Paleoenvironment and Provenance Studies of Ajali Sandstone in Igbere Area, Afikpo Basin, Nigeria

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ABSTRACT

The stratigraphy and sedimentology of the Ajali Sandstone successions in Igbere area, Afikpo Basin were studied in order to determine palaeoenvironmental setting and source model of the deposits. The studied deposits consist of five lithofacies namely: pebbly-sandstone facies, cross-bedded, laminated, bioturbated facies and mudstone facies. Palaeoenvironmental interpretation based on facies associations and sedimentary structures revealed tide-influenced fluvial deposits, while inferences from bivariate plots of calculated univariate parameters indicated fluvial deposits. The granulometric analyses of the sediments indicated a predominantly moderately sorted, medium-grained sandstone with some poorly sorted populations. The kurtosis ranged from mesokurtic through leptokurtic to extremely leptokurtic sand populations and generally with somesymmetrical, positive and negative skewness. This result is suggestive of a sand population with different tails, especially for the facies representing the poorly sorted populations. The sandstone in the area is essentially quartz sandstone or quartz arenite based on petrographic analysis. The relative abundance of the framework elements (Q96, F0, and R4) suggests a super-mature sand with a maturity index ≥ 19.0. The mineralogical and textural maturity of the sandstone therefore, indicated a polycyclic deposit. This together with the constituent heavy minerals and paleocurrent directions inferred that sources of detritus were from both the uplifted continental pluton and old sedimentary domain, respectively. The Crystalline Basement rocks of both the Cameroon and Adamawa Highlands, the Oban Massif and western Nigeria Ilesha Spur on the one hand and the Abakaliki Anticlinorium on the other hand both satisfied such source models for the post-Santonian Ajali quartz-sand deposit.

Keywords: Paleoenvironment, Facies, Provenance, Maturity, Polycyclic, Source Model.

I. INTRODUCTION

The Nigerian sedimentary basins are broadly divisible into coastal Calabar Flank, Niger Delta, Dahomey (Benin) Basins and interior basins - Abakaliki, Makurdi, Wukari, Gongola Yola Arm, Chad, Nupe, SE Ile-Ile and Medmenen (Sokoto), Afikpo and Anambra Basins (Fig. 1). The Afikpo Basin, located south-east of the Nigerian Southern Benue Trough, is a product of the second tectonic event responsible for the evolution of the southern Nigerian sedimentary basins. This second episode - the Santonian-Maastrichtian compressional folding, flexural inversion, faulting and alkaline - sub-alkaline magmatism resulted in the formation of the Anambra and Afikpo Basins (Murat, 1972; Nwachukwu, 1972; Burke et al., 1972; Olade, 1975). Within the latter were deposited the post-Santonian Nkporo Formation as the basal units on folded older strata. It is superposed by an offlap complex of the coaliferous Mamu Formation, the Ajali Sandstone and the paralic Nsukka Formation that terminated the Cretaceous proto-Niger Delta sedimentation in southern Nigeria. The first phase produced the Abakaliki-Benue Trough, the Calabar Flank and the Mamfe Embayment, while the third phase gave rise to the Tertiary Niger Delta Basin (Umeji, 2010). The geologic histories of both the Afikpo and Anambra Basins are thus related. Andlike the Anambra Basin the dispersal patterns, provenance and geographic extent of the Afikpo Basin have not been clearly ascertained (Onyekuru et al., 2013). Therefore, a study synthesizing data accruing from lithofacies, sedimentary structures and petrology and paleocurrent trend to infer the palaeoenvironment, source model and paleogeography of the lithostratigraphic units in the basin would aid in delineating spatial facies relationships and possible lithostratigraphic units' boundaries, thus enhancing correlation. Such an integrated multifaceted analysis would also provide a widespectrum of data source for a definitive environmental decision and source model for the units. To achieve the aforementioned aim, the exposures in Igbere area have been chosen for the study. The area lies within Latitudes 5° 38' and 5° 43' N and longitudes 7° 38' and 7° 45' E in the Afikpo Basin, Nigeria (Fig. 2). According to Ibe (2004), the exposure at Igbere is subdivided into a quartz-rich subjacent unit which is overlain by bioturbated sub-facies. The latter unit grades upwards into bands with profuse trace fossils of Ophiomorpha isp, especially, in the section south of Abiriba.
II. REGIONAL STRATIGRAPHY AND BASIN FILL

Murat (1972), Olade (1975) and Petters (1978) identified three main unconformity bounded sedimentary packages which were deposited in Nigeria in response to upwelling and cessation of mantle plume under the present Niger Delta. The packages are Albian-Cenomanian, Turonian-Santonian and Campanian-Maastrichtian. The deposition of the packages was controlled by several factors including epeirogenic movements resulting in transgressive and regressive movements of the sea cycles, worldwide eustatic changes in sea level, basin tectonism and local diastrophism (Murat, 1972; Agumanu, 2009; Odigi, 2012). The Albian-Cenomanian transgressive pulse is represented in southern Nigeria by the Asu River Group - the oldest marine sedimentary deposit in the Southern Benue Trough. The group is composed of the Abakaliki Formation (Mid Albian) and the Late Albian-Cenomanian Ebonyi Formation (Agumanu, 1986; 1989).

The Turonian-Santonian transgressive phase deposited the Ezziyaku and Aawgu Formations (Petters and Ekweozor, 1982; Agumanu 1986; 2011). The former is a thick flaggy, grey or black calcareous shale and siltstone with limestone which grades into thick sandstone sequences such as the Amasiri Sandstone, the Makurdi Sandstone and the Agala Sandstone (Murat, 1972; Dessauvagie, 1975; Hoque, 1977; Banerjee, 1980; Nwajide, 1982). Alater deposit, the super-adjacent Awgu Formation, is composed of lower limestone shale and upper feldspathic and glauconitic sandstone (Agumanu, 2011).

The paralic Enugu Formation, Coal Measures (Mamu and Nsukka Formations) and the Ajali Sandstone were deposited in the Anambra Basin (Tijani and Nton, 2010). The Nkporo Formation with intertongues of the Afikpo Sandstone - lateral equivalents of the Enugu Formation and the Owelli Sandstone (Campanian) - were deposited in the Afikpo Basin (Nwajide, 2005). The Nkporo Formation dated with Syncolporites Lisamae subtulis and auriculi ditto sp. (Ojoh, 1990), and the Enugu Formation mark the beginning of the third Cretaceous marine depositional cycle in southern Nigeria.

The Nkporo Formation comprises of dark grey, often friable, shale with occasional thinbands of limestone and intertonguing of the Afikpo Sandstone. Sedimentation continued in the Afikpo Basin throughout the Campanian to the Oligocene as demonstrable on Fig. 3 and Table 1 with a large offshore complex of the paralic Mamu Formation followed by the fluvio-deltaic sequence of the Ajali Sandstone (Tijani and Nton, 2009) and superposed by the paralic Nsukka Formation which together constitute the Coal Measures Group of Umeji (2010), deposited on the Nkporo Formation.

The Ajali Sandstone (Maastrichtian), the False Bedded Sandstone of Simpson (1954), is an extensive sandstone body covering a vast area of southern Nigeria and beyond. Sincethe description and formalization by Reyment (1965) of the sedimentary formations in southern Nigerian sedimentary basins, the study of the Ajali Sandstone has received considerable attention by several workers (Hoque, 1977; Hoque and Ezepue, 1977; Amajor, 1986; Ladipo, 1986; Anyanwu and Arua, 1990). On the bases of paleocurrent studies, mineralogical analysis and provenance decision, the formation was considered to have been derived from the Post-Santonian Abakaliki Anticlinorium (Nwachukwu, 1972; Murat, 1972; Amajor, 1987). Different workers had adduced different paleoenvironmental settings for the sandstone on the basis of sedimentological analysis, namely, fluvial (Murat, 1972); fluvio-deltaic (Reyment, 1965; Hoque and Ezepue, 1977) and fluvio-marine (Amajor, 1987).

The present study synthesizes data from lithofacies, sedimentary structures and petrology and paleocurrent trend to infer the paleoenvironment, source model and paleogeography of sediments in Igbere area.

Fig. 1. Geological Sketch Map of Nigeria showing the bounds of sedimentary basins. Sedimentary Basins are numbered as described: 3. Northern Benue Trough, 4 Central Benue Trough, 5 Southern Benue Trough (Afikpo Syncline), 6 Bida Basin, 7 Ullemmeden Basin, 8 Chad Basin, 9 Dahomey Basin, 10 Anambra Basin, 11 Niger Delta Basin (After Nwajide, 2005)
III. METHODOLOGY

Sedimentological Studies
Detailed descriptions, measurements and sampling of profiles of the Ajali Formation were done at Igbere area and its environs. An E–Trex global positioning system (GPS) was used to determine and geo-reference the positions of the outcrops on the base map. Sedimentological study of the sections involved description and sampling of the various lithological successions, appraisal of the physical and biogenic sedimentary structures and textural characterization of the exposed unit. The granulometric parameters and petrologic studies were determined by conventional methods (Folk, 1974). Plots of bivariate diagrams (Friedman, 1967; Moiola and Weisser, 1968) to discriminate the depositional processes and characterize the environmental model were done.

Table 1. Stratigraphic correlation of the southeastern Nigerian basins (Modified after Nwajide, 2005)

<table>
<thead>
<tr>
<th>Age</th>
<th>Basin</th>
<th>Stratigraphic Units</th>
</tr>
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<tbody>
<tr>
<td>Oligocene-Recent</td>
<td>Niger Delta</td>
<td>Ogwashi-Asaba Fm / Benin Formation</td>
</tr>
<tr>
<td>Eocene</td>
<td>Anambra Basin</td>
<td>Ameiki/Nanka Fm/Nsugbe Sandstone (Ameiki Group) / Agbada Formation</td>
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<tr>
<td>Thanetian</td>
<td></td>
<td>Imo Formation / Akata Formation</td>
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<td>Danian</td>
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<td>Nsukka Formation</td>
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<tr>
<td>Maastrichtian</td>
<td></td>
<td>Ajali Formation</td>
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<td>Campanian</td>
<td></td>
<td>Mamu Formation</td>
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<tr>
<td>Santonian</td>
<td>Southern Benue Trough</td>
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<td></td>
<td></td>
<td>Nkporo Fm / Nkporo Shale Enugu Fm / Owelli Ss / Afikpo Ss / Otobi Ss / Lafia Ss</td>
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<tr>
<td></td>
<td></td>
<td>Agwu Formation</td>
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</table>
The data accruing from the studies were used to classify the Ajali Sandstone based on the schemes of Folk (1974); Iwuagwu and Lerbekmo (1982). Deductions from paleoenvironmental and maturity studies of the deposits aided the determination of provenance derived from paleocurrent data of the Ajali Sandstone in Igbere area.

IV. RESULTS AND DISCUSSION

Facies Analysis

Lithofacies analysis of the stratigraphic successions in the study area distinguished five lithofacies namely, pebbly sandstone facies, cross-bedded sandstone facies, laminated sandstone, bioturbated sandstone and mudstone facies. The distinguishing features of each facies are as follows:

Pebbly Sandstone Facies: The pebbly sandstone facies usually occurs towards the base of sequences in the study area. They are usually poorly-bedded, fine-medium but occasionally coarse grained sandstones with Ophiomorpha burrows and abundant mudclasts and conglomerates (Fig. 4).

Cross-Bedded Sandstone Facies: Cross-bedded sandstone facies are common occurrence in the exposures at Igbere and wherever the Ajali Sandstone outcrops. The cross-beds include trough, planar, climbing ripples and herring bone crossstratified units according to Amajor (1986). The section commonly ranges from 0.7-5.0 m thick while the cross - strata are between 2 and 10 cm thick. Lithologically, they are usually coarse-to medium-grained, fairly well sorted and sub-angular to sub-rounded with fining-upward trends (FU). The fining-upwards strata terminate in laminations and current and climbing ripples, (Fig. 5), with ripple indices of between 5 and 16 thus inferring water current ripples (Reineck and Singh, 1975). The top and bottom sets are marked by laminated clay/siltstone drapes which are usually iron-stained (Fig. 5). Some exposures are characterized by hydraulically deformed structures, convolute bed lamina tions and stratifications. The deformations are said to be produced by the drag of strong sediment-laden current across the bottom and common in several environments. Some workers have used them to indicate turbidity current deposition because they are usually found in places where current and turbulence values are high (Coleman and Gagliano, 1965). Overturning is oriented in a down current direction and the top of the fore - set lamination is usually truncated.
The deformations were probably water escape structures and related to tectonic(earthquake) microseisms as opposed to storm induced shocks. They could also result from rapid sedimentation and sporadic water in distal alluvial fan environment (Agumanu, 2009). Similar structures were described by Jones (1962) from the Cretaceous Bima Sandstone in northeastern Nigeria and confirmed by Samaila et al. (2005) from the upper member of the Bima Sandstone in the Yola Arm, northeastern Nigeria. The absence of apparent faulting or destruction in the convolution and orientation of the fold axes along the paleocurrent direction from our study probably suggested that deformation occurred during or immediately after deposition (Samaila et al., 2005) or indicative of saturated condition.

This is because convolute beds are common place occurrences along river banks due to falling river stage when super-saturated bank sediments tend to slump or readily subside (Coleman and Gagliano, 1965). They probably were triggered by liquefaction due to seismicity or rapid fluctuation of water table (Doe and Dott, 1980). They demonstrate the effect of hydrodynamic instability of the sediment due to rapid deposition in loose-packed state arising from seismic shocks. The frequent occurrence of the structure is more probably linked with pore-pressure buildup during earthquake other than storm effect (Johnson, 1977, Agumanu, 2009). There was probably syn-deposition tectonism and inherent loose sediment instability (Braide, 1992).

**Laminated Sandstone Facies:** This facies consists of laminated fine-grained lithologies, siltstone and claystone. They occur towards the top of the sequence and along the boundary with the overlying Nsukka Formation (Danian). Minor scour-and-fill structures about 45 cm thick and approximately 100 cm long occur towards the top (Fig. 6). Laminations are horizontal except where scour or channeling occurs. Contact of channel with the rest of the exposure is usually smooth, brown-stained and sometimes clayey. They occur probably as a result of localized linear erosion or scouring and represent the downstream and distal terminal flood out channel sediments where the amount and size of coarse clasts are diminished. The fine grained silty sandstone contact and associated flat beds are reminiscent of lower flow regime (Wakelin-King and Webbs, 2007).

**Bioturbated Mudstone Facies:** This is an intensely burrowed siltstone and claystone on the top of profiles with fine texture. The burrowing is usually horizontal and usually overlies the coarse to medium-grained cross-bedded unit. Isolated Ophiomorpha traces may occur in thicker laminated lithology (Figs. 4, 6 and 7). Ophiomorpha is considered
as part of the Skolithosichnofacies and as a burrowing organism living in the nearshore environment (Onyekuru and Iwuagwu, 2010). The mudstone facies often terminates the sequence thus stimulating a generally fining-upward (FU) sequence. The intense preferential reworking and the preponderance of concentric diagenetic structures on surfaces of this facies (Fig. 8) probably suggests epigenetic mineralization (Dill, 2012) especially as the section grades into the paralic Nsukka Formation.

**Fig. 8.** Concentric diagenetic and epigenetic mineralization at the upper sections of the Ajali Sandstone and lower sections of the Nsukka Formation.

**Sediment Granulometry**

From the granulometric studies, the Ajali Sandstone is predominantly medium-grained with size ranging between 1.33 to 2.10. The cumulative frequency curves (Fig. 9), display mainly saltation loads with steep slopes. Gravelly, coarse-grained sand together with silt and clay sized particles were generally negligible or of minor components. The majority of the samples were moderately sorted with a few poorly sorted populations due to the mixture of sand with gravel and some clay. The kurtosis was between 0.99 and 4.51 indicative of mainly mesokurtic, leptokurtic and extremely leptokurtic sand. The skewness was mainly symmetrical, positively and negatively skewed with uniform medium-coarse and fine tail populations for the sorted and poorly sorted populations, respectively.

Bivariate plots of computed univariate parameters, using the discriminatory fields proposed by Friedman (1967), Moiola and Weisser (1968) differentiated the adjacent depositional environments shown in Figs. 10 - 12.
Fig. 9. Representative Cumulative Frequency Curves of some of the analyzed Samples in the Study Area.

Fig. 10. Bivariate Plots of Skewness Vs Standard Deviation (after, Friedman, 1967).

Fig. 11. Bivariate Plots of Skewness Vs Standard Deviation (after, Friedman, 1967).
V. COMPOSITION, MATURITY AND CLASSIFICATION

Mineralogical study of the Ajali Sandstone revealed the abundance of quartz of fairly uniform size grades suggestive of moderate sorting (Folk 1974) and generally subrounded to rounded grains (Fig. 13). The average composition of the rocks from thinsection microscopy showed that the average modal compositions of the framework elements, cement (iron and silica), and void are 75, 15 and 10 % respectively. Graincounting of quartz, heavy mineral and other minerals that constitute the rock fragments revealed an average composition of the quartz, heavy mineral and other rock fragments to be 96, 1 and 3 %, respectively. Feldspar was absent in all the studied samples (Fig.13). Feldspar is less stable than quartz in sandstones (Pettijohn, 1975); its total absence from the studied samples suggests probable low relief, humid climate, low rate of erosion (Pettijohn, 1975); flat topography in order to effect thorough weathering (Folk, 1980); prolonged weathering, transportation and recycling (Tijani et.al., 2010). With themajor framework elements of the Ajali Sandstone sediments in Igbere area being quartz (Q) and rock fragment (Lithic component) (R). The other element – feldspar which is a common constituent of most sandstone is absent from the deposits at Igbere. The Qpole will consist of quartz (Mono-crystalline); Rock fragment (R) and the F-pole(feldspars), which is absent. The percentage modal composition of framework elements (Quartz, feldspar and rock fragment) of the sandstone are as follows: Quartz – 96%, Feldspar -0 %, rock fragment – 4 %. The framework elements plotted in the tenary diagrams of Iwuagwu and Lerbekmo (1982) and Folk (1980) classified the sandstone in the study area as quartz sandstone and quartz arenite, respectively (Figs. 14 and 15). The ratio of undulatory quartz to total in sandstone is often used as an index of texturalmaturity. Quartz undulosity, therefore, is an indication of high stress state of the grain with resultant thermodynamics and mechanical instability (Blatt and Christie, 1963; Nwajide and Hoque, 1985). The quartz in the samples is rich in non undulose monocrystalline species suggestive of prolonged domiciliation in sedimentary environment with consequent selective elimination of undulatory grains by both mechanical and chemical processes. The high percentage (96 %) of mono-crystalline quartz in the samples probably is due to dilution of the original plutonic detritus by nonundulatory quartz grains derivable from an older sedimentary terrain (Nwajide and Hoque, 1985). The average mono-crystalline quartz in samples from Igbere area is 96 % thus making it a super mature sandstone (Blatt and Christie, 1963).

The heavy minerals consist of a narrow suite of ultra-stable species including Zircon, Tourmaline and Rutile with ZTR Index of over 90 % (Hubert, 1962). The Zircon included types J3, L5, M1, P5, S1-S10, S12, S15, S19, U20 of Pupin (1967) which typically have their origin from crystalline Basement Complex (Pupin, 1967). Agumanu (1993) concluded from the deposited Owelli Sandstone (Maastrichtian) in the adjacent Southern Benue Trough with the lithic fill of the Afikpo Basin, that diastrophism of the source and tectonics of the depositional area probably controlled the concentration of the ultra-stable heavy minerals. This is because tectonism enhances the maturity of sandstone and determines the assemblage of heavy mineral species (Hubert, 1962). The ZTR index of the sandstone being over 90 % (Hubert, 1962) thus confirms themineralogical maturity of the sandstone in the study area. Using the quartz-feldspar ratio in the Ajali Sandstone (Q96 F0 R4) as an index of mineralogical maturity (Pettijohn, 1949), and applying Nwajide’s and Hoque’s (1985) expression for maturity index: (Q/F+R) which is Pettijohn’s compositional maturity: it follows that the Ajali Sandstone is mineralogically super mature with a maturity index > 19; it is a quartzarenite/quartz sandstone which agrees with Folk’s (1980) and the conclusion of Iwuagwu and Lerbekmo (1982) that “measures the progress towards the ultimate endtype-a pure quartz sand” (Pettijohn, 1975).
Paleocurrent Pattern

The paleocurrent attributes used in the study included trough and planar cross-beds and ripple marks. Pebble imbrications and sole marks were not readily available. Because Ajali Sandstone is synonymous with cross-beds (the False Bedded Sandstone of Simpson, 1954), the study depended on them to determine paleocurrent rose diagrams which were prepared from the Azimuth of trough and dip of planar cross-beds. Rosediagrams with a class interval of 30° were adopted (Figure 16). Dip corrections were made for dips greater than 15° (Ramsay, 1961). The current direction indicated by the cross-beds was mainly unimodal in the west-southwest within 90° (180 - 270°) sector.

Fig. 13. Representative Photomicrographs of Ajali Sandstone Sediments in the Study Area

Fig 14. Classification of sandstone (after Iwnagwu and Lerbekmo, 1982)

Fig 15. Classification of sandstone using the scheme of Folk (1974)
VI. SUMMARY AND CONCLUSION

The study synthesized data accruing from lithofacies, sedimentary structures, petrology and paleocurrent trend to infer paleoenvironment, source model and paleogeography of the lithostratigraphic units in Igbere area, Afikpo Basin. The analyses of the stratigraphic sections in the area of study distinguished five lithofacies namely, pebbly sandstone facies, cross-bedded sandstone facies, laminated sandstone, bioturbated sandstone and mudstone facies. The sequence, from the base, comprised of pebbly and coarse grained facies, through trough and planar cross-bedded facies in the middle section, terminating with mudstone facies at the upper sections, thus stimulating a generally fining-upward (FU) sequence. The inferred depositional environment is fluvial with tidal influences. The granulometric studies have shown that the Ajali Sandstone is predominantly medium-grained with sizes ranging between 1.33 to 2.10 phi. Petrographic study of the Ajali Sandstone revealed the abundance of quartz of fairly uniform size grades and generally sub-rounded to rounded grains suggestive of moderate sorting. The average composition of the rocks from thin section microcopy showed that the average modal compositions of the framework elements, cement (iron and silica), and void are 75, 15 and 10 % respectively. Grain counting of quartz, heavy mineral and other minerals that constitute the framework elements revealed an average composition of the quartz and rock fragments to be 96, 1 and 3 % respectively. Feldspar was absent in all the studied samples and the percentage modal composition of framework elements (Quartz, Feldspar and Rock Fragments) of the sandstone are as follows: Quartz – 96 %, Feldspar – 0 %, Rock Fragment – 4 %. The Ajali Sandstone in Igbere area was therefore expressed as mineralogically super mature deposit with an maturity index >19 and also classified as quartz arenite based on ternary diagrams plots. As a super mature deposit, therefore, the deposition of the Ajali Sandstone sediments in the Afikpo Basin can be said to have occurred in more than one cycle (polycyclic) of sedimentation. The accompanying heavy minerals consist of a narrow suite of ultra-stable species including Zircon, Tourmaline and Rutile with ZTR Index of over 90 %, thus confirming the mineralogical maturity of the Ajali Sandstone. The paleocurrent direction deduced from cross-beds was mainly unimodal in the west-southwest, within 90° (180 - 270°) sector. The super maturity status and the paleocurrent directions of the Ajali Sandstone sediments in the study area are indicative that detritus were sourced from both the uplifted continental pluton and old sedimentary domain, respectively. The Crystalline Basement rocks of both the Cameroon and Adamawa Highlands, the Oban Massif and western Nigeria Ilesha Spur on the one hand and the Abakaliki Anticlinorium on the other both satisfied such source models for the post-Santonian Ajali quartz-sand deposit.

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