PETROGRAPHIC AND OPTICAL CATHODOLUMINESCENCE STUDY OF DETRITAL QUARTZ: PROVENANCE INDICATOR FOR THE SEDIMENTS OF THE CAMPANIAN LOKOJA-BASANGE FORMATION, ANAMBRA BASIN, NIGERIA

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ABSTRACT

The provenance of the Campanian quartz arenitic sediments of the Lokoja-Basange Formation had been investigated using integrated optical Cathodoluminescence and Petrographic characteristics approach. Results showed the presence, in abundance, of detrital quartz with characteristic dull red to violet CL colour and mottled texture. The common occurrence of compactional features such as Boehme Lamella, and micro fracturing within individual quartz grains, but without corresponding compressional features at the grain to grain boundaries suggested complex diagenetic history for the sandstones of Lokoja-Basange Formation. These features were indication of quartz derived from low grade metamorphic and which had undergone multiple reworking before final deposition. The sediments of the formation were texturally immatured and mineralogically matured, suggesting a high degree of chemical weathering.

Keywords: Provenance, Cathodoluminescence, Campanian, Anambra Basin, Lokoja-Basange Formation

INTRODUCTION

The processes of siliciclastic sediment generation, transportation and accumulation in sedimentary basins make provenance study an important component of sedimentology. The sources of siliciclastic sediments are commonly diverse, including weathered products of pre-existing rocks (igneous, metamorphic and even pre-existing sedimentary rocks). Some of the mechanically and chemically resistant minerals from these sources survive the usually complex transportation from the source areas to the depocenter. Some new minerals are formed in situ due to reactions within the pore waters or through other means during the different stages of diagenesis. Consequently, provenance study embraces several traditional geological disciplines including mineralogy, geochemistry, geochronolology, sedimentology, igneous and metamorphic petrology (Haughton *et al.*, 1991). Provenance study techniques are primarily targeted at discriminating between detrital minerals and those formed through crystallization after the initial weathering processes. Eduardo *et al.* (2009) indicated that each single sediment layer contains billions of detrital grains and that every grain preserves imprint of geological history which if properly read, compared and combined could lead to robust provenance study. However, the same authors noted that interpreting detrital codes could be complex due to the fact that provenance signals issued from source rocks become progressively blurred by multiple noises in the sedimentary environment and also through diagenesis.

Detrital quartz is one of the most important minerals used for provenance study in a siliciclastic setting due to its mineralogical and textural stability (Augustsson and Bahlburg, 2003). Despite its stabilities, matured sediments dominated by quartz have been suggested to undergo considerable modification from source area to the depositional basin (Augustsson and Bahlburg, 2003). This, coupled with lack of provenance-indicative rock fragments, the traditional petrology of quartz-rich sandstone is not always reliable as a provenance indicator. In the present work, traditional petrographic analysis (optical microscopy) is integrated with cathododoluminescence (CL) method for provenance study of the Campanian Lokoja-Basange Formation in the Benin flank of the Anambra Basin.

The light given off when a material is bombarded by electron beam is known as cathodoluminescence (Garlick, 1966). Luminescence in quartz has been suggested to generally depend on crystal structure defect, intracrystalline variation in trace element concentration, or may result from Al^{3+} substitution for Si^{4+} (e.g. Ramseyer and Mullis, 2000; Stevens-Kalceff *et al.*, 2000). Therefore, the weak but highly variable CL colours and emission spectra of quartz is related to genetic condition of quartz formation (Götze *et al.*, 2001). Also, quartz CL imaging has the ability to reveal internal structures and growth zoning in quartz crystals which is not detectable by means of other analytical techniques (i.e. Götze *et al.*, 2001). Cathodoluminescence is also useful in diagenetic reconstruction, for example, it discriminates between detrital quartz and authigenic quartz overgrowths. Grain dissolution in quartz (a diagenetic feature) has been observed to be properly imaged by CL. The CL characteristics of quartz have been indicated to depend on variations in temperature, pressure, and geochemical environment during quartz crystallisation and other associated events (Zinkernagel, 1978; Matter and Ramseyer, 1985; Augustsson and Bahlburg, 2003).

Integration of the two methods (optical microscopy and cathodoluminescence) provide the advantage of correct provenance determination for detrital quartz. Many workers have investigated the relationship between provenance and cathodoluminescence colours of quartz over the years (e.g. Götze *et al.*, 2001; Richter *et al.*, 2003; Bernet and Bassett, 2005; Bassett *et al.*, 2006).

The focus of the present investigation is to provide information on the possible source(s) of the sediments of the Lokoja-Basange Formation using both optical and cathodoluminescence microscopy. The objectives, therefore, are to quantify the mineralogical composition, evaluate the textural features, transport and diagenetic histories and cathodoluminescence characteristics of the detrital quartz present in the sediments of the formation.

Geological Setting

The studied section lies between Latitudes N 07° 07´14" to N 07°08´38" and Longitudes E 06°13´ to E 06°14´20" in the Benin Flank of the Anambra Basin (Fig. 1). The section (Figs. 2 and 3), generally known as Bawa, Hill is located along the Auchi-Igarra Road, Edo State. The Anambra Basin is a NE-SW trending intracratonic rift basin taking its source from the Benue Trough of Nigeria. The basin is bordered in the south by the Niger Delta, in the west by the West African Massif, to the north by the Bida Basin and Northern Nigerian Massif and at its eastern border is the middle Benue Trough and Abakaliki Anticlinorium.

Evolution of the Anambra Basin

The origin of the Anambra Basin is linked to the tectonic processes that accompanied the separation of the African and South American plates in the Early Cretaceous (Murat, 1972). Murat (1972) and Nwajide (2013) supported the idea of a megatectonic setting for the southern domain of the Benue Trough which was a longitudinally faulted crust having its eastern sector subsided preferentially to become the Abakaliki sub-basin. Up till the Santonian, the western sector of the Abakaliki sub-basin remained a platform whereas the eastern sector which was already subsided became a depocenter (Nwajide, 2013). The flexural inversion of the Abakaliki sub-basin as a result of the Santonian folding and uplift in the Abakaliki area (Nwajide, 2013) led to the shifting of the depobelt to the west and northwest of the sub-basin and hence the formation of the Anambra Basin.

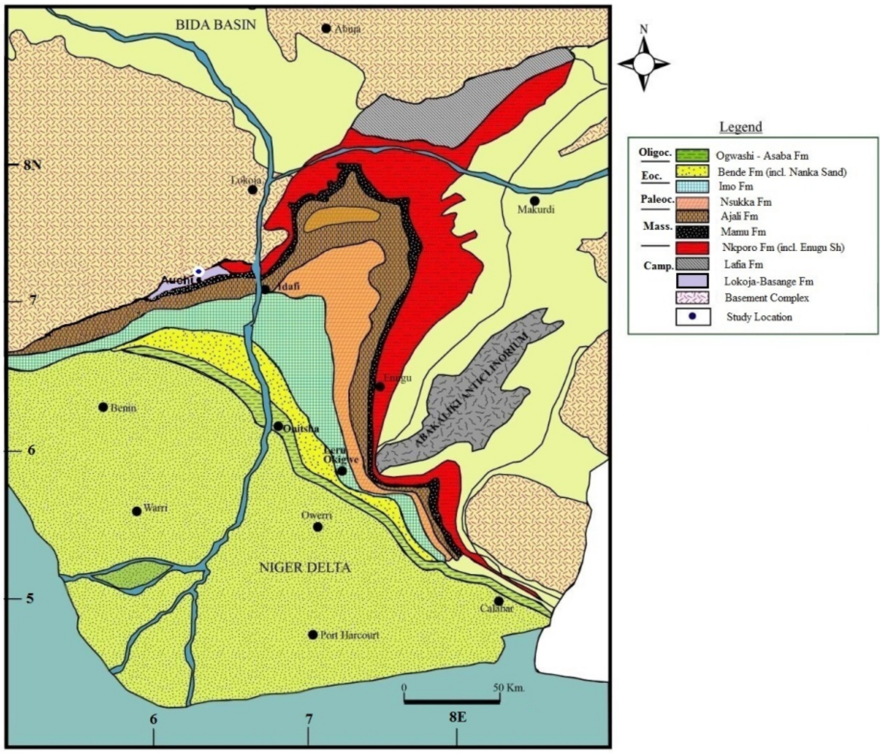


Fig. 1: Sketch Map of the Anambra Basin, Nigeria. (Modified after Nwajide, 1990)

Stratigraphy of the Benin Flank of the Anambra Basin

The Lokoja-Basange Formation which is the focus of the present investigation is the oldest sedimentary unit in the Benin flank of the Anambra Basin. This sedimentary sequence (rarely mentioned in the stratigraphy of the Anambra Basin) is a continental deposit directly lying non-conformably on the basement complex of the Igarra Schist Belt. Conformably overlying the Lokoja-Basange Formation is the Mamu Formation with the Ajali Formation capping the series in that sector of the Anambra Basin.

Fig. 2: Photograph of Bawa Hill section of the Lokoja-Basange Formation outcropping in a road cut along the Auch-Igarra road. Note the hammer resting on the through crossbed

Lokoja-Basange Formation

Lokoja-Basange Formation is the oldest sedimentary unit in the Benin Flank of the Anambra Basin. It lies non-conformably on the basement complex and outcrops in a road-cut along the Auchi-Igarra road. The formation which is massively bedded (Fig. 2) is characterized by sandy horizons, siltstones, mudstones, and claystones (Fig. 3). The basal units as observed at the contact with the basement complex is ferruginised and highly consolidated. The middle units are friable and poorly sorted whereas the upper units are slightly consolidated with evidence of iron oxide cement. The generally fine to coarse grained sandstones are angular to sub-angular in texture and generally poorly sorted. They display normal grading with basal conglomerates. Mud chips, kaolinite beds of limited lateral continuity are also common in the middle units of the formation. Sedimentary structures are largely dominated by large scale trough cross-beddings and lag deposits indicating the presence of channels which were observed to be stacked.

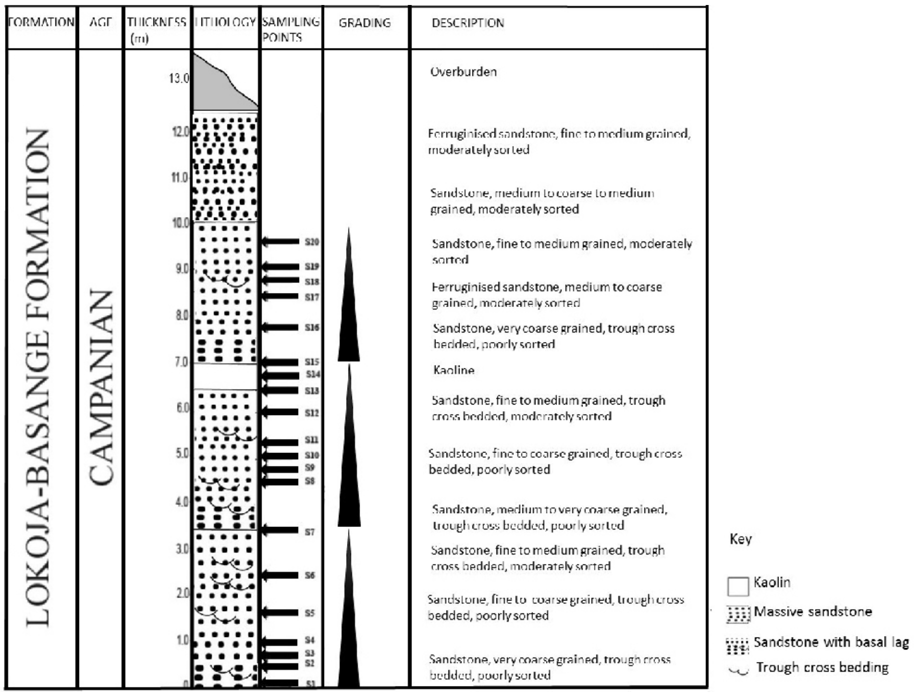


Fig. 3: Bawa Hill log section of the Lokoja-Basange Formation Outcropping in a Road Cut Along Auchi-Igarra Road

Mamu Formation

This is a rhythmic sequence of fine- to medium-grained sandstone, black shale, grey mudstone and thin coaly beds. Mamu Formation noted for its abundant coal units also outcrop along the Auchi-Igarra just before the Military Barracks. The formation also outcrops in a road cut before Okpekpe town off Auchi-Fugar road. Very thin coal bed was observed below the first black shale bed at the road cut section just about a kilometre before Okpekpe town. Thicker coal seams of up to 3.5 m at the center of Anambra Basin in Enugu have been documented in the work of Reyment (1965).

Ajali Sandstone

Ajali Sandstone is the youngest of the three formations identified in the Benin Flank of the Anambra Basin. Outcropping at various localities along Okpekpe road off Auchi-Fugar road and most especially about a kilometre to Okpekpe town where it is observed directly overlying the basal Mamu Formation. Perhaps the most spectacular exposure of Ajali Sandstone in this Flank of the Anambra Basin is at the road cut about 500 m to Agenebode town. Ajali Sandstone is highly loosely packed with little cement or lack of it. The basal unit is medium to very fine grained and moderate to poor sorting. Observation in hand specimen shows that the grains are angular to sub-rounded with few being rounded. Brownish clay laminae were observed at certain interval within the basal units. The upper units are better sorted and better consolidated. Mud chips are common occurrences within the Ajali Sandstone and have been interpreted by Nwajide (2013) as rip-up clasts derived from the immediate vicinity and transported only a few meters before deposition on an erosion surface. Sedimentary structure is hugely dominated planar and lenticular cross bedding.

MATERIAL AND METHODS

Fourteen sandstone samples recovered at one meter interval from outcrop section were used for the present study. Thin sections were prepared from all the fourteen samples while four samples selected at targeted intervals were subjected to cathodolominescence analysis.

The thin section preparation (including impregnation with blue epoxy) and cathodoluminescence analyses were carried out at the Calgary Rock and Material Services Incorporation, Calgary, Alberta, Canada. Microscopic study for petrological investigation was done at the geological laboratory, Department of Geosciences University of Lagos. The microscopic scanning was carried out using Leitz Laborlux 12 Pol microscope while photomicrographs were taken with Amscope FMA050 camera attached to the microscope.

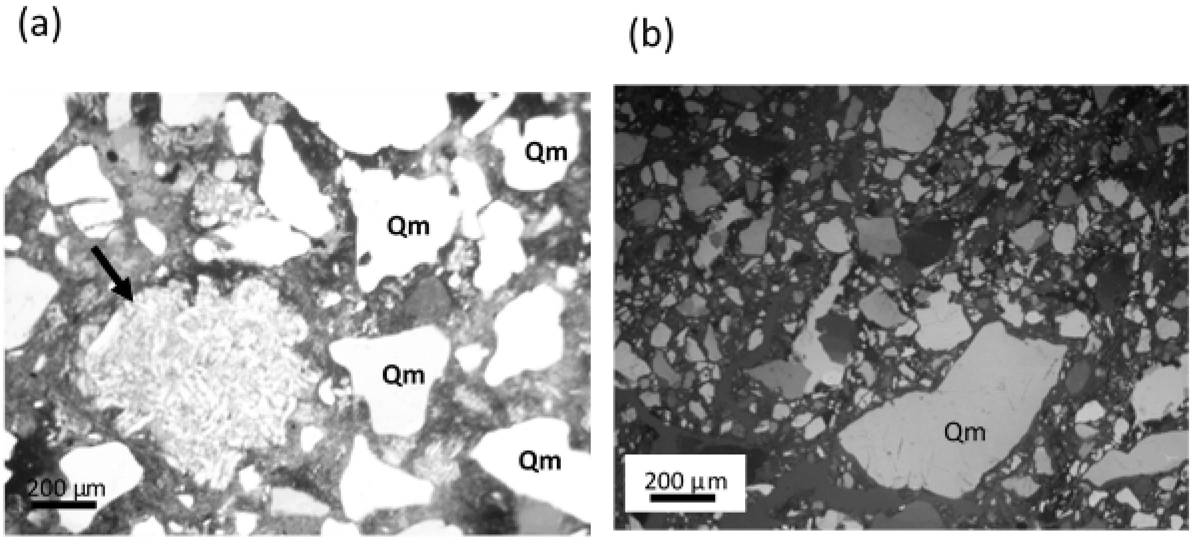
Techniques for CL at Calgary Rock involved the use of thick thin sections (~50 μm) viewed on a Nuclide Corporation Luminoscope Model ELM2D. Images were captured using a Nikon D810. Calgary Rock utilized a cold cathode optical microscope cathodoluminescence system. In this system the electrons were generated by an electric discharge between two electrodes under a low vacuum system (Marshall, 1988).

RESULTS

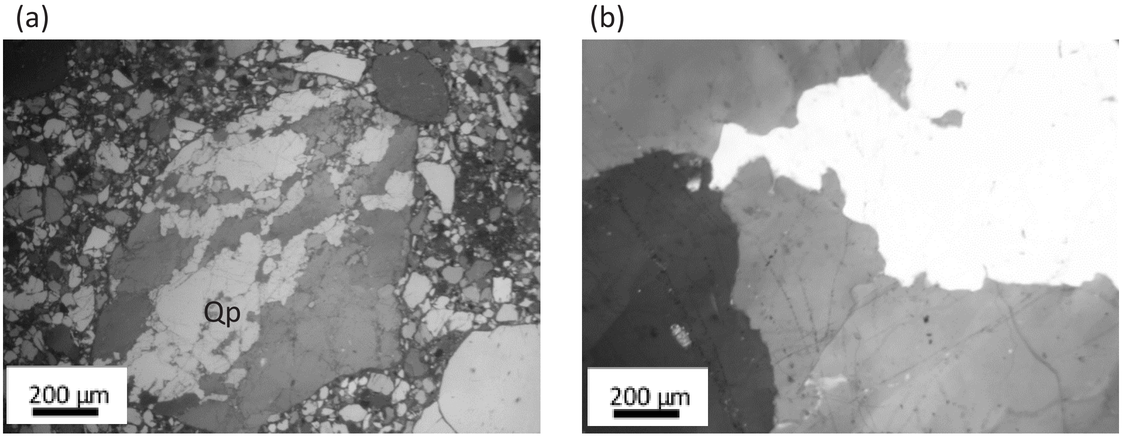
The studied section is approximately 13 m thick (Fig. 3). It is generally massively bedded with large channels cutting through the massive beds in places (Fig. 2). The channels are stacked with each channel displaying normal grading (fining upward). Quartz is the most common detrital mineral in the sediments of the Lokoja-Basange Formation, primarily displaying mono- and polycrystalline (Figs. 4 and 5) optical character under the microscope. The grain sizes range from coarse at the bottom to very fine grained at the top of each channel. Lag deposits were observed at the bottom of the channels. The uppermost unit consists of red coloured well consolidated sandstone, the colouration results from the percolation of iron oxide from the thick lateritic overburden into the uppermost unit of the section. Large scale trough cross-bedding is prevalence at the middle of the section

Petrography

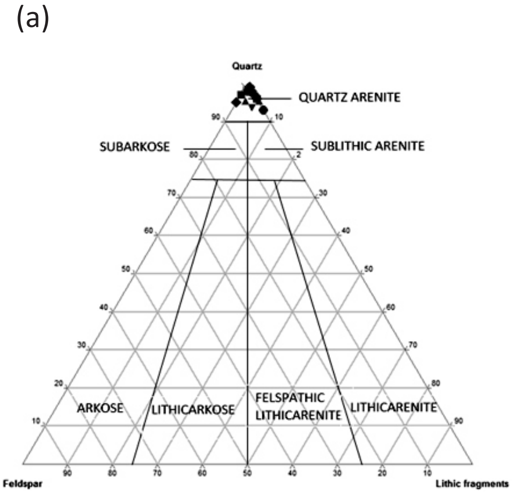
The Lokoja-Basange Formation consists of lightly consolidated sandstone dominated by quartz with no trace of feldspar. The grains are fine to coarse sand-sized, poorly sorted with angular to subangular shape. Of particular note herein is the presence of smaller grains being more rounded than the larger grains (Figs. 4, 5a and 7). Detrital quartz predominates (98%) the mineral components in all the twenty samples investigated. Rock fragments (Fig. 4a) of sedimentary origin constitute approximately 2%. On the basis of this percentage mineral composition as plotted on the QFL diagram (Fig. 6a), Lokoja-Basange Formation is classified as quartz arenite (Folks, 1968; Dickinson and Suczek, 1979) in a recycled orogenic setting (Fig. 6b). The quartz types include monocrystalline and polycrystalline quartz (Qm and Qp respectively, Figs. 4 and 5). Polycrystalline quartz slightly dominates (About 58%). The margins of individual grains of the polycrystalline quartz are highly sutured (Figs. 5a and b). Majority of the monocrystalline quartz display undulatory extinction under cross polarised light. Compactional features such as micro-cracks (Fig. 7) are common within some of the quartz grains. This high compactional features of the individual grains are not reflective of the overall rock fabric (e.g. no sutured grain to grain contacts, preservation of delicate clay clusters, preservation of primary porosity, no quartz overgrowth, etc.). Haematite dominates the cement type in all the samples, with some cements identified as kaolinite.



Figs. 4a, b: Photomicrograph; The black arrow in (a) shows a rock fragment, probably of sedimentary origin. Note the monocrystalline (Qm) quartz grains in (a) and (b).



Figs. 5a, b.: Photomicrograph of large crystals of polycrystalline quartz (Qp). (a), shows a sub-rounded crystal, (b) shows a large single crystal covering the entire field. Note the sutured grain margins in both figures.



Figs. 6a, b: Fig. 5a, QFL Ternary Diagram for the Classification of the Lokoja-Basange Formation (Folk, 1968).

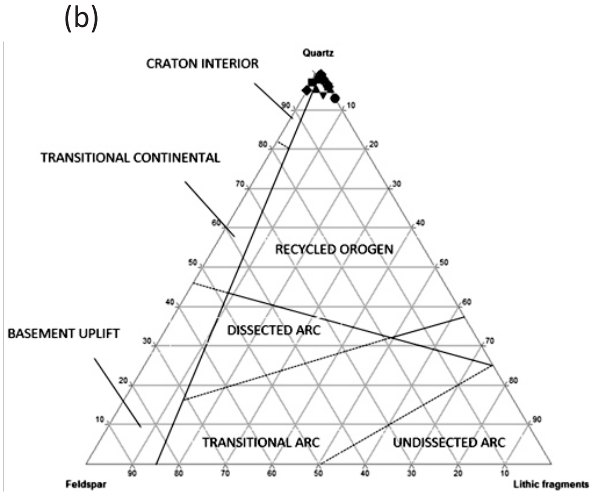
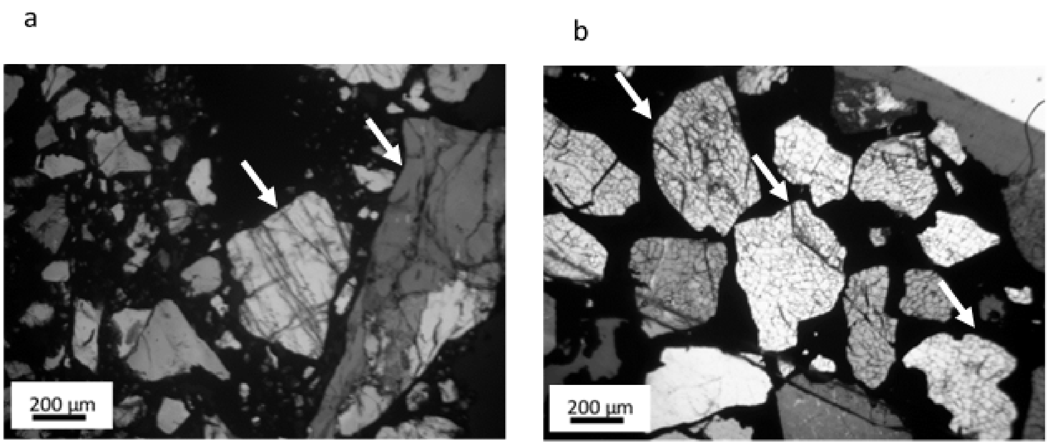


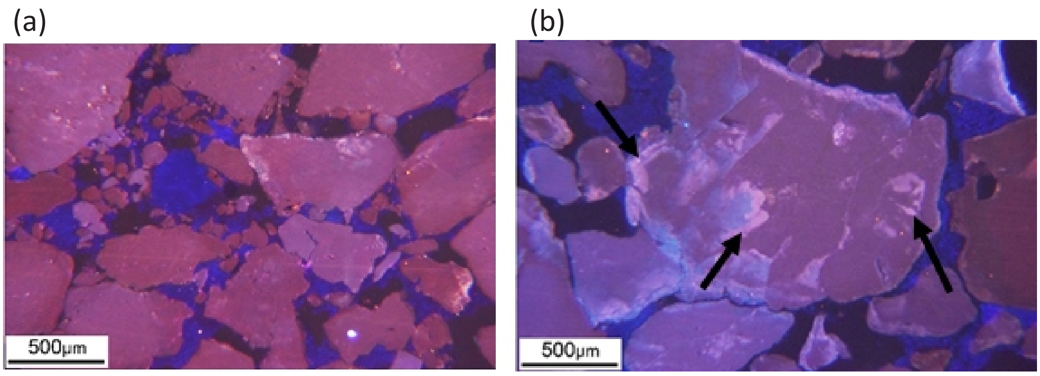
Fig. 6b: QFL Ternary Diagram Indicating the Tectonic Setting for the Lokoja-Basange Formation (Dickinson and Suczek, 1979).

Optical Cathodoluminescence

Majority of the quartz grains in the studied samples exhibit dull red (Fig. 8a) to brighter violet (Figs. 8b, 9, 10b, 11b) luminescence under electron bombardment. The internal texture of the quartz grains exhibit mottled texture. Grains with mottle texture are observed as violet and blue heterogeneously coloured grains (Fig. 9). Also, Boehme lamellae are seen in some grains (Figs. 7a, 10a, 11a). This special type of lamellae is due to high stress regime. Some of the grains present in the samples have more complex textures which appear as concentric zonations under cross-polarized light and electron bombardment (Figs. 10a and b). These zonations under electron bombardment show a discrete compositional boundary between the outer and inner structure of the zonation (Fig. 10b). Also, disjointed pseudo micro-zonations have been observed in some of the quartz grains (Fig. 8b).



Figs. 7a, b.: Photomicrographs showing, (a), Bohme Lamella (arrows) (b), Microfracturing (arrows) in the Individual Quartz Grains of the Lokoja-Basange Formation



Figs. 8a, b: CL Images , (a), the Dull Red to (b) Violet Colour of Quartz under Electron Bombardment, (b), Arrows Show Disjointed Pseudo Micro-Zonations in the Large Quartz Grain at the Centre of the Figure.

DISCUSSION

A high degree of textural immaturity is evident from the poor sorting, angular and clay-rich sandstone. Though the sandstone is texturally immatured, the absence of feldspars and mica may be indicative of mineralogical maturity. These two lines of interpretation (textural immaturity and mineralogical maturity) are suggestive of the dominance of chemical weathering of the parent rock. The dominance of polycrystalline quartz and the presence of undulose extinction in majority of the monocrystalline quartz is an indication of metamorphic origin (Boggs, 2003).

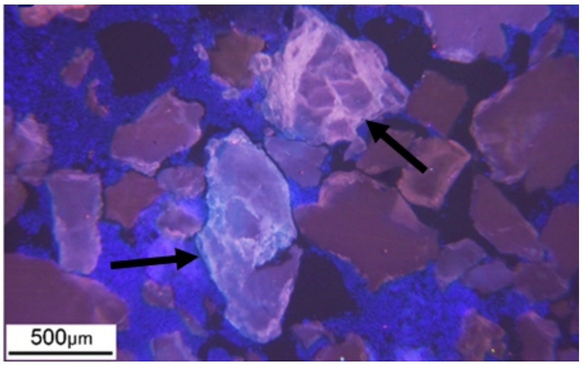


Fig. 9: CL Image showing Mottled Texture in Violet and Blue Heterogeneously Coloured Grains Highlighted by Bright lighter Coloured Lineations (arrows)

Quartz is the main mineral that exhibits luminescence in the studied samples. The dull red to violet luminescence of quartz has been associated with metamorphic grade rocks by several authors (i.e. Götze and Zimmerle, 2000; *Götze et al.*, 2001; Augustsson and Bahlburg, 2003; Bassett *et al.*, 2006; Richter *et al.*, 2003). Regarding the internal texture of the quartz grains, mottled textures is characteristic of metamorphic quartz (Seyedolali *et al.*, 1997) which is independent of their CL coloration. However, when taken in conjunction with the CL coloration, these two lines of evidence strongly infer a metamorphic origin. The mottle texture is attributed to random/irregular lattice defects and activator ions within the mineral and can be caused by deformation during metamorphism (Seyedolali *et al.*, 1997). Sprunt (1978) also attributed the dull reddish luminescence quartz to low temperature metamorphism. The presence of uncharacteristic multiple curved surfaces infer corrosion or dissolution diagenesis. Uniform luminescence is a subtle texture and represents a compositional and structurally (lattice) uniform mineral character. The dull uniform luminescence has been associated Uniform luminescence is a subtle texture and represents a compositional and structurally (lattice) uniform mineral character. The dull uniform luminescence has been associated with recrystallization that has eliminated the luminescent properties (i.e. crystal defects, compositional differences, etc.) of the mineral (personal communication).

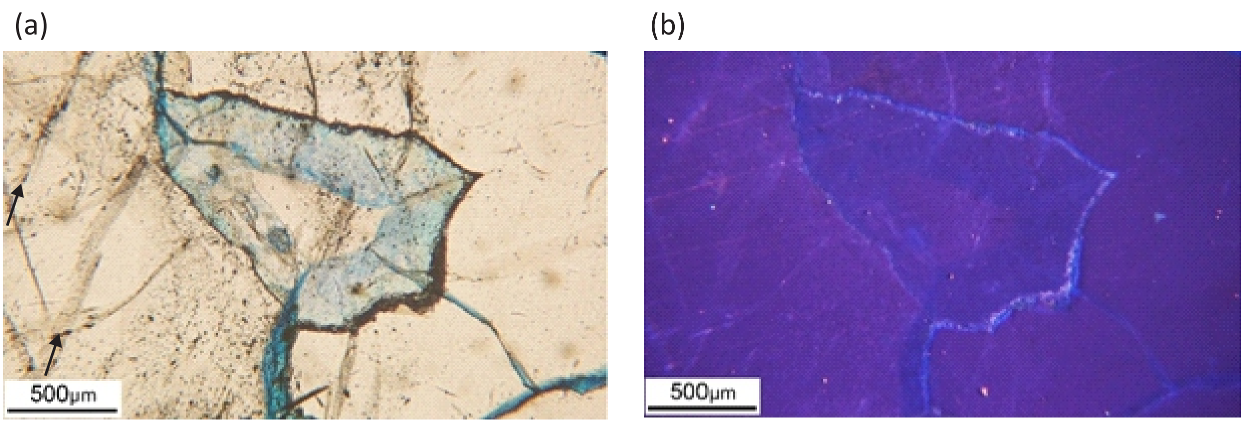
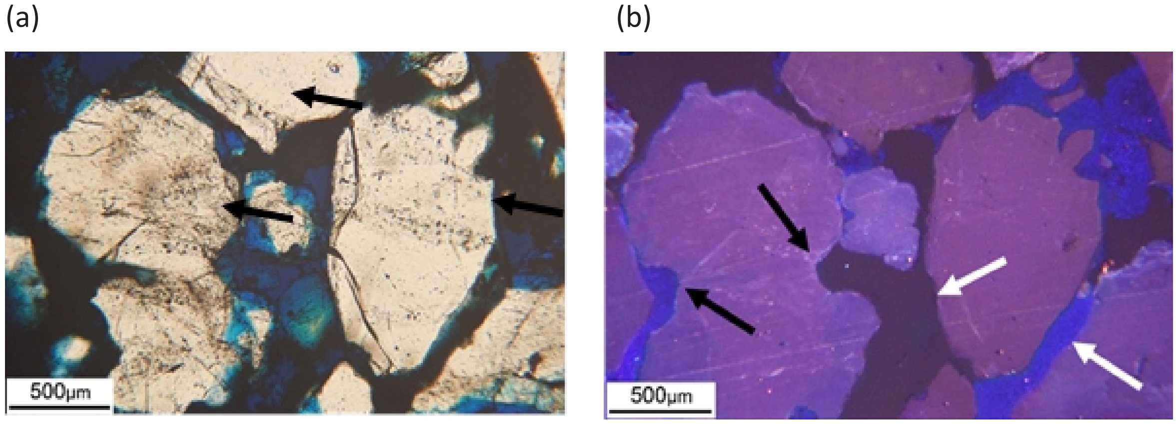


Fig. 10: a, b.: CL Images of Well Developed Zonation within a Large Qaurtz Grain. (a), Image under Cross Polarised Light, note the Arrows Showing Boehme Lamella; (b), CL Image, note the Colour Variation within each Zone.

The non-luminescent and the luminescent cements under electron bombardment are identified as hematite and kaolinite respectively. Kaolinite is one of the few clays that exhibit luminescence (personal communication).



Figs. 11: a, b: CL Images; (a), Boehme lamella (arrows) in Cross Polarized Light, (b), Curved Surfaces of Dissolution (black arrow) in the Quartz Grain, Dark Brown Haematite Cement (white arrow) and Sky Blue Kaolinite Cement (white arrow)

Both the linear structures observed under electron bombardment and cross-polarized light represent structural defects within the grain caused by mechanical stresses. Some grains have higher frequencies of these features. These linear structures are most commonly observed on grain boundaries and may represent deformation features from grain to grain contacts. This is a point of interest due to the lack of mechanical stress features observed within the fabric of the rock (i.e. no quartz overgrowth) compared with the high mechanical stress features within the grains. These micro vs macro differences are important to note which further details. The micro-textures are not the products of the current in-situ stress but a secondary diagenetic event that has overprinted onto the grain. This detail also infers a more complex diagenetic history of these sediments which may have been reworked multiple times before the current deposition. Also the CL coloration/textures observed within the grains (uniform luminescence vs. mottled texture) represents different spectra of the metamorphism process and therefore can represent multiple metamorphic sources for the rock constituents.

CONCLUSION

The sandstones of the Lokoja-Basange Formation are mineralogically matured but texturally immatured. These indicate the dominance of chemical weathering of the parent rocks from where the different aggregates of the rocks were formed and transported. Quartz cathodoluminescence of the sediment shows the dominance of grains from low grade metamorphic sources. The detrital quartz grains were not only subjected to metamorphism/stresses that altered internal textures, but subsequent external influences that slightly altered grain exteriors (chemical alteration and/or corrosion).

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