	22.2	24.4
North East District	Domboshaba Granite	Medium grained K-granite	27.9	25.1	25.2
North East District	Makuta Hills	Leucocratic granite	14.6	14.6	12.4
North East District	Francistown-Mosetse road	Leucocratic migmatite	19.5	20.8	21.6
North East District	Ntimbale	Medium/coarse grained granite	24.5	20.1	16.6
North East District	Tshesebe road	Doleite	32.5	32.0	29.4
North East District	Bisoli Hill	Granodiorite	7.9	9.5	10.6
North East District	Francistown-Dumela	Diorite		26.0	29.0
North East District	Tshilo Hill	Adamellite		22.0	21.0

Table 6: Shows physical strength test results for rock samples in North east Region (Data collected from Botswana Geological Survey's Bulletins and District memoirs) (Continued)

Metamorphic					
District	**Place**	**Rock Description**	**LA**	**AIV**	**ACV**
North East District	Siviya	Tonalitic Gneiss	14.4	17.2	14.1
North East District	Siviya	Granitic Gneiss	10.1	9.9	8.2
North East District	Siviya	Granitic Gneiss		26.0	26.9
North East District	Shashemooke	Gneissic Granodiorite		32.0	28.9
North East District	Siviya	Gneissic Granodiorite		19.0	21.0
North East District	Marobela	Tonalitic Gneiss		25.0	26.8
North East District	Siviya	Granitic Gneiss		22.0	19.8
North East District	Mafungo/Mberikama	Granitic Gneiss		15.0	13.7
North East District	Siviya	Gneissic Granodiorite		19.0	20.0
North East District	Phanga Hill	Migmatitic gneiss		12.0	16.0
North East District	Bodumatau Hill	Tonalite Gneiss		21.0	22.0

5.3 Greater Gaborone Region

Most samples from the Greater Gaborone region belong to the Kaapvaal Craton and Karoo sediments. A detailed investigation of the Greater Gaborone by the Department of Geological Surveys (Lekula, et al., 2015) revealed the presence of suitable rocks types, for the manufacture of sand, construction and road use. For this work, 30 igneous rock samples, 4 metamorphic rocks and 2 sedimentary rocks were compiled from previous work done by various authors (Table 7).

AIV for igneous rocks range from 9.17 % to 28.58 %, metamorphic rocks range from 15.62 % to 23.94 % and sedimentary rocks range from 15.49 % to 26.79 %. LA values for igneous rocks range from 8.04 % to 34.42 %, metamorphic rocks range from 23.08 % to 32.07 % and sedimentary values range from 20.81 % to 40.3 %. ACV for igneous rocks range from 9.0 % to 20.70 %, metamorphic rocks range from 13.20 % to 21.50 % and sedimentary rocks range from 19.0 % to 21.10 %. Water absorption values for igneous rocks range from 0.24 % to 1.39 %, the value for metamorphic rocks range from 0.43 % to 1.18 % and the value for sedimentary rocks range from 1.62 % to 1.96 %. Generally, most igneous rocks and metamorphic rock samples show very good aggregate properties with LAA and AIV of less than 20 %. Sedimentary rock samples show good aggregate properties, with LAA and AIV values of less than 25 %. Five samples (Oodi Hill felsite, Diphawana quartzite, Manyana sandstone, Kanye granite and Semarule Syenite) have LAA values outside the limits (Appendix 5).

Table 7: Shows physical strength test results for rock samples in Greater Gaborone (Data collected from Botswana Geological Survey's Bulletins and District memoirs)

Igneous					
District	**Place**	**LA**	**AIV**	**ACV**	**Water absp**
Bikwe	Dolerite	10.16	10.93	9	0.37
Bokaa	Granite	24.58	22.77	13.1	0.44
Diphawana	Dolerite	11.28	13.49	17.8	0.39
Fikeng	Granite	23.53	24.46	17	0.57
Lotlhakane	Felsites	15.64	15.65		0.3
Lotlhakane	Dolerite	9.17	8.04	5.8	0.48
Kgomokasitwa	Granite	20.81	26.62	18.8	0.95
Kanye	Granite	20.79	26.41	12.3	0.9
Kanye	Granite	28.58	32.08		0.99
Kopong	Felsites	17.6	15.25		0.50
Kgoro	Granophyre	15.58	12.76	12.4	0.74
Kubung	Dolerite	11.2	10.4		0.67
Manyana	Dolerite	10.05	11.92	11	0.32
Molepolole	Dolerite	9.13	12.54	10.4	0.24
Moshupa	Granite	26.02	22.68	20.7	0.25
Modipane	Gabbro	10.53	14.24	10	0.24
Mahetlwe	Diabase	10.44	8.46		0.33
Mehane	Granite	18.03	19.08	20.9	0.46
Mokolodi	Felsites	12.14	11.39		0.37
Moshaneng	Dolerite	11.98	17.87	9.2	0.78
Metsimotlhabe	Dolerite	9.41	13.17	8.7	1.39
Nnneke	Dolerite	9.37	12.46	9.8	0.53
Ntlhantlhe	Granite	14.7	11.52		0.33
Rasesa	Dolerite	13.46	13.23		0.39
Rasesa	Granite	21.18	18.09		0.35
Semarule	Syenite	23.03	34.42	17.1	0.81
Sephatlhaphatl	Granite	21.63	22.13	20.3	0.56
Sephatlhaphatl	Granite	23.97	16.25	16.5	0.29
Tloaneng	Granite	25.05	20.84		0.56
Thamaga	Granite	21.48	25.73	13.6	1.29

Table 7: Shows physical strength test results for rock samples in Greater Gaborone (Data collected from Botswana Geological Survey's Bulletins and District memoirs) (Continued)

Metamorphic					
District	**Place**	**LA**	**AIV**	**ACV**	**Water absp**
Diphawana	Quartzite	23.65	23.08	21.5	1.18
Moshaneng	Quartzite	15.62	27.42		1.04
Moshaneng	Quartzite	21.33	24.51	13.2	0.43
Diphawana	Quartzite	23.94	32.07		0.94
Sedimentary					
Manyana	Sandstone	26.79	40.3	22.1	1.96
Mankgodi	Sandstone	15.49	20.81	19	1.62

5.4 Ngamiland Region

A few outcrops exist in the Ngamiland area; nevertheless, some igneous and sedimentary rocks were sampled for testing. Eight samples (Kgwebe rhyolite, Lesoma basalt, Toteng diabase, Qangwa granitic gneiss, Dikgathong silcrete, Talpan conglomerate, Bothathogo quartzite and Matabologa sandstone) were all tested for AIV, LA, water absorption (Table 8) and XRD for mineralogical identification (Appendix 4).

Talpan aggregate material constitute fluvial deposits, consisting of boulders and cobbles, which were released from their parent rocks by physical weathering and cemented to form conglomerates (Appendix 1). The deposit comprise Toteng diabase with a vesicular texture, Kgwebe meta rhyolite, Matabologa fine grained feldspathic sandstone with fragments of chert, ferruginous quartzitic sandstone and brown silicified sandstone. The boulders and cobbles are cemented by calcareous sediments, which are more likely to be of post Karoo age and belong to the Kalahari system. AIV values for Talpan conglomerate is 11.85 %, LA value is 16.63 % and water absorption value is 0.41 %. Aggregate source rocks in Qangwa forms part of the basement rocks, which are exposed along Qangwa valley and adjacent to it. These rocks comprise of granitic gneiss and pegmatites locally. The basement complex in the Qangwa valley occurs as sporadic rocks, which covers a stretch of up to 10 km along a NE-SW strike. The granitic gneiss is medium grained and consists of quartz, sericite orthoclase, minor sodic plagioclase, microcline, biotite and apatite. The rocks have been affected by shearing and green schist facies metamorphism in some places. AIV for Qangwa granitic gneiss is 26.70 %, LA value is 28.60% and water absorption value is 2.30 %.

Lesoma basalt is dark grey in colour and composed of fine grains because of rapid cooling when magma was exposed to the ground surface (Figure 6). The mineral grains within the Lesoma basalt are mostly indistinguishable to the naked eye. The dark greenish to black color in the basalt is given by pyroxene and magnetite. The basalts in the study area comprise of parallel sporadic joint spacing of about 1-3 meters wide. Most of the joints are closed, and a few are filled with whitish weathered residue. A thin layer of weathering on the surface of the outcrop and along the joints range from fresh to slightly reddish brown, due to alteration of iron (Fe) which is contained in the pyroxene and magnetite. AIV for Lesoma basalt is 9.54 %, LA value is 13.84 % and water absorption value is 1.20 %.

Generally, AIV for igneous rocks range from 7.85 % to 26.60 % and sedimentary values range from 11.85 % to 25.30 %. LA values for igneous rocks range from 7.98 % to 28.60 % and sedimentary values range from 14.30 % to 26.70 %. Water absorption for all rock samples ranges from 0.41 % to 2.70 %.

Mineral identification for Talpan conglomerate is generally dominated by bavenite, a group of feldspars (Albite, microcline, oligoclase, orthoclase, anorthoclase, anorthite) and quartz (Figure 5). The mineralogy of this aggregate rock shows a variety of minerals found in mafic igneous rocks e.g, Bytownite and in sedimentary rocks. Bavenite ($H_{2.95}$ $Al_{1.05}$ $Be_{2.99}$ Ca_4 O_{28} $Si_{8.96}$) is highest at 22 % weight fraction, followed by quartz (SiO_2) at 13 % weight fraction. Oligoclase ($Al_{1.94}$ $Ca_{0.86}$ $Na_{0.14}$ O_8 $Si_{2.06}$) and clinopyroxene ($Ca_{0.96}$ $Fe_{0.086}$ $Mg_{0.914}$ $Na_{0.08}$ O_6 Si_2) are rock-forming minerals, which occur in mafic igneous rocks such as the rhyolites of the Kgwebe Formation. The high amount of silica is because of quartzitic and silicified sandstones, which are part of the conglomerates found in the study area. Kyanite, Quartz and feldspars (orthorclase, anorthite, albite and microcline) generally dominate Kgwebe igneous rock samples (rhyolite).

Lesoma basalt is dominated by three silicate minerals, which are sodium feldspar (plagioclase), pyroxenes and olivine. Albite (Al_1 Na_1 O_8 Si_3) and anorthoclase-which is an alkali feldspar (Al_1 $K_{0.14}$ $Na_{0.85}$ O_8 Si_3) are the most abundant plagioclase minerals, with a quantification of 12% and 15% weight fraction respectfully. Pyroxene mineral species include orthopyroxene ($Fe_{0.15}$ $Mg_{1.82}$ O_6 Si_2), clinopyroxene ($Ca_{0.75}$ $Na_{0.25}$ O_6 $Sc_{0.25}$ Si_2 $Zn_{0.75}$) and enstatite ($Fe_{0.498}$ $Mg_{1.502}$ O_6 Si_2)-which is an orthopyroxene rich in magnesium.

Table 8: Shows physical strength test results for rock samples in Ngamiland Region (Samples were analyzed in Botswana Geoscience Institution laboratory)

Igneous				
District	**Place**	**AIV**	**ACV**	**Water absp**
Kgwebe hill	Rhyolite	7.85	7.98	0.42
Qangwa	Granitic gneiss	26.70	28.60	2.30
Maun Quarry/Toteng	Diabase	14.60	15.80	0.36
Lesoma	Basalt	9.54	13.84	1.20
Sedimentary				
	Fine sandstone	25.30	26.70	2.70
Bothathogo	Greyish meta-sandstone	22.90	14.30	1.80
Dikgathong	Silcrete	15.60	14.90	0.51
TalPan	Conglomerate	11.85	16.63	0.41

5.6 Gantsi Region.

Gantsi region comprises three different rock types, which are potential sources of aggregate. The purplish arkosic sandstones of the Kgwebe rhyolite, Ngwako Pan Formation and Okwa granitic gneiss are widely distributed in the region and are used as source rocks for aggregate (Figure 6). The Kgwebe metamorphosed rhyolites, have phenocrysts of quartz/calcite and feldspar minerals (Figure 7). The phenocrysts vary locally in size and spacing, with feldspar phenocrysts ranging from 1mm to 11 mm and quartz/calcite ranging from 0.5 mm to 2 mm. The black to dark grey metamorphosed rhyolites have a porphyritic texture and flow banding in some places. The phenocrysts (quartz and feldspars) within the rhyolite varies in size and spacing, probably due to metamorphism or different lava flow. Low-grade metamorphosed Mamuno Formation arkosic rocks are the most dominant aggregate source rocks in Gantsi region (Figure 6). The rocks are hematite-stained purple arkoses with no cleave. The textural composition shows that the rocks metamorphosed under dry conditions hence reduced original grain size. Karakubis rocks have undergone low-grade metamorphism with mineral assemblages including, chlorite, epidote, calcite, muscovite, microcline, quartz and iron oxide. The well exposed arkosic rocks, shows a massive uncleaved arkose with metamorphic texture and reduced original grain size. The rock contains vertical joints, which are filled with chloritized material, at an interval of about 1-2 meters.

AIV values for igneous rock ranges from 18.95 % to 20.27 %, metamorphic rock values ranges from 8.95 % to 7.22 % and sedimentary values ranges from 8.13 % to 15.16 % (Table 9). LA values for igneous rocks ranges from 4.96 % to 6.18 %, metamorphic values ranges from 7.38 % to 8.90 % and sedimentary values ranges from 7.58 % to 19.79 %. Water absorption for all rock samples ranges from 0.41 % to 1.48 %. Generally, rocks in the Gantsi region are good source rocks of aggregates, and most of these rocks are currently being used for road and building construction.

The meta-arkosic rock samples from Gantsi region are generally dominated by a basic calcium beryllium aluminosilicate mineral (Bavenite), which belongs to the zeolite group and analcime (Figure 5). Quartz and feldspar minerals (anorthoclase and anorthite) are also abundant at 15 % and 14 % by weight fraction respectively. Feldspars are one of the primary minerals that constitute arkosic sandstone. Anorthoclase feldspar is a crystalline solid solution in the alkali feldspar series, while anorthite is a calcium endmember of the plagioclase feldspar mineral series. The amount of biotite ($H_{0.32}$ $Al_{3.785}$ $F_{1.82}$ $Fe_{3.77}$ $K_{1.9}$ $Li_{0.34}$ $Mg_{0.2}$ $Na_{0.06}$ $O_{22.18}$ $Rb_{0.04}$ $Si_{5.885}$ $Ti_{0.04}$) and phlogopite ($Al_{1.25}$ $Ba_{0.03}$ $F_{0.14}$ $Fe_{0.78}$ $K_{0.85}$ $Mg_{2.22}$ $Na_{0.11}$ $O_{11.86}$ $Si_{2.75}$) are relatively low (below 2 % weight fraction). These are mica minerals, which may result in deleterious materials such as silt, dust and clay in aggregates.

Kuke rhyolite samples (igneous) are generally dominated by polymorphic aluminum-silicate mineral kyanite (Al_2 O_5 Si_1) at 35% weight fraction and Quartz (SiO_2) at 18 % weight fraction (Figure 5). The sample is also composed of a good amount of feldspars; orthorclase, anorthite, albite and microcline being the highest at 9 % by weight fraction.

Table 9: Shows physical strength test results for rock samples in Gantsi Region (Samples were analyzed in Botswana Geoscience Institution laboratory)

Igneous				
District	**Place**	**AIV**	**ACV**	**Water absp**
Okwa 1	Granitic rock	20.27	6.18	0.83
Okwa 1	Granitic rock	20.17	5.84	
Okwa 2	Granitic rock	19.59	5.38	1.10
Okwa 2	Granitic rock	18.95	4.96	
Metamorphic				
KUKE	Meta-rhyolite	7.22	8.90	0.43
KUKE	Meta-rhyolite	6.95	7.38	

Table 9: Shows physical strength test results for rock samples in Gantsi Region (Samples were analyzed in Botswana Geoscience Institution laboratory) (Continued)

Sedimentary				
KARAKUBIS - 01A	Arkose	10.79	19.79	0.54
KARAKUBIS - 01B	Arkose	11.07	19.72	
CHARLESHILL - 01A	Arkose	13.29	7.58	0.52
CHARLESHILL - 01B	Arkose	15.16	8.53	
Gantsi	Arkose	10.36	9.00	0.41
Gantsi	Arkose	8.13	8.95	
MAKNDA	Arkose	8.28	9.38	1.48
MAKNDA	Arkose	7.27	7.98	

5.7 Kgalagadi Region.

Kgalagadi region comprise mostly metamorphic rocks and sandstones, with only one known igneous exposure (felsite) in Kokong village. Metamorphic rocks consist of quartzites, exposed on low-lying hills of the Olifantshoek Group. Aggregate material from sandstones is found in the Upper Karoo strata of the Lebung Group in Lokgwabe village and Sekoma quartzose-sandstone.

Kgalagadi South generally compose of reddish brown rocks that formed when quartz-rich sandstones went through a process of metamorphism. The individual quartz grains were altered by temperature without melting, pressure, and some chemical processes into a glassy stone. In places where the quartzite is not well-matured, medium and well-rounded quartz grains, which are milky opalescent and clear grains are a characteristic feature. The grainy, sandpaper-like surface turns into glassy look. Minor amounts of former cementing substances, iron oxide, silica, carbonate and clay, often migrate during recrystallization and metamorphosis. This causes streaks and lenses to shape in the quartzite.

Aggregate rocks from Kgalagadi North are dominated by orange, red sandstone, locally calcareous with reddish siltstone increasingly common downwards (Figure 6). The sandstone looks fibrous from multiple quartz veins, which are milky to white in colour. The medium grained clastic sedimentary rocks belong to the Lebung Group, which consists of concealed clastic sedimentary rocks of late Triassic–Early Jurassic Upper Karoo.

Sekoma quarry stones, comprise greyish quartzite which is ferruginous in some places (Figure 7). Parts of the rock are not well metamorphosed and comprise medium rounded quartz grains having a rusty color due to the presence of ferric oxide. The Sekoma sandstone is well cemented to quartzite, some of the character quartz grains have recrystallized to form an interlocking mosaic of quartz crystals. In some places, unique texture and sedimentary structures of the Sekoma sandstone are visible, making the rock to be quartzose-sandstone with grainy like sandpaper on the surface.

One igneous rock sample from Kokong was analysed, with AIV of 24.60 %, LA 26.30 % and water absorption of 0.55 % (Table 10). AIV for metamorphic rock samples range from 17.40 % to 21.30 %, LA range from 18.90 % to 28.12 % and water absorption range from 0.37 % to 0.57 %. Two sedimentary samples from Sekoma and Lokgwabe villages were also sampled, with AIV of 9.56 % and 8.70 %, LA of 17.34 % and 19.59 % and water absorption of 0.65 % and 3.07 respectively. Generally, all the rock samples from Kgalagadi region fulfil the aggregate strength requirements.

Table 10: Shows physical strength test results for rock samples in Kgalagadi Region (Samples were analyzed in Botswana Geoscience Institution laboratory)

Igneous				
District	**Place**	**AIV**	**ACV**	**Water absp**
kokong 2	felsite	24.60	26.30	0.55
Metamorphic				
Maralaleng 1	Quarzite	21.30	18.90	0.55
Maralaleng 2	Quarzite	19.80	19.87	0.51
Omaweneno	Quarzite	18.78	22.30	0.57
Maleshe	Quarzite	20.60	23.40	0.53
Maleshe Hill	Quarzite	10.93	24.50	0.37
Maubelo	Quarzite	20.68	28.12	0.55
Kolonkwane	Quarzite	18.90	19.80	0.47
khuis	Quarzite	17.40	23.40	0.39
Kisa	Quarzite	17.90	20.30	0.56
Sedimentary				
Sekoma	reddish/brown sandstone	9.56	17.34	0.65
Lokgwabe	Orange sandstone	8.70	19.59	3.07

Generally, Kgalagadi South metamorphic rock samples are constituted by almost similar minerals, dominated by analcime, forsterite, and quartz, at almost similar proportions within the rock samples (Appendix 3). Analcine (H_4 $Al_{1.806}$ $Na_{1.71}$ O_{14} $Si_{4.194}$) values are the highest in all samples, ranging between 34 % - 36 % weight fraction, followed by forsterite ($Fe_{0.34}$ $Mg_{1.14}$ $Ni_{0.52}$ O_4 Si_1) ranging between at 18 % - 20 % weight fraction with quartz values occupying third largest proportion (18 % - 20 % weight fraction) in all samples. Analcite is highest because it is found mostly in saline-pans in warm and arid conditions. Kgalagadi south area is surrounded by saltpans, hence the high amount of analcime mineral. Forsterite has tinted most quartzite rocks reddish brown because it contains Fe and Mg elements. The high amount of quartz is because of quartz-rich sandstone and the silica cement that binds the sand grains together during metamorphism. Another mineral that is generally found in all samples from Kgalagadi south is Bavenite ($H_{2.1}$ $Al_{1.9}$ $Be_{2.1}$ Ca_4 O_{28} Si_9), ranging from 18 % - 16 % weight fraction in all samples. Quartz and forsterite have a positive effect on the strength of the rock samples.

Figure 7: A) Okwa granitic gneiss (Gantsi District B) Sekoma quartzose-sandstone c) Talpan aggregate rock (Ngamiland) D) Kgwebe rhyolite (Gantsi and Ngamiland) E) Maubelo quartzite (Kgalagadi District) F) Maleshe quartzite (Kgalagadi District

5.8 Industrial Minerals Map of Botswana

Industrial Minerals Occurrence Map of Botswana (Figure 8) was compiled from both historical and data collected during the project life with the main objective of illustrating their distribution throughout the country. The map is aimed at guiding prospectors and the community on suitable areas for consideration for further exploration or mining activities.

Two hundred thirty seven (237) aggregate occurrence has been recorded in this compilation, nineteen aggregate quarries and ten recommended manufactured sand quarry sites. Most quarries and aggregate occurrence are more centred around eastern side of Botswana. The area encompasses the greater Gaborone region, Southern District, part of Central District and Northeast District. This is evident from the geologic characteristics, which is dominated by well exposed basement rocks of the Kaapvaal, Zimbawe Cratons and the Limpopo Mobile Belt. Greater Gaborone has ten quarries, Northeast District six quarries and Central District has three quarries.

Quarries and aggregate occurrence in Ghanzi region lies along the Ghanzi, Kgwebe Formation and the granitic gneiss belonging to the Okwa Group. Ghanzi region has five quarries sites, but only two are currently active. Kgalagadi region has one quarry site that is situated in Lokgwabe village, mining quartz-rich arenites of the Lebung Group. The southern western part of the Kgalagadi region is dominated by recrystallized and metamorphosed quartz rich stones belonging to the Olifantshoek Sequence.

Ngamiland District has five widespread aggregate occurences and three quarries sites. The western side of Ngamiland region is dominated by sub-cropping granitoid gneisses, which forms part of the Precambrian basement rock units. The southern part of this region comprise meta-rhyolites of Kgwebe Formation. The central part of Ngamiland region comprise siltstones, conglomerates and diabase, which are mined for aggregate use. Chobe area is dominated by basaltic lavas of the Stomberg Lava Group. The area has one quarry site, which is situated in Lesoma viallge.

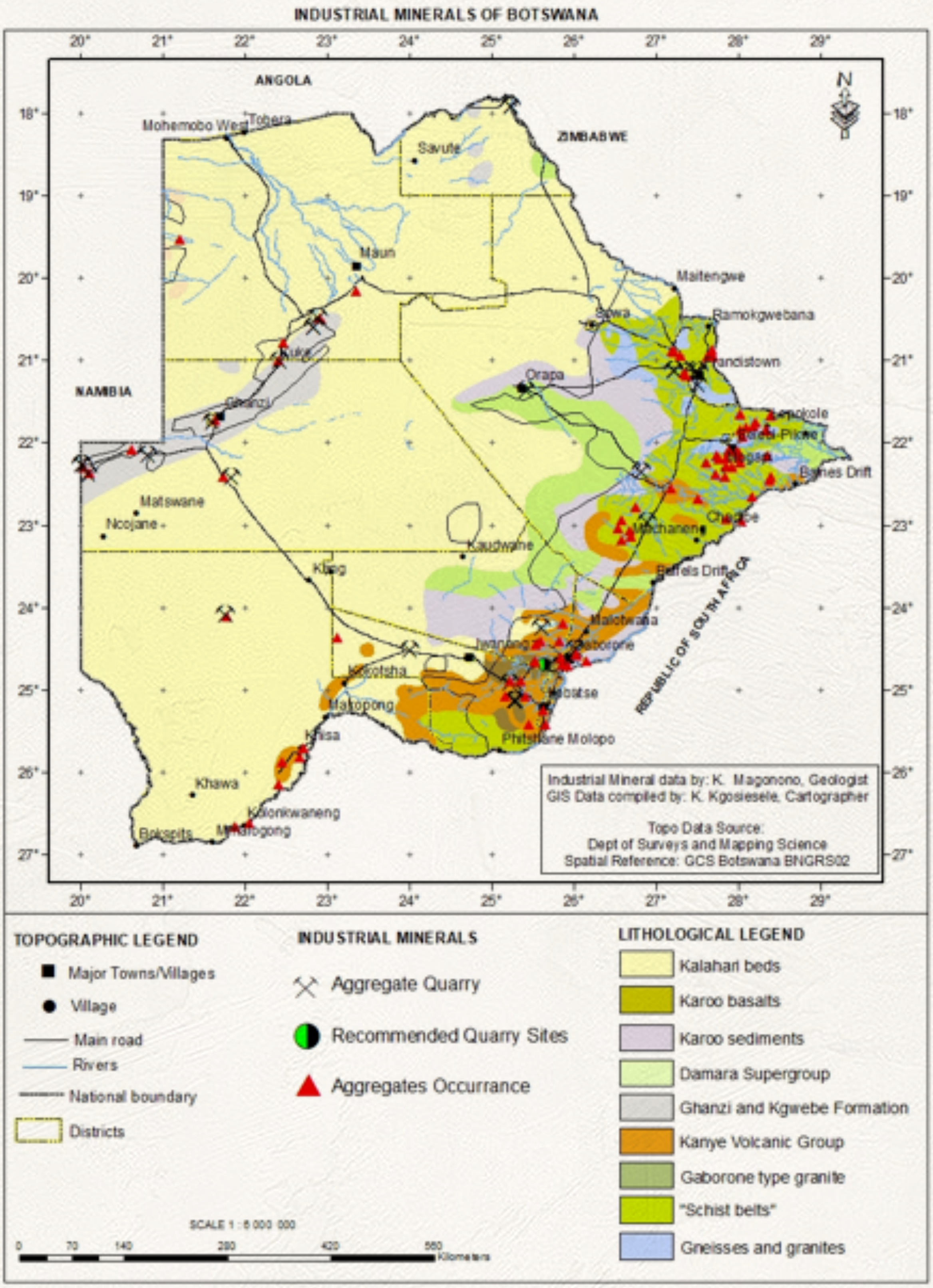

Figure 8: Industrial Minerals Map of Botswana, showing mineral occurrence and quarries

6. Conclusion

Mineralogy, water absorption and three approved fundamental laboratory physical tests (Aggregate impact value (AIV), Los Angeles test (LA) and Aggregate crushing value (ACV)) were used to characterize rocks in Botswana for potential aggregate purposes. Kgalagadi and Gantsi Districts comprise quartzitic rocks that fall within aggregate test limits. The quartzites from these Districts have generally low water absorption and high silica content which binds the rock grains together for good strength. Southern, Central and North East Districts generally comprise granite, dolerite and metamorphosed granite, with good physical strength and low in water absorption. Most of these rocks qualify as aggregate material for road and building construction. The strength of sedimentary rocks ranges from (AIV: 8.7 % - 25%, LA: 14.3 % - 40.3 %), which is significantly lower than those of igneous are (AIV: 7.9 % - 28.5 % LA: 7.9 % - 34.4 %) and metamorphic rocks (AIV: 9.5 % - 31.6 % LA: 7.9 % - 34.6 %). This phenomenon is caused by high porosity in sedimentary rocks, hence high water absorption rate and poor compressive strength. The new knowledge that was derived from this study is that, Botswana has a wide distribution of industrial minerals as shown in Appendix 5. Even though aggregates seem to be deficient in some regions, this study has revealed that there are occurrences, which can be evaluated for production.

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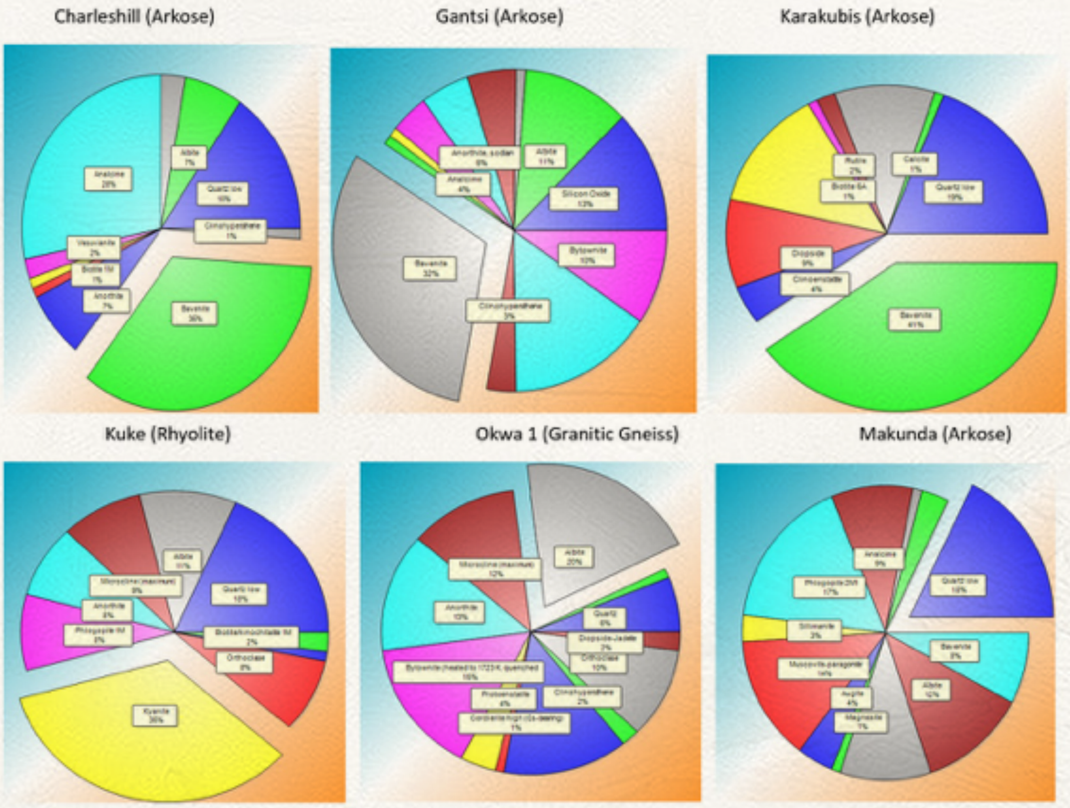
Appendix 1:

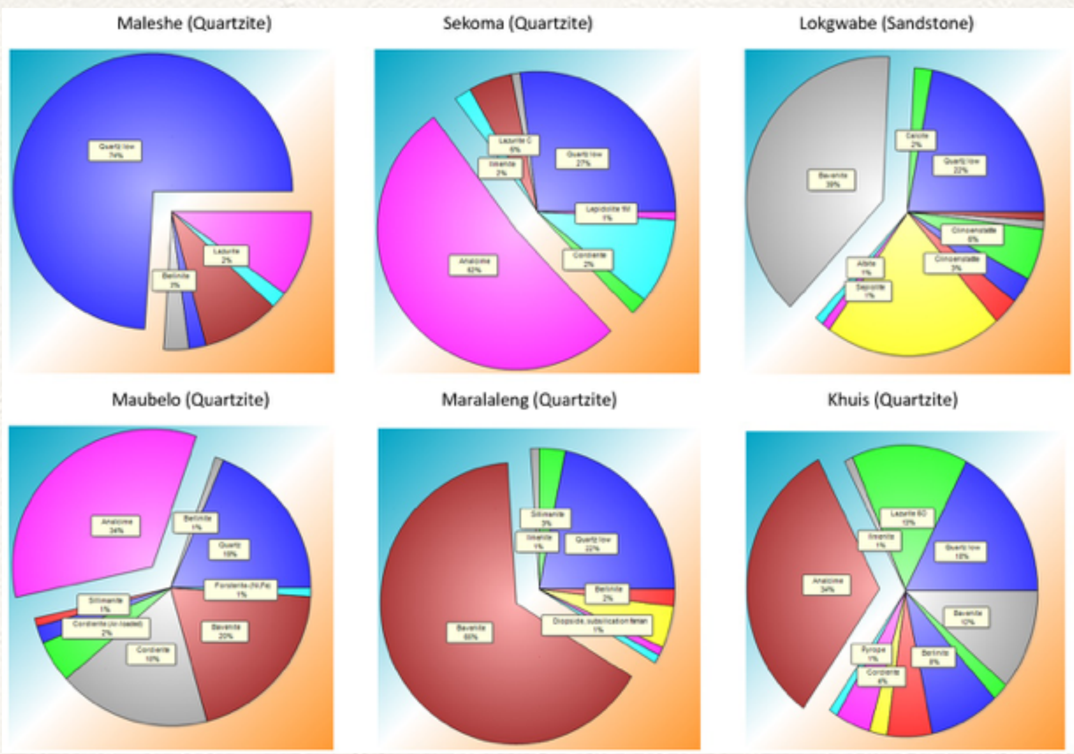
(A) Talpan area composed of fluvial deposits, consisting of boulders and cobbles which were released from their parent rocks by physical weathering and cemented to form conglomerates. B)Talpan re-worked rocks after crushing to remove cementing material C) Dry 19 mm crushed rock D) Wet 19 mm crushed rock

Appendix 2:



XRD results for Gantsi District. The results comprise mineral composition and the elements that form that minerals present in the rock.

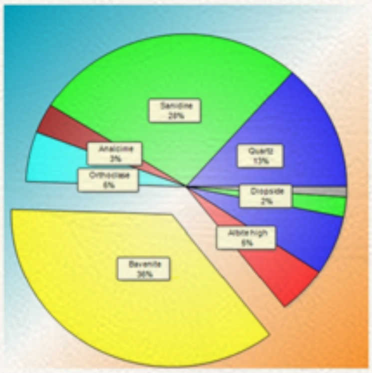
Appendix 3:



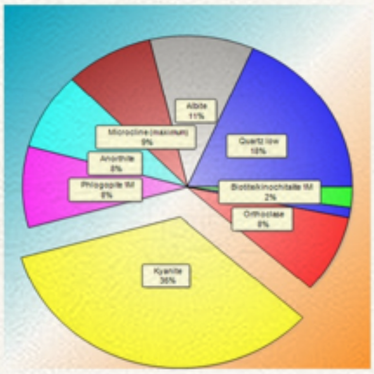
XRD results for Kgalagadi District. The rocks are dominated by quartz low, and bavenite

Appendix 4:

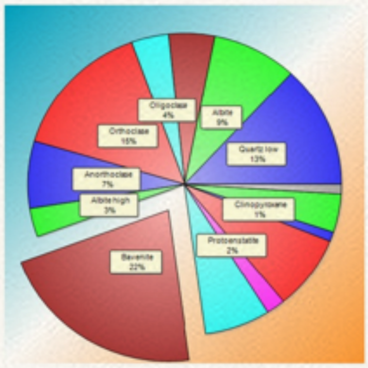
Botlhatlhogo (Quartzite)



Kgwebe (Rhyolite)



Talpan (Conglomerate)



XRD results for some of Ngamiland samples. Botltlhaogo area is dominated by bavenite and sanidine, Kgwebe rhyolite is dominated by kyanite, quartz and microcline. The Talpan conglomerate is dominated by bavenite and quartz.

Appendix 5:

Aggreagte test results. (Source: Geological Survey of Botswana Bulletins, District memoirs and relinquished exploration reports)

District	Location	Cordinates		Description	LA (%)	AIV (%)	ACV (%)	10% FACT	Bulk Density	Water Absorbtion	Methylene Blue
		Eastings (X)	Northings (Y)				Dry	Dry			
Central District	Molomowapudi	605862	7605533	Granitic Gneiss		0.20	22.00				
Central District	Mashambi Hill	644481	7603418	Porphyritic granitic gneiss		0.19	21.00				
Central District	Magogaphate	626033	7593271	Gray banded gneiss		0.18	26.00				
Central District	Thobolotona Hill	622129	7589980	Banded gneiss		0.25	18.00				
Central District	Tshokwe Drought relief road	613330	7588477	Dolerite		0.12	20.00				
Central District	Tshutshumane Hills	606153	7584467	Banded gneiss		0.16	26.00				
Central District	Romane Hills	638133	7583976	Granitic Gneiss		0.18	20.00				
Central District	Lepokole Hills	638872	7583108	Red augen gneiss (granitoid)		0.26	0.26				
Central District	Tobane	608446	7575503	Gabbro		0.13	0.13				
Central District	Majeaditshwene Hills, BPT 163	591206	7556424	Granitic Gneiss		0.18	0.20				
Central District	Mowana Lands, Trig. BPT 168	602209	7556079	Granitic Gneiss		0.19	0.21				
Central District	Lekgawe, NE Dibokolodi	577077	7550288	Red granitic gneiss		0.19	0.21				
Central District	Makgwaphe Hills	577077	7550288	Granitic Gneiss		0.18	0.20			0.34	
Central District	SE Makgwaphe Hills, BPT 167	588429	7546723	Red Banded Gneiss		0.23	0.24			0.63	
Central District	Mosatse Hill	579800	7545047	Banded gneiss		0.20	0.22			1.29	
Central District	Maore Hills	563918	7540477	Granitic Gneiss		0.21	0.23			2.18	
Central District	Matale Hills	588537	7535467	Banded gneiss		0.21	22.80			1.07	
Central District	Marutujwe Hills	595398	7534166	Red granitic gneiss		0.16	0.18			0.13	
Central District	Mabalelo Hills	595398	7534166	Leucocratic granitic gneiss		0.20	0.22			0.48	
Central District	Tloupye Hill, BPS 31	575352	7525328	Leucocratic granitic gneiss		0.21	0.23			0.16	

Appendix 5:

Aggreagte test results. (Source: Geological Survey of Botswana Bulletins, District memoirs and relinquished exploration reports) (Continued)

District	Location	Cordinates		Description	LA (%)	AIV (%)	ACV (%)	10% FACT	Bulk Density	Water Absorbtion	Methylene Blue
		Eastings (X)	Northings (Y)				Dry	Dry			
Central District	Setshweu Hills	587256	7521391	Banded gneiss		0.21	0.23			0.14	
Central District	Thune #2/Sefo-phe-Bobonong road	603853	7553393	Banded quart-zo-feldspathic gneiss		0.26	0.26			0.34	
Central District	Ntswaneng Hill, BPS 42	603804	7546044	Granitic Augen Gneiss		0.27	0.26			0.36	
Central District	Dikanti Hill, BPS 71	639930	7550284	Banded gneiss		0.19	0.21			0.48	
Central District	Manatswele Hills	606548	7541074	Dolerite		0.13	0.13			0.21	
Central District	Matsatsa Lands	619871	7494385	Banded gnesis and magmatite		0.22	0.24				
Central District	Tsetsebjwe Hill,Tsetsebjwe Village	643872	7521214	Paragneiss		0.19	0.21				
Central District	Mmalogong Hills	642513	7516459	Paragneiss		0.24	0.25				
Central District	Lesenapole Hills	552845	7491751	Foliated adamellite		0.29	30.00				
Central District	Shapane Hills	587900	7464496	Siliceous breccia		0.23	30.00				
Central District	Mmasehumana Hills	606534	7460993	Banded gnesis(ag-matite)		0.23	24.00				
Central District	Palapye	519462	7506696	Dolerite	7.36	7.77	9.81		3.15	0.34	0.29
Central District	Mokgware	474785	7480120	Granite	11.76	21.04	19.86		2.64	0.63	0.35
Central District	Bonwapitse	468338	7448812	Granite to quartz diorite	16.00	19.00	21.00		2.64	0.45	0.3
Central District	Tobela	457143	7436431	Granite	16.63	18.58	19.00		2.66	2.18	0.45
Kweneng District	Lekgalong	384901	7323164	Melanocratic diabase	24.46	23.60	23.00			0.57	
Kweneng District	Kopong	381988	7300376	Kanye Volcanics	8.04	23.53	17.00			0.48	
Kweneng District	Semarule Hill	353026	7295181	Igneous rock/ feldspar	26.41	9.17	5.80			0.90	
Kweneng District	Mokgopeetsane	357485	7299842	Kanye Felsites	15.25	20.79	12.30			0.50	
Southern District	Moshaneng	321564	7244967	Dolerite sill	10.40	17.60				0.67	
Southern District	Polokwe Hills	333900	7246044	Kanye Felsite	12.54	11.20				0.24	
Kweneng District	Gaborone Quarry	382453	7278539	Gaborone Granite	14.24	9.13		160kN		0.24	
Southern District	Kgale Quarry	384500	7269174	Gaborone Granite	19.08	10.53		190kN		0.46	
Southern District	Gaborone Dam Quarry	391544	7266923	Gaborone Granite	17.87	18.03	20.90			0.78	
Kgatleng District	Modipe Mountain	415391	7273241	Melanocratic Gabbro	12.46	11.98	9.20			0.53	
Kgatleng District	Oodi Hill	401830	7282688	Gaborone Granite	13.23	9.37	9.80			0.39	
Kgatleng District	Oodi Hill	402542	7281463	Felsite/gaborone granite	34.42	13.46				0.81	
Southern District	Kgoro Hill	344822	7186786	Granophyre	16.25	23.03	17.10			0.29	
Southern District	Lobatse	365071	7187621	Quartz-feldspar porphyry	25.73	23.97	16.50			1.29	
Southern District	Kanye-Lobatse road	361243	7206658	Kanye Felsite, Granite		21.48	13.60			1.62	
Southern District	Letlapana	315668	7224270	Red-brown syenite	22.36	20.36	19.89			1.04	

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Appendix 5:

Aggreagte test results. (Source: Geological Survey of Botswana Bulletins, District memoirs and relinquished exploration reports) (Continued)

District	Location	Cordinates		Description	LA (%)	AIV (%)	ACV (%)	Water Absorb-tion	Methylene Blue
		Eastings (X)	Northings (Y)				Dry		
Central District	Molomowapudi	605862	7605533	Granitic Gneiss		20	22		
Central District	Mashambi Hill	644481	7603418	Porphyritic granitic gneiss		19	21		
Central District	Magogaphate	626033	7593271	Gray banded gneiss		18	26		
Central District	Thobolotona Hill	622129	7589980	Banded gneiss		25	18		
Central District	Tshokwe Drought relief road	613330	7588477	Dolerite		12	20		
Central District	Tshutshumane Hills	606153	7584467	Banded gneiss		16	26		
Central District	Romane Hills	638133	7583976	Granitic Gneiss		18	20		
Central District	Lepokole Hills	638872	7583108	Red augen gneiss (granitoid)		26	26		
Central District	Tobane	608446	7575503	Gabbro		13	13		
Central District	Majeaditshwene Hills, BPT 163	591206	7556424	Granitic Gneiss		18	20		
Central District	Mowana Lands, Trig. BPT 168	602209	7556079	Granitic Gneiss		19	21		
Central District	Lekgawe, NE Dibokolodi	577077	7550288	Red granitic gneiss		19	21		
Central District	Makgwaphe Hills	577077	7550288	Granitic Gneiss		18	20	0.34	
Central District	SE Makgwaphe Hills, BPT 167	588429	7546723	Red Banded Gneiss		23	24	0.63	
Central District	Mosatse Hill	579800	7545047	Banded gneiss		20	22	1.29	
Central District	Maore Hills	563918	7540477	Granitic Gneiss		21	23	2.18	
Central District	Matale Hills	588537	7535467	Banded gneiss		21	23	1.07	
Central District	Marutujwe Hills	595398	7534166	Red granitic gneiss		16	18	0.13	
Central District	Mabalelo Hills	595398	7534166	Leucocratic granitic gneiss		20	22	0.48	
Central District	Tloupye Hill, BPS 31	575352	7525328	Leucocratic granitic gneiss		21	23	0.16	
Central District	Setshweu Hills	587256	7521391	Banded gneiss		21	23	0.14	
Central District	Thune #2/Sefo-phe-Bobonong road	603853	7553393	Banded quartzo-felds-pathic gneiss		26	26	0.34	
Central District	Ntswaneng Hill, BPS 42	603804	7546044	Granitic Augen Gneiss		27	26	0.36	
Central District	Dikanti Hill, BPS 71	639930	7550284	Banded gneiss		19	21	0.48	
Central District	Manatswele Hills	606548	7541074	Dolerite		13	13	0.21	
Central District	Matsatsa Lands	619871	7494385	Banded gnesis and magmatite		22	24		
Central District	Tsetsebjwe Hill,Tsetsebjwe Village	643872	7521214	Paragneiss		19	21		

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Appendix 5:

Aggreagte test results. (Source: Geological Survey of Botswana Bulletins, District memoirs and relinquished exploration reports) (Continued)

District	Location	Cordinates		Description	LA (%)	AIV (%)	ACV (%)	Water Absorb-tion	Methylene Blue
		Eastings (X)	Northings (Y)				Dry		
Central District	Mmalogong Hills	642513	7516459	Paragneiss		24	25		
Central District	Lesenapole Hills	552845	7491751	Foliated adamellite		29	30		
Central District	Shapane Hills	587900	7464496	Siliceous breccia		23	30		
Central District	Mmasehumana Hills	606534	7460993	Banded gnesis(ag-matite)		23	24		
Central District	Palapye	519462	7506696	Dolerite	7.4	7.8	9.8	0.34	0.29
Central District	Mokgware	474785	7480120	Granite	11.8	21.0	19.9	0.63	0.35
Central District	Bonwapitse	468338	7448812	Granite to quartz diorite	16	19	21	0.45	0.3
Central District	Tobela	457143	7436431	Granite	17	19	19	2.18	0.45
Kweneng District	Lekgalong	384901	7323164	Melanocratic diabase	25	24	23	0.57	
Kweneng District	Kopong	381988	7300376	Kanye Volcanics	8.0	24	17	0.48	
Kweneng District	Semarule Hill	353026	7295181	Igneous rock/feldspar	26	9.2	5.8	0.90	
Kweneng District	Mokgopeetsane	357485	7299842	Kanye Felsites	15.3	20.8	12.3	0.50	
Southern Dis-trict	Moshaneng	321564	7244967	Dolerite sill	10	18		0.67	
Southern Dis-trict	Polokwe Hills	333900	7246044	Kanye Felsite	13	11		0.24	
Kweneng District	Gaborone Quarry	382453	7278539	Gaborone Granite	14	9.1		0.24	
Southern Dis-trict	Kgale Quarry	384500	7269174	Gaborone Granite	19	11		0.46	
Southern Dis-trict	Gaborone Dam Quarry	391544	7266923	Gaborone Granite	18	18	21	0.78	
Kgatleng Dis-trict	Modipe Moun-tain	415391	7273241	Melanocratic Gabbro	13	12	9.2	0.53	
Kgatleng Dis-trict	Oodi Hill	401830	7282688	Gaborone Granite	13	9.4	9.8	0.39	
Kgatleng Dis-trict	Oodi Hill	402542	7281463	Felsite/gaborone granite	34	14		0.81	
Southern Dis-trict	Kgoro Hill	344822	7186786	Granophyre	17	23	17	0.29	
Southern Dis-trict	Lobatse	365071	7187621	Quartz-feldspar porphyry	26	24	17	1.29	
Southern Dis-trict	Kanye-Lobatse road	361243	7206658	Kanye Felsite, Granite		22	14	1.62	
Southern Dis-trict	Letlapana	315668	7224270	Red-brown syenite	22	20	20	1.04	
Southern Dis-trict	Moshupa	340605	7224585	Porphyritic rapakivi granite	21	22			
Kweneng District	Thamaga	351719	7272400	Porphyritic rapakivi granite	22	24			
Kweneng District	Thamaga Hill	352154	7271174	Coarse grained granite	20	26			
Central District	Molowapudi Hills	605862	7605533	Porphyroblastic gran-itoid gneiss	20	20	23		
Central District	Mashambi Hills	644481	7603418	Porphyritic granitic gneiss	25	20	21		

Appendix 5:

Aggreagte test results. (Source: Geological Survey of Botswana Bulletins, District memoirs and relinquished exploration reports) (Continued)

District	Location	Cordinates		Description	LA (%)	AIV (%)	ACV (%)	Water Absorb-tion	Methylene Blue
		Eastings (X)	Northings (Y)				Dry		
Central District	Magogaphate Lands	626033	7593271	Quartzo feldspathic gneiss	20	19	24		
Central District	Morale			Granite	16	19	15	1.07	0.3
Central District	Shoshong	452506	7451565	Granite	7.6	8.0	10	0.13	0.35
Central District	Mahalapye	468937	7441230	Granite	23	18	17	0.48	0.35
Central District	Patayamatebele			Granite	9.4	8.2	13	0.16	0.35
Central District	Mmutlane			Granite	8.0	7.7	11	0.14	0.35
Central District	PNDGR2			Granite	6.3	8.2	14	0.34	0.4
Central District	Kalamare	457336	7463379	Granite	12	11	16	0.36	0.35
North East District	Siviya	565217	7683454	Tonalitic Gneiss	28	24	18	0.34	0.4
North East District	Siviya	571070	7691632	Granitic Gneiss	35	32	31	0.28	0.4
North East District	Siviya	535753	7661543	Granitic Gneiss	25	22	24	0.45	0.35
North East District	Shashemooke	538049	7657977	Gneissic Granodiorite	28	25	25	0.39	0.4
North East District	Siviya	521332	7691043	Gneissic Granodiorite	15	15	12	0.30	0.35
North East District	Marobela	524076	7689534	Tonalitic Gneiss	20	21	22	0.37	0.35
North East District	Siviya	520938	7690661	Granitic Gneiss	24	20	17	0.32	0.45
North East District	Siviya	565791	7683507	Dolerite	14	17	14	0.31	0.35
North East District	Siviya	572826	7682923	Dolerite	10	10	8.2	0.023	0.4
North East District	Mafungo/Mber-ikama	531519	7684272	Granitic Gneiss	33	32.0	29	0.29	0.55
North East District	Siviya	571826	7686322	Gneissic Granodiorite	8.0	10	11	0.33	0.45
Central District	Changate Hills	525230	7754533	Coarse grained K-granite		26	26		
North East District	Domboshaba Granite	536644	7721466	Medium grained K-granite		32	27		
North East District	Makuta Hills	509694	7718121	Leucocratic granite		19	20		
North East District	Phanga Hill	515895	7695214	Migmatitic gneiss		26	29		
North East District	Francistown-Mo-setse road	518780	7691368	Leucocratic migmatite		25	24		
North East District	Ntimbale	543918	7691629	Medium/coarse grained granite		22	22		
North East District	Tshesebe road	561467	7710327	Doleite		15	19		
North East District	Bisoli Hill	561861	7675985	Granodiorite		19	20		
North East District	Francistown-Du-mela	555735	7665769	Diorite		12	16		
North East District	Bodumatau Hill	554463	7647326	Tonalite Gneiss		22	21		
North East District	Tshilo Hill	579198	7643321	Adamellite		21	22		

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Appendix 5:

Aggreagte test results. (Source: Geological Survey of Botswana Bulletins, District memoirs and relinquished exploration reports) (Continued)

District	Location	Cordinates		Description	LA (%)	AIV (%)	ACV (%)	Water Absorb-tion	Methylene Blue
		Eastings (X)	Northings (Y)				Dry		
Central District	Foley	537791	7603408	Augen Gneiss		21	22		
Central District	Selebi-Phikwe	588204	7572923	Amphibolite/tonalitic gneiss		26	24		
Gantsi District	Okwa 1	575199	7522829	Coarse grained Granit-ic gneiss	6.2	20		0.83	
Gantsi District	Okwa 2	576064	7523307	Coarse grained Granit-ic gneiss	5.4	20		1.10	
Gantsi District	Karakubis	459233	7559182	Metamorphosed Purple Arkose	20	11		0.54	
Gantsi District	Charleshill	521587	7840897	Metamorphosed Purple Arkose	7.6	13		0.52	
Gantsi District	Gantsi	563972	7596127	Metamorphosed Purple Arkose	9.0	10		0.41	
Gantsi District	Makunda	407744	7526949	Metamorphosed Purple Arkose	9.4	8.3		1.48	
Gantsi District	Kuke			Slightly metamorpho-se rhyolite	7.0	9.0		0.32	
Kgalagadi District	Maralaleng 1	667755	7149523	Greyish Quartzite with milky veins	19	21		0.55	
Kgalagadi District	Maralaleng 2	669840	7149122	Greyish Quartzite with milky veins	20	20		0.51	
Kgalagadi District	Omaweneno	665420	7147378	Greyish Quartzite with milky veins	22	19		0.57	
Kgalagadi District	Maleshe	643091	7140113	Greyish Quartzite with milky veins	23	21		0.53	
Kgalagadi District	Maleshe Hill	643091	7140113	Greyish Quartzite with milky veins	25	11		0.37	
Kgalagadi District	Maubelo	637484	7112243	Purplish quartzite	28	21		0.55	
Kgalagadi District	Kolonkwane	601761	2917062	Greyish Quartzite with milky veins	20	19		0.47	
Kgalagadi District	khuis	585488	7050582	Greyish Quartzite with milky veins	23	23		0.39	
Kgalagadi District	Kisa	670200	7157349	Greyish Quartzite with milky veins	20	18		0.56	
Kgalagadi District	kokong 2	714020	7305464	Fine grained felsites	26	25		0.55	
Kgalagadi District	Sekoma	197210	7286002	Quartz rich sandstone	17	10		0.65	
Kgalagadi District	Lokgwabe	579240	7336685	Orange sanstone with multiple quartz veins	20	9.0		3.07	
Ngamiland District	TalPan	691935	7723208	Conglomerate com-prising of rhyolite, sandstones, quartzite	17	12		0.41	
Ngamiland District	Dikgathong	747025	7770539	Baige silcrete	15	16		0.51	
Ngamiland District	Bothathogo	697686	7735402	Greyish slightly meta-morphosed sandstone	14	23		1.80	
Ngamiland District	Gate-small	653135	7702717	Reddish brown, fine grained sandstone	27	25		2.70	
Ngamiland District	Qangwa	157863	2838899	foliated medium grained granite	29	27		2.30	
Chobe District	Lesoma	313523	8019563	Basalt	13.84	9.54		1.20	

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