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Compaction-induced porosity loss in the Cretaceous Bima Formation around Lakwaime and Dogon Dutsi, Yola Sub-basin, Northern Benue Trough, NE Nigeria.

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Abstract

The Bima Sandstone is an alluvial fan to braided river sedimentation that represents purely a siliciclastic depositional system. It is the oldest formation and the main reservoir unit in the entire Benue Trough. Porosity loss is an essential component of petroleum reservoirs that needs to be properly investigated for the purpose of hydrocarbon exploitation. Compaction and cementation processes are partly responsible for porosity loss in many known reservoirs around the world. Outcropping units of the formation around Lakwaime and Dogon Dutsi in Yola Sub-basin have been subjected to an integrated approach involving field observations, petrographic analysis and porosity measurements in order to understand the contribution of each of the processes. Modal composition of the samples shows that they are mostly lithic arkose to feldspathic litharenite, with quartz as the most common detrital mineral grain. Grain fracturing has been attributed to mechanical compaction, whereas grain contacts like sutured and concavo-convex are products of chemical compaction. The average values of compactional-porosity loss (COPL), cementational-porosity loss (CEPL), and compaction index (ICOMPACT) in the studied samples stand at 19.51%, 4.18% and 0.82 respectively. The study indicates that the role of compaction in porosity loss is greater than that of cementation as shown by the COPL-CEPL diagram and, as such considered to be generally responsible for the porosity loss in Bima Sandstone.

Keywords: siliciclastic, alluvial fan, arkose, porosity, compaction index

Introduction

A reservoir is the rock plus void space contained in a trap (Gluyas and Swarbrick 2004). Sandstone (siliciclastic) and limestone (carbonate) are the commonest reservoir lithologies, with siliciclastic dominating North Africa, Europe, USA, Australia, while carbonate remains the dominant reservoir in the Middle East (Gluyas and Swarbrick, 2004). The most important reservoir quality parameters are porosity and permeability. Porosity is the voids per unit volume, usually expressed as a percentage while permeability is the ability to transmit fluids measured in millidarcies (mD). Reservoirs are subject to various forms of modifications which either enhance or destroy their quality (porosity). For instance, cementation of the pores

spaces by quartz overgrowth or mechanically infiltrated clays, and compaction destroy initial pores spaces thereby reducing the quality of the reservoir, whereas dissolution of detrital grains greatly enhances the porosity. Hence, compaction (mechanical and chemical), quartz overgrowth, and mechanical clay infiltration are among the porosity loss mechanisms in the studied Bima Sandstone samples.

The early Cretaceous Bima Sandstone is the most viable reservoir unit of the Northern Benue Trough. The impact of compaction (mechanical and chemical) as it relates to processes leading to porosity loss in reservoirs is important in several ways. Compactional porosity loss and cementational porosity loss have been attributed to various reservoirs including the Bima Sandstone (Samaila and Singh, 2010; Bello et al., 2022). Understanding the level of porosity loss in reservoirs is not only important in predicting reservoir quality but also in understanding the overall reservoir architecture up to field-wide or formation level. This present research employed an integrated approach using field observations, petrographic analyses, and porosity measurements to analyze the microscopic impact of mechanical and chemical compaction based on the grain contacts, and also compare the impact of compactional porosity loss and cementational porosity loss in Bima Sandstone around Lakwaime and Dogon Dutsi, Yola Sub-basin.

Geologic setting and stratigraphic framework

The Benue Trough is an intracratonic structure that is part of the mega-rift system termed West and Central Africa rift system (WCARS). It is arbitrarily subdivided into southern, central and northern segments based on tectonic, geographical, and stratigraphic components (Whiteman, 1982; Ramanathan and Fayose, 1990); though no clear demarcation is established. The Benue Trough stretches NNE-SSW extending for over 1000 km long and 250 km wide (Wilson and Guiraud, 1992; Nwajide, 2013) and contains up to 6,000 m of Cretaceous–Tertiary sediments. Those sediments predating the mid-Santonian compressional episode became folded, faulted, and uplifted (Obaje, 2009).

The Northern Benue Trough is about the most important of the entire inland sedimentary basins of Nigeria. In its northern portion, it bifurcates into N-S trending Gongola basin and E-W trending Yola basin (Figs. 1 A and B). Several oil discoveries have been made in other basins within the WCARS e.g. in Sudan, Chad, and Niger among others. Oil exploration activities have been conducted in the basin since the early 1990s which led to the drilling of three exploration wells; Kolmani River-1, Nasara-1, and Kuzari-1 with no commercial discovery made. Recently in 2019, the Nigerian National Petroleum Corporation (NNPC) was mandated to revisit the inland sedimentary basins in search of oil and gas. This led to the success recorded in Kolmani River-2 well in Gongola sub-basin where older formations of Bima and Yolde were targeted. It is important to state that all the discoveries within the WCARS were in formations that have been correlated with the Bima sandstone.
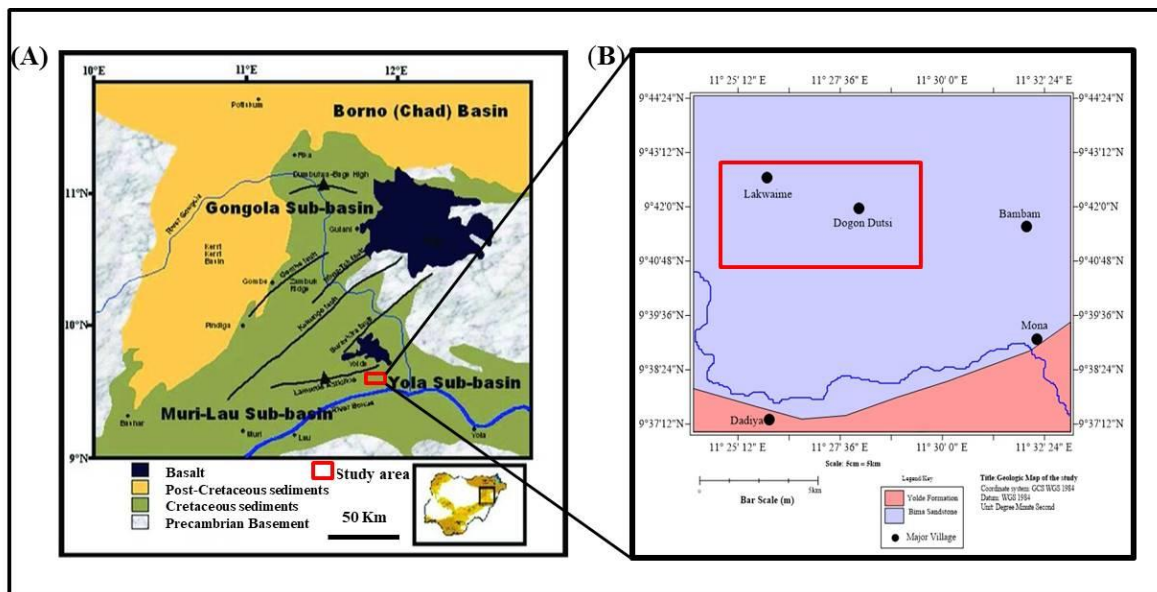
Fig 1. (A) Geological map of Northern Benue Trough showing the study area (Adopted from Shettima et al., 2017). (B) Geological Maps of the study area.

The Bima Sandstone is entirely continental and forms the basal unit of the stratigraphic succession in the basin. The formation was first named by Falconer, 1911, however, several other names have been proposed by other workers. It is an alluvial fan to braided river sedimentation (Benkhelil, 1989; Guiraud, 1990). Carter et al., (1963) subdivided the formation into lower (B1), middle (B2), and upper (B3) Bima members based on sedimentary structures. A two-member model, the Lower and Upper Bima Members was proposed (Tukur et al., 2015), based on lithofacies associations. The early Cretaceous Bima Sandstone non-conformably overlies the Precambrian crystalline basement rocks (Carter et al., 1963; Obaje, 2009) across the Northern Benue Trough, making it the oldest stratigraphic unit in the basin. The Cenomanian Yolde Formation conformably overlies the Bima Sandstone and it is a variable sequence of sandstone and shale which marks the onset of marine transgression giving rise to transitional environments that are composed of fine to medium-grained, well-sorted sandstones (Abubakar, 2006; Shettima et al., 2011). The deposition of Dukul, Jessu, Sekule, Numanha and Lamja Formations during the Cenomanian-Santonian is the expression of full marine incursion into the basin (Carter et al., 1963; Usman et al., 2020). The stratigraphic succession of the Yola Sub-basin is shown in Fig 2.
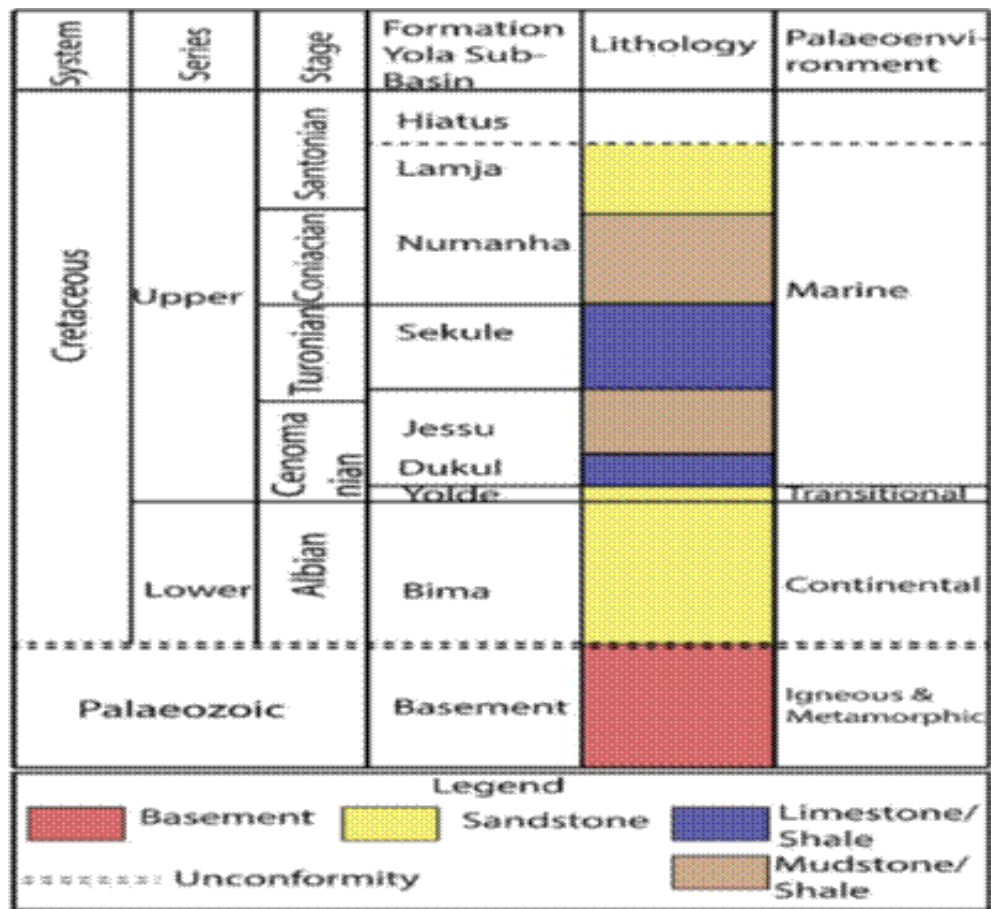
Fig. 2. Stratigraphic succession of the Yola Sub-basin (Adopted from Bello et al., 2022).

Materials and methods

Sedimentary logging

Topographical maps of Northern Benue Trough that are located within the Yola Sub-basin were used during the fieldwork. Road cuttings and stream channels provided accessibility to some excellent outcrops of Bima Sandstone. The exposed lithostratigraphic sections of the formation were logged and data on lithology, color, geometry, texture, and sedimentary structures were systematically recorded. Different lithofacies were encountered in the process. The outcome of the field work led to the generation of a detailed geological map of the study area (Fig. 1 B)

Petrography

Seven (7) thin sections from the sandstone samples of Bima Sandstone were prepared and studied using a petrographic microscope. Sample selection was done based on identified lithofacies. Modal point count analysis was conducted using JMicroVision 1.3.1 software based on 300 counts per sample to determine the detrital and authigenic components and pore space properties. The minus cement porosity determination method using photomicrograph was employed to get the initial porosity of the samples before oil emplacement. This involved subtracting the estimated volume (percentage) of hydrocarbon contained within the pores of individual sand from the estimated volume (percentage) of detrital grains and cement (Bata, 2016; Cooper and Hunter, 1995). The minus cement porosity is the original porosity of the samples before the onset of any diagenetic alteration (compaction, cementation, precipitation

and dissolution). Granulometric analysis was done to get the mean grain size and sorting of the sediments.

Results and Discussion

Field observation

Field observations revealed 5 lithofacies of the Bima Sandstone across the study area (Fig. 3 A-D). Detailed descriptions of these identified lithofacies are as follows:

Massive sandstone facies (Sm)

This lithofacies is a poorly sorted gravel facies without any defined sedimentary structure (Fig. 3 A). It is a channelized alluvial deposit which represents shallow channel deposition in a proximal braided river system due to changes in flow direction and flow stage and strength (A Tukur et al., 2015). Similar facies have been interpreted to represent deposition from debris flow. This is due to its poor sorting and mineralogically immature grains that lack internal organization (Rust, 1978; Miall, 1996, 2010). It is found mostly associated with mudstone facies.

Planar cross-bedded sandstone facies (Sp)

This lithofacies is fine-very coarse-grained sandstone and occurs as amalgamated units of poorly to moderately sorted sediments (Fig. 3 B). It ranges in thickness from 43 cm to about 842 cm, with individual foresets occurring in mm scale. It occurs in association with other lithofacies like horizontally laminated sandstone facies. Planar cross-bedding is interpreted to form by the migration of large-scale, straight-crested ripples and dunes formed during lower flow regime conditions which results in downstream migration of dunes in a fluvial channel (Boggs, 2006, Miall, 1978, 1996).

Parallel or horizontally laminated sandstone facies (Sh)

The parallel or horizontally laminated sandstone facies in the Northern Benue Trough is a fine to very coarse-grained sandstone that is poorly to moderately sorted (Fig. 3 C). Its color varies from whitish to pale brown and is characterized by sub-rounded to sub-angular grains. They are interpreted as either upper or lower plane-bed phase lamination (Tucker, 2003), or formed under fluctuating conditions of high flow, upper regime under critical flow (Boggs, 2006). Under such conditions, the irregular surfaces are eroded and flattened because the energy exceeds the formation of ripples or dunes, and this led to the deposition of plane beds of varying grain sizes.

Ripple laminated sandstone facies (Sr)

This lithofacies is thin, around 28 cm and forms the topmost unit in Lakwaime (Fig. 3 D). The ripples, brownish and ferruginised are mostly asymmetrical and poorly sorted. They are interpreted as waning flood deposits (Collinson and Thomson, 1992; Jensen and Pederson, 2010); however, Miall (1996) interpreted similar facies to be formed by the migration of very small, two- or three-dimensional bedforms under lower flow regime.

Mudstone (M)
The mudstone lithofacies is a laterally extensive unit with variable thickness in the basin. But here it is greyish in color with thickness of about 165 cm. It occurs mostly as blocky basal unit (Fig 3 A). It represents a low energy environment deposit (Miall, 1977; Tucker, 2003). Similar clay-sized facies have been interpreted as suspended loads or wash loads with very low settling velocities (Boggs, 2006). This may perhaps represent the lacustrine deposit within Bima Sandstone as suggested by Allix (1983).
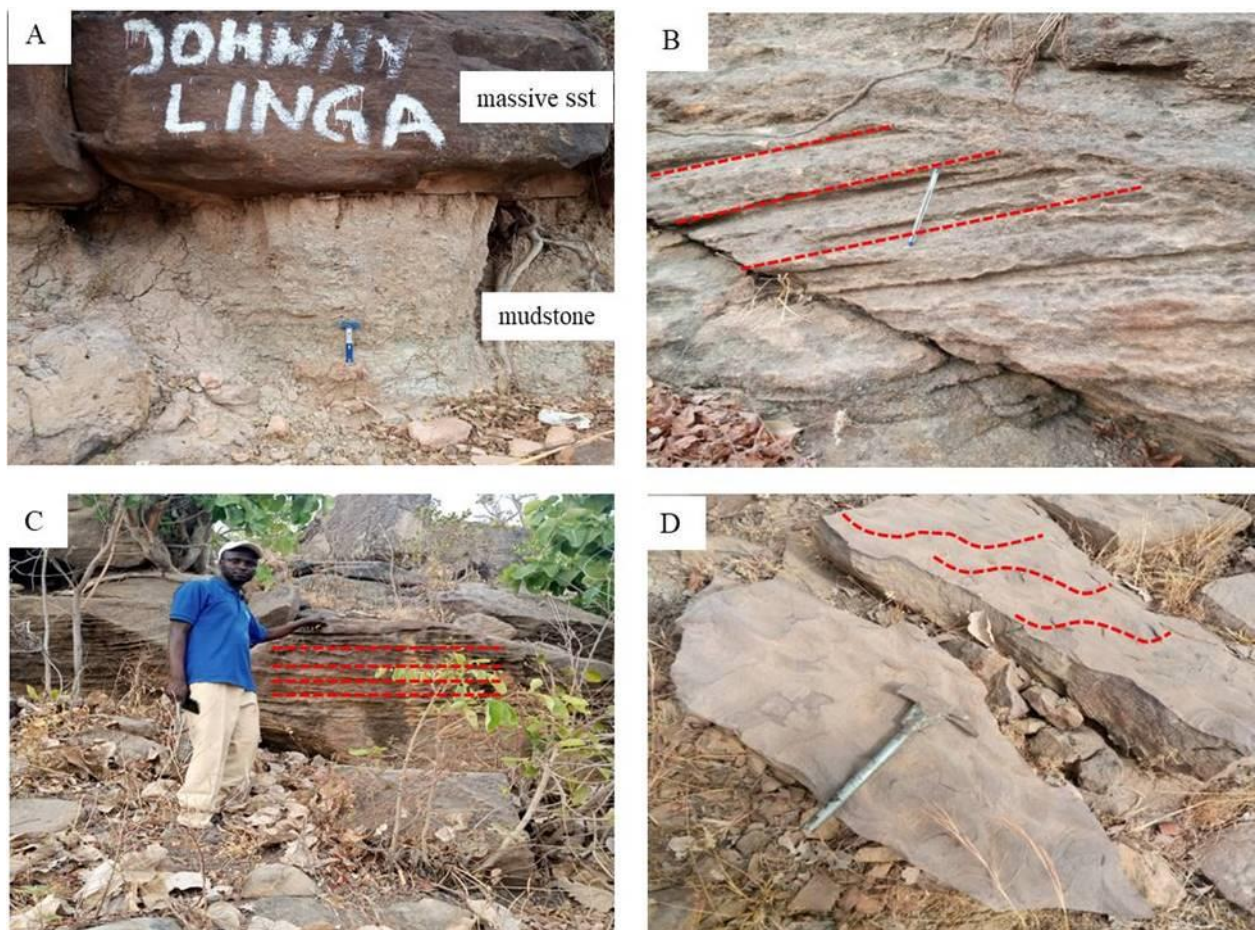

Fig. 3. Field occurrence (A) massive sandstone and mudstone facies. (B) planar cross-bedded sandstone facies. (C) horizontally laminated sandstone facies. (D) rippled laminated sandstone facies

Diagenesis

Thin sections
The sandstones show quartz, feldspars and rock fragments as the main constituents. Various grain contacts like point, long, concavo-convex and sutured contacts (Fig. 4 A-D) were observed from the thin sections. The horizontally laminated and massive sandstones show long, sutured, and concavo-convex contacts (Fig. 4 B & C) which indicate more matured sediments with reduced pore spaces, and eventually reduced matrix, usually < 15%. The planar-cross bedded sandstone has more sutured contacts (Fig. 4A) and this indicates that the sediments have been subjected to chemical compaction. The ripple sandstone facies show more or less point and long contacts (Fig. 4D); this is an indication that the sediments only suffered low compaction levels and mineralogically less matured. The massive sandstone

facies are mostly quartz-dominated, and well-sorted which makes it texturally and mineralogically more matured compared to the planar, horizontal and ripple sandstone facies.
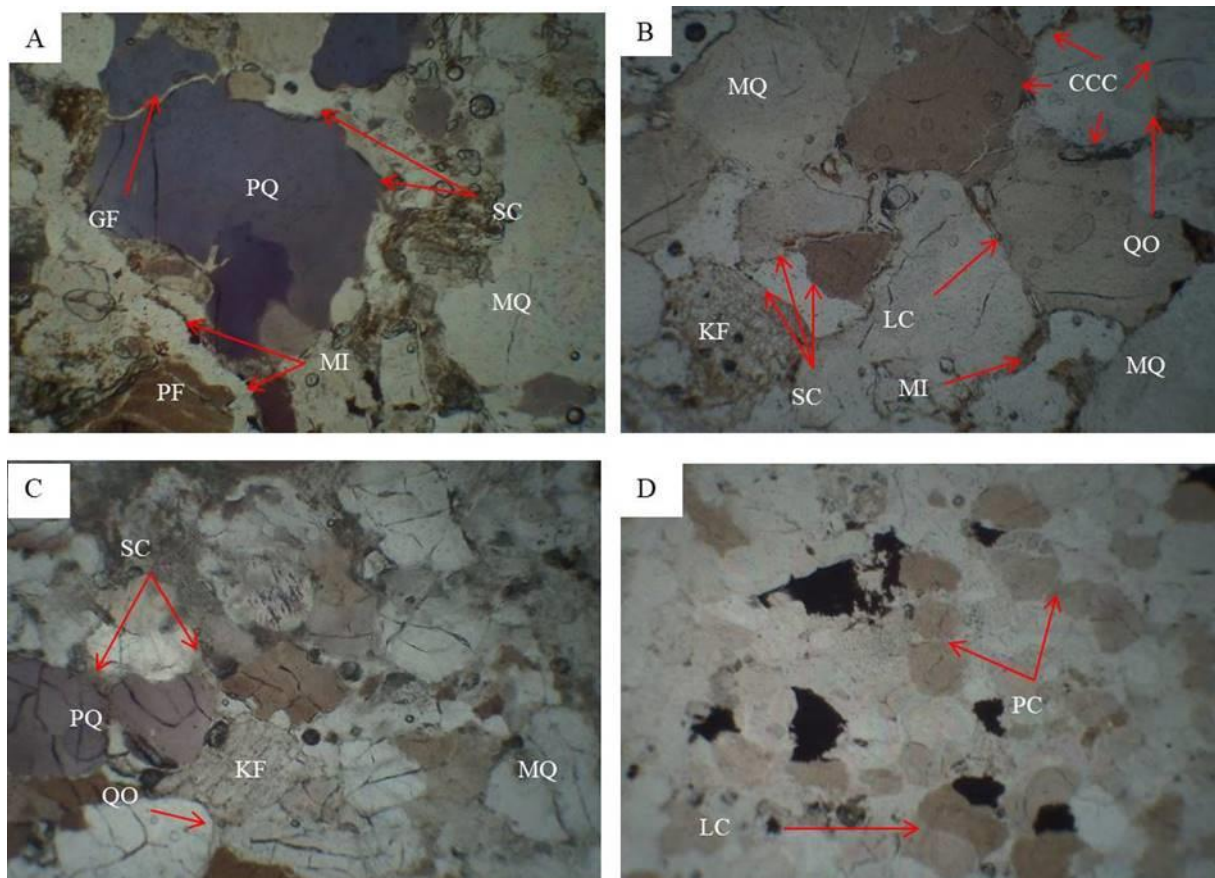

Fig. 4. Photomicrograph (A) planar cross-bedded sandstone showing grain fracturing (GF), sutured contact (SC), polycrystalline quartz (PQ), monocrystallline quartz (MQ), mud intraclast (MI), plagioclase feldspar (PF). (B) horizontally laminated sandstone showing concavo-convex contact (CCC), Long contact (LC), sutured contact (SC), quartz overgrowth (QO), mud intraclast (MI), potassium feldspar (KF), monocrystalline quartz (MQ). (C) massive sandstone showing sutured contact (SC), quartz overgrowth (QO), potassium feldspar (PF), and monocrystalline quartz (MQ). (D) ripple sandstone showing point contact (PC) and long contact (LC).

Sandstones composition
Modal analysis data (Table 1) show that the most common detrital mineral grain is quartz. Monocrystalline quartz dominates over polycrystalline quartz. Orthoclase is the dominant detrital potassium feldspar (K-feldspar) whereas micas are dominated by muscovite. Lithic fragments are dominated by metamorphic and volcanic rocks and polycrystalline quartz.

Table 1. Average, maximum and minimum modal composition and petro-physical data of the analyzed samples of Bima Sandstone

Features	Components	Min.	Max.	Ave.
Detrital grains	Monocrystalline quartz	26.5	71.3	32.2
	Polycrystalline quartz	0	21.4	6.9
	K-feldspar	3.5	19.2.	18.3
	Plagioclase	0	6.1	2.2
	Total rock fragments	0	10.5	6.4
	Mud intraclasts	0	6.4	1.2
	Biotite	0	3.4	1.2
	Muscovite	0	1.0	0.3
	Heavy minerals	0	4.1	1.1
Diagenetic minerals	Kaolin	0.3	12.8	3.5
	Quartz overgrowth	4.2	9.3	5.3
	Pseudomatrix	0	5.3	1.9
Porosity	Intergranular porosity	21	27	25.14
	Intragranular porosity	0	7.4	3.5
Porosity loss	Compaction-porosity loss	7.69	24.05	19.51
	Cementation-porosity loss	0.00	9.23	4.18

Based on Folk (1980) classification scheme, the sandstones of the studied Bima Sandstone samples are compositionally lithic arkose to feldspathic litharenite and, less commonly subarkose and litharenite (Fig. 5)
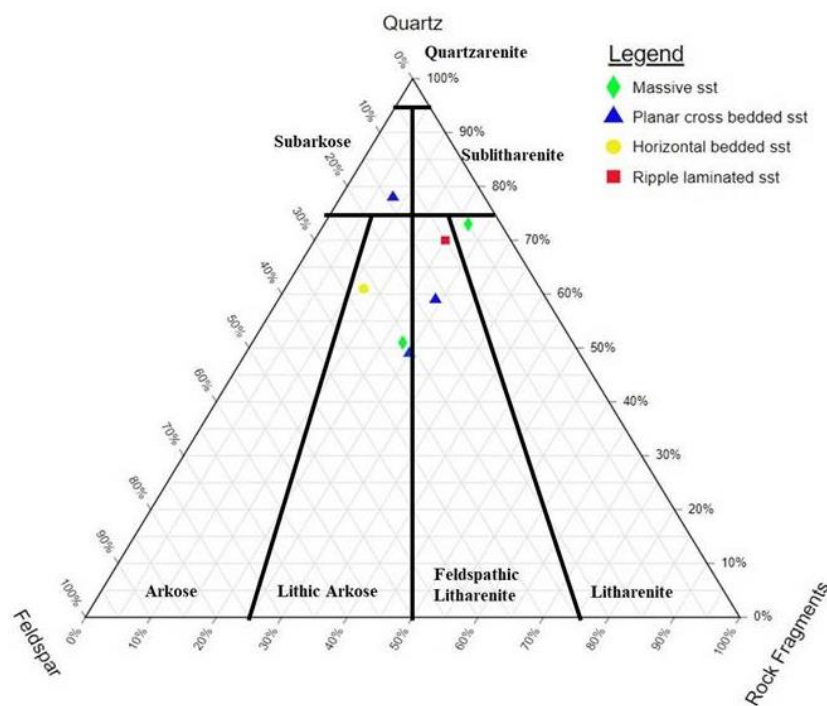

Fig. 5. QFR plot showing the modal compositions of the studied Bima sandstone samples (after Folk, 1980).

Compactional porosity loss (COPL) versus cementational porosity loss (CEPL)
Compaction and cementation are variably responsible for porosity loss in sandstone reservoirs. It is important to show the relative impact of compactional and cementational porosity loss on the Bima Sandstone in order to ascertain which of these two processes is responsible for the porosity loss. Lundegard (1992) shows that compactional and cementational porosity loss can be calculated from the initial porosity (P_i), and two petrographically determined parameters, total optical porosity (P_o), and volume-percent pore-filling cement (C). The sum of P_o and C is what is referred to as minus-cement porosity (P_{mc}) or intergranular volume (IGV). Using equations 1-3 below, the COPL, CEPL and ICOMPACT were calculated as shown in Table 3 based on the method of Lundegard, 1992.
Compactional porosity loss (COPL) = P_i - (((100- P_i) X P_{mc})/(100 - P_{mc}))   equation 1
Cementational porosity loss (CEPL) = (P_i - COPL) X (C/ P_{mc})   equation 2

Also, an important parameter that shows which of the two processes is responsible for the porosity loss is called the compaction index (ICOMPACT), and can be calculated as;
ICOMPACT = COPL/(COPL + CEPL)   equation 3

The effect of COPL against CEPL loss was plotted (Fig. 6). The compaction index (ICOMPACT) equals 1.0 when all porosity loss is due to compaction, and equals 0.0 when all porosity loss is by cementation (Table 3)
The initial porosity of Bima Sandstone around Lakwaime and Dogon Dutsi is assumed to be 40% because the disaggregated samples are medium to very coarse grain and moderately to poorly sorted (Tables 2 & 3).
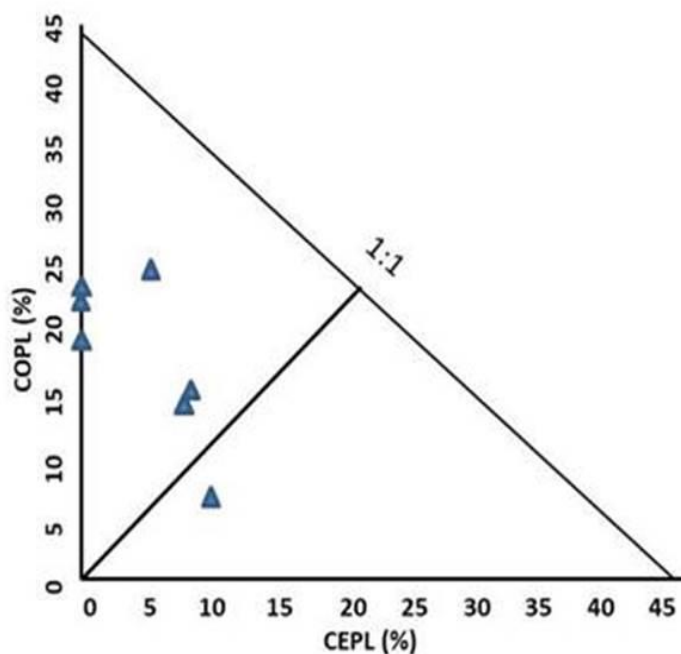

Fig. 6. Plot of compactional porosity loss (COPL) against cementational porosity loss (CEPL)
(after, Lundegard, 1992).

Table 2. Granulometric parameters showing the grain size and degree of sorting of the studied Bima Sandstone (after Folk and Ward, 1957)

Lithofacies	Sample ID	Grain size	Sorting
Massive sandstone	LK5	1.87	1.23
		Medium sand	Poorly sorted
	DD1A	0.21	1.20
		Coarse sand	Poorly sorted
Planar cross-bedded sandstone	LK 2	0.01	1.38
		Very coarse sand	Poorly sorted
	DD1	0.02	0.87
		Very coarse sand	Moderately sorted
	DD8	1.65	1.41
		Medium sand	Poorly sorted
Horizontally laminated sandstone	LK5B	2.03	1.07
		Fine sand	Poorly sorted
Ripple sandstone	LK9	1.66	1.37
		Medium sand	Poorly sorted

Table 3: Parameters used in determining porosity loss in the studied Bima Sandstone with assumed initial porosity of 40% (after Lundegard, 1992)

Sample ID	Pi	IGV	IGV*100	Pi*IGV	100-IGV	CEM	COPL	CEPL	ICOMPACT
LK2	40	25	2800	1000	75	0	20.00	0.00	1.00
LK5	40	22	900	880	78	0	23.08	0.00	1.00
LK5B	40	27	800	1080	73	9	17.81	7.40	0.71
LK9	40	26	1800	1040	74	10	18.92	8.11	0.70
DD1	40	20	2100	800	80	6	25.00	4.50	0.85
DD1A	40	35	3300	1400	65	10	7.69	9.23	0.45
DD8	40	21	1400	840	79	0	24.05	0.00	1.00
Average	40	25.14	25.14	1005.71	74.86	5.00	19.51	4.18	0.82

Conclusion

The Bima Sandstone around Lakwaime and Dogon Dutsi, like other known siliciclastic reservoirs has suffered porosity loss. Several processes have been identified to be responsible for porosity loss in the studied sandstone samples. The effect of compaction, both mechanical and chemical is primary, and evident in the studied samples. Mechanical compaction in the sediments was responsible for grain fracturing in the planar cross-bedded sandstone lithofacies which could enhance the intragranular porosity. Chemical compaction in the studied samples is responsible for the different types of grain contacts which indicate progressive compaction during diagenesis thereby destroying intergranular porosity. Younger sediments, rippled sandstone lithofacies tend to show point and long contacts and are little affected by compaction. The deformation of mud intraclasts within the pore spaces, especially in the planar and horizontally laminated sandstone lithofacies, forming pseudomatrix could also be responsible for porosity deterioration at micro scale (pore space) and this could create baffle or barrier to flow. The average values of COPL, CEPL and ICOMPACT in the studied samples of Bima Sandstone stand at 19.51%, 4.18% and 0.82 respectively. Subtracting the sum of these values from the initial porosity (40%) clearly showed a reduction of the initial porosity to 15.49%. Morse, 1994 indicates that the porosity range for some giant and super giant oil and gas fields found in siliciclastic reservoirs is 14-32%; this makes the Bima Sandstone to fall within this range. Quartz overgrowth which is usually enhanced through intergranular pressure dissolution of quartz grains is also responsible for loss of primary porosity. The COPL-CEPL diagram shows that the

contribution of compaction to porosity loss is greater than that of cementation and, as such considered to be generally responsible for the porosity loss in the studied Bima Sandstone.

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