

## Problems of classification and maturity evaluation of a diagenetically altered fluvial sandstone

C.S. Nwajide<sup>1</sup> & M. Hoque<sup>2</sup>

<sup>1</sup>*Geological Survey of Nigeria, P.M.B. 2007, Kaduna South, Kaduna State, Nigeria;* <sup>2</sup>*Dept. of Geology, University of Nigeria, Nsukka, Nigeria; Dept. of Geology & Planetary Science, University of Pittsburg, Pittsburg, PA 15260, USA*

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### Abstract

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The fluvial sandstones of the late Cretaceous Makurdi Formation of the middle Benue Trough of Nigeria are composed of feldspathic wackes (average matrix content 25.4%) and subarkosic arenites (average matrix content 9.3%). Except for the differences in the matrix content, the framework mineralogy of the two groups of sandstones is very similar. The interstitial clay matrix is both primary and diagenetic in origin. Regression analysis shows an inverse correlation between the proportion of matrix and the incidence of detrital feldspars in the sandstones. It implies that postdepositional alterations of feldspars have given rise to a mineral assemblage which is more mineralogically and less texturally mature than the original deposit, thus invalidating genetic significance in sandstone nomenclature.

Neither the clay content nor the zircon-tourmaline-rutile (ZTR) index is a reliable measure for textural or mineralogical maturity of the Makurdi sandstones. It is proposed that several other attributes, such as roundness, ratio of undulose-to-nonundulose quartz, and MQ/PQ ratio which are less susceptible to diagenetic alteration, can be used as reliable indices of textural maturity. A mineralogical maturity scale, based on inert versus labile components (Q/F+L) of framework composition of a sandstone, is proposed to facilitate quantitative analysis of maturity data.

### Introduction

The Benue Trough of Nigeria is an intracratonic, folded graben. Its width varies from 80 to 150 km and it stretches inland for about 800 km in a northeasterly direction from the West African re-entrant at the Gulf of Guinea. The Turonian Makurdi Formation is one of several thick units of the trough. It covers an area of more than one thousand square kilometres in the middle part of the Trough (Fig. 1), where it consists of approxi-

mately 500 m of thick fluvial sandstones and mudrocks with a minor carbonate member.

This paper presents a petrographic analysis of Makurdi sandstones and, in particular, it attempts to demonstrate that post-depositional alterations of detrital feldspars have changes the primary grain-matrix ratio in such a manner that the sandstone nomenclature does not have any genetic significance. The maturity concept is evaluated in terms of primary and diagenetic features. The current usages of maturity scale are considered

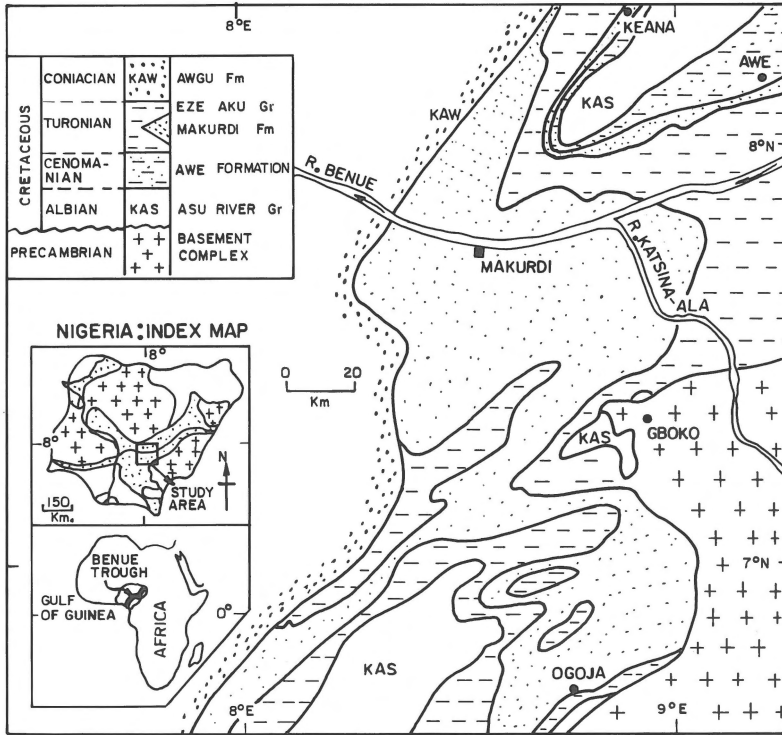


Fig. 1. Generalised geological map of the middle part the Benue Trough showing the Makurdi Formation and the Adjacent units in the study area.

inadequate. As a contribution towards a fuller use of the maturity concept in sedimentary petrology, we propose a numerical scale of mineralogical maturity index as an aid in comparative studies of maturity of a suite of common sandstones.

### Sandstone composition

Forty-one Makurdi sandstone samples have been studied mineralogically. An average Makurdi sandstone consists of 67.65% quartz, 10.75% feldspars, 1.66% mica, and 19.94% matrix. Lithic grains are either absent or rare. Precipitated cement occurs mostly as quartz over-growths; limonitic coats are present in many thin sections. The results are summarized in Table 1.

Quartz occurs as undulose monocrystalline, as nonundulose monocrystalline and as polycrystalline grains. The size of quartz grains in ten randomly selected thin-sections averages 0.47 mm

(with a standard deviation of 0.29 mm).

Feldspars occur as microcline, orthoclase, and sodic-plagioclases; all show some degree of alteration. In extreme alteration cases, a grain can easily be mistaken for void-filling. The most common plagioclase is albitic in composition with andesine plagioclase following closely. In general, the frequencies of different species of feldspars conform to the well-known stability-order in a weathering profile (Goldich 1938), in which K-feldspars are the most stable and calcic-plagioclases are the least. Franzinelli & Potter (1983) observed similar trends in modern sands of the Amazon River system in which potash-feldspars are several times more abundant than plagioclases. In the Makurdi sands, the ratio of potash-feldspars to plagioclases is about 5.44; the feldspar content averages 10.75. Clarke's (1924, p. 3) average sandstone contained 11.5% feldspars. A range of 10-15% feldspar is normal for an average sandstone, according to Blatt et al. (1980, p. 295). Potter (1978), in a study

Table 1. Summary of petrographic modal analysis of forty-one Makurdi sandstones\*.

Number of Samples and Measures	Percent of Quartz				Percent of Feldspar			Mica and Lithic gr (L)	Matrix %	Rock Name: Average Composition; Ratios	
	UMQ	NMQ	PQ	(Q)	Or	Ab	(F)				
27 Samples	Mean	19.71	35.68	7.98	63.37	8.54	1.23	9.77	1.40	25.44	Feldspathic Wacke
	Std. Dev.	7.46	8.76	5.18	12.67	4.67	0.97	4.55	1.14	6.44	Q <sub>85.0</sub> F <sub>13.1</sub> L <sub>1.9</sub>
	Range	6.33–36.33	23.60–55.12	3.16–13.67	50.36–73.34	0.62–22.78	0.00–3.67	1.24–22.78	0.00–5.38	15.54–44.72	MQ: PQ = 6.94
14 Samples	Mean	24.74	39.54	11.64	75.92	10.14	2.52	12.66	2.10	9.32	Subarkosic Arenite
	Std. Dev.	8.33	10.38	7.15	9.99	6.93	2.05	8.06	2.66	4.14	Q <sub>83.7</sub> F <sub>13.9</sub> L <sub>2.4</sub>
	Range	10.51–38.34	17.93–63.40	1.86–24.43	59.86–97.66	1.07–22.05	0.00–6.03	1.18–25.00	0.00–10.08	0.00–14.49	MQ : PQ = 5.52
All 41 Samples	Mean	21.42	37.00	9.23	67.65	9.08	1.67	10.75	1.66	19.94	Feldspathic Wacke
	Std. Dev.	8.03	9.40	6.09	13.54	5.51	1.54	6.03	1.81	9.61	Q <sub>84.5</sub> F <sub>13.4</sub> L <sub>2.1</sub>
	Range	6.33–38.34	17.93–63.40	1.86–24.43	50.36–97.66	0.62–22.78	0.00–6.03	1.18–25.00	0.00–10.08	0.00–44.72	MQ : PQ = 6.33

\*K:UMQ – Undulose Monocrystalline Quartz; NMQ – Nonundulose Monocrystalline Quartz; PQ – Polycrystalline Quartz; Q – Total Quartz; Or – Microcline plus Orthoclase; Ab – Sodic Plagioclase; F – Total Feldspars.

of thirty-six modern large rivers, found the average feldspar content in the sands to be 10.7%. The average value for the Makurdi samples compares fairly well with these observations.

Detrital mica, mostly muscovite, constitutes on average about 1.7%. It shows varying degrees of bending and even fracturing; a few grains are apparently altered to hydromica.

Void-filling materials are precipitated cement and interstitial particulate matter (matrix), usually of clay and silt size. The matrix is an assemblage of quartz, mica, feldspar and heavy minerals (notably zircon and opaques), all enmeshed in clay. Primary clay, often fibrous, is the most important void-filler. It is allogenic and syndepositional, often constituting a precursor for other kinds of void-fillers. Commonly, the clay laminae extend from the larger interstices into the narrowing orifices, forming cushions between rigid framework grains.

The secondary matrix is constituted by kaolinite; it occurs, often in vermicular form, as aggregates of

plates within relict detrital boundaries or as disaggregates booklets scattered within interstitial spaces. The origin of kaolinite can mostly be related to an alteration of detrital feldspars.

The heavy minerals of the sieved fractions of 0.250-0.062 mm of fifteen sandstone samples have been studied. Fourteen heavy mineral species were identified: four opaques and ten non-opaques. The opaques constitute on average 56% (limonite 31.7%, hematite 12.3%, ilmenite 7.8% and leucocene 4.4%). The non-opaques (about 44%) consists of two groups: the metastables (7.6%) and the ultrastables (36.2%) (Folk 1980, p. 95). The metastables are mostly garnet (3.1%), fluorite (2.1%), anatase (1.5%), and occasionally, epidote, apatite, hornblende and kyanite. The ultrastables are zircon (19.2%), tourmaline (14.2%) and rutile (2.8%).

### Problems of genetic classification of sandstones

Numerous classifications of sandstones have been proposed and reviewed by several authors (De Vries Klein 1963, Okada 1971, Pettijohn et al. 1972, p. 149). The major components of the framework fraction of a sandstone are quartz, feldspar and lithic grains; these form the three end-members of a composition triangle. The ternary scheme of Pettijohn (1975, p. 211, fig. 7-6) incorporates matrix as an independent component at the fourth pole to distinguish between the arenites (the so-called clean sandstones with less than 15% matrix) and the wackes (the 'dirty' sandstones with 15% or more matrix). Apart from the difficulties of formulating a workable definition of matrix, it is also polygenetic in origin. It is often difficult to impossible to determine accurately how much of the matrix is really primary. In absence of such a determination, the classification of sandstones into clans of arenites and wackes becomes artificial and, consequently, the parameters of sandstone classification lose their presumed genetic significance with respect to provenance or to depositional processes of the sand. Cummins (1962), Dickinson (1970, 1971) and others have drawn attention to this problem.

The Q-pole, in this study, consists of both monocrystalline and polycrystalline quartz, as well as of chert. The F-pole includes all types of feldspars. Mica is fairly well represented in Makurdi sandstones, and is here put in the little pole L (see Hubert 1962, Okada 1971). As stated earlier, the lithic grains in Makurdi sandstones are either absent or rare. Therefore, the L-pole consists in most cases of mica only. Pettijohn's terminology (1975, p. 211, fig. 6-7) is used to describe the rock type. Table 1 shows that the average Makurdi sandstone is feldspathic wacke ( $Q_{84.5}F_{13.4}L_{2.1}$ ) with 19.94% matrix. Of the 41 samples studied, fourteen samples have a matrix content of less than 15% and are therefore arenites; their average composition is subarkosic ( $Q_{83.7}F_{13.9}L_{2.4}$ ). The remaining 27 samples have an average matrix content of 25.44% and the average composition of a feldspathic or arkosic wacke ( $Q_{85.0}F_{13.1}L_{1.9}$ ).

The two groups of sandstone appear to differ only in their matrix content; their framework mineralogy is remarkably similar. It is, therefore, possible that the observed differences in the average values of quartz (Q), feldspars (F) and lithic grains (L) are geologically insignificant, and that all of these materials are derived from one source region. We used the t-statistic to test the hypothesis ( $H_0$ ) that there was no significant difference between the two means in each case of the three framework elements (i.e. Q, F, and L). We found that the null hypothesis ( $H_0$ ) could not be rejected at 0.05 level of significance with 39 degrees of freedom in each case.

Table 1 shows that the fourteen subarkosic arenites have an average of 12.66% feldspars and 9.32% matrix, whereas the 27 feldspathic wackes have an average of 9.77% feldspars and 25.44% matrix. Has *in situ* decay of feldspars reduced to original frequency of feldspars by converting some into secondary (i.e. diagenetic) clay matrix? Can the observed difference in the matrix content between the two groups of sandstone be the result of post-depositional alteration rather than a reflection of their different modes of transport (fluidity factor of Pettijohn 1975, p. 212), or of their relative degrees of textural maturity (Folk 1980, p. 100)?

In an attempt to answer these questions, a regression analysis of the proportions of feldspar and matrix in forty-one modal analysis was made. We observed that an inverse relationship exists between the two ( $y = 23.99 - 0.38x$ ), with a correlation coefficient,  $r = -0.24$ . The confidence limit of  $r$  (i.e.,  $r$  is different from zero) lies between 90 and 95 percent by t-test with 39 degrees of freedom (calculated  $t = -1.544$ ). Although the correlation is not a very strong one, the result reaffirms our earlier observation that part of the clay matrix could originate from the degradation of detrital feldspars in the diagenetic realm.

If the diagenetic origin of part of the clay matrix is accepted, the classification of Makurdi sandstones into arenites and wackes with implication in their provenance and mode of transport becomes untenable. It is very likely that the sandstones were originally deposited as an arkosic or subarkosic

sand (Folk 1980, p. 127), or as a feldspathic arenite (or *feldsarenite* for brevity: a better term in a purely petrographic nomenclature of a sandstone than the term 'arkose' which has a provincial implication as well as a bewildering array of interpretations!). Later (diagenetically) and for reasons not entirely understood, a large volume of Makurdi sand was selectively converted into wackes. The term 'wacke' is therefore used purely in a textural or descriptive sense without any primary i.e. genetic implication either to a presumed orogenic provenance or to a transport system propelled by density currents.

### **Maturity: concept & classification**

The concept of maturity was first introduced into sedimentology by Plumley (1948) who defined it in terms of roundness, sphericity and lithology. Pettijohn (1949, p. 236 and 382) used both textural and mineralogical characteristics of a deposit to identify its maturity. He (Pettijohn 1975, p. 491) defined the maturity of a clastic sediment as the extent to which it has approached the ultimate end-product to which it is driven by the formative processes operating on it.

Folk (1951; 1980, p. 101) described four distinct stages of textural maturity of a sandstone (e.g. immature, submature, mature and supermature) in terms of removal of clay content, degree of sorting and increase in roundness of grains. Based on Folk's indexed of maturity, the average Makurdi sandstone is immature. It has a high clay content (19.44%) and is poorly sorted (inclusive graphic standard deviation, 1.10). But the average roundness value (3.11) of Makurdi sands is high and seems anomalous in Folk's maturity scale. Post-depositional enrichment of clay matrix, as assumed earlier, however, may create this type of anomalous situation in an otherwise subangular to subrounded sand. One should, therefore, be cautious in assigning a particular textural maturity stage to a sandstone solely on the basis of clay content without first ascertaining the origin of clay in the sand.

The proportion of undulose quartz in total

quartz of a sandstone is often used as an index of textural maturity. Undulosity in quartz indicates a high stress state of the grain resulting in thermodynamic and mechanical instability (Blatt & Christie 1963, Blatt 1967). These grains are, therefore, more susceptible to fracturing or to solution (Hoque 1976). Blatt (1967) reported that an average granitoid *grus* releases about 14% nonundulatory monocrystalline quartz crystals in a total quartz population. If such an assemblage of quartz grains spends a long period in a sedimentary environment, the undulatory grains will be eliminated selectively by mechanical and chemical processes and the assemblage will become relatively enriched in nonundulatory monocrystalline quartz grains. This progressive enrichment of nonundulatory quartz explains why in most quartz arenites almost all quartz grains display sharp rather than undulatory extinction. However, non-quartz arenites, such as feldspathic or lithic sandstones, show variable amounts of undulatory end nonundulatory quartz grains in their quartz populations. Blatt & Christie (1963) observed an average of only 16.8% nonundulatory quartz in non-orthoquartzitic sandstones. In contrast, nonundulatory monocrystalline quartz averages 54.7% of the total quartz in Makurdi sandstones, indicative of a substantial reduction in strained quartz grains during formation in the presumed plutonic source detritus (Nwajide 1982). As there are still considerable amounts of strained and unstable quartz particles preserved, an incompleteness of the textural maturation process is suggested. However, the high percentage of nonundulatory quartz grains may not be totally due to selective elimination of undulatory quartz grains, it may as well be dilution of the original plutonic detritus by nonundulatory quartz grains derived from a sedimentary terrain. The relatively high roundness value of Makurdi quartz grains (3.11 roundness) and the abraded outlines of many quartz overgrowth observed in several thin sections suggest multiple provenance.

Because of the mechanical and thermodynamic instability of polycrystalline quartz grains, the amount of PQ in a sandstone has been used to evaluate the maturity of sandstones (Blatt & Christie 1963, Conolly 1965, Blatt 1967). Potter &

Pryor (1961) found a strong correlation between abundance of PQ and high angularity of tourmaline. Hoque (1976) correlated the high incidence of PQ in several Cretaceous sandstones of the lower Benue Trough with their low textural maturity. Blatt (1967) reported that 46% of all quartz grains released from granitoid rocks are polycrystalline quartz grains. But their low survival potential in a sedimentary regimen is evidenced in earlier work of Blatt & Christie (1963) who recorded an average of only 6% in 24 randomly selected feldspathic and lithic sandstones and of only 2% in 20 pure quartz sandstones. It would appear that the Makurdi samples (with 13.7% PQ) have still a considerable amount of polycrystalline grains in their quartz population. This high incidence of PQ is indicative for a low textural maturity stage of the sandstones.

An average MQ/PQ ratio in disaggregated granitoid rocks was found to be 1.17 (Blatt 1976). Franzinelli & Porter (1983) reported that sands carried by rivers of the Amazon system, draining Precambrian terrains, have an MQ/PQ ratio of 6.67, that sands carried by rivers draining Precambrian-Palaeozoic terrains show an MQ/PQ ratio of 10.75 and that this ratio increases to 13.50 in sands of rivers which drain the Tertiary. Reworked sediments thus become progressively more mature as the proportion of polycrystalline quartz grains decreases in successive cycles or in a down-current direction. Potter (1978) recorded a similar inverse relationship in sands of 36 modern large rivers with an average MQ/PQ ratio of about 8.0. Regression analysis of the percentages of PQ and MQ in the Makurdi samples show similar inverse relationship between the two types of quartz grains. The MQ/PQ ratio for the Makurdi sandstones is about 6.33, very similar to what Franzinelli & Porter (1983) reported from sands of rivers of the Amazon system draining the Precambrian terrain, and is indicative of a low textural maturity for the Makurdi samples.

The mineralogical maturity of Makurdi sandstones can be evaluated by considering types and amounts of heavy and light minerals. Hubert (1962, table 1) reported that the zircon-tourmaline-rutile (ZTR) index ranges from as low as 2% in

some arkoses to 100% in some orthoquartzites. In most orthoquartzites the ZTR index is over 90%, although contrasting cases have also been reported (Hubert & Neal 1967). The number of non-opaque heavy mineral types range from 17 in some arkoses to 3 in some orthoquartzites. Hubert (1962) also observed that with the increase of ZTR index, the number of heavy mineral species decreased. Eight fluvial sandstones cited by him (1962, table 1) have ZTR index ranging from 2% to 88% and a total number of species varying from 5 to 17. In these eight samples there is an inverse relationship between the ZTR index and the number of species ( $r = -0.64$ , which is significant at 95% level by t-test). This relationship also indicated that the mineralogical maturity of a sandstone cannot be defined by only the ZTR index. In other words, a sandstone with a large number of non-opaque heavy mineral species can be as immature as one with a low ZTR index. Therefore, we consider the Makurdi sandstone with a total of 10 non-opaque heavy mineral species as mineralogically immature, although its ZTR index is appreciably high at 83.5%.

Pettijohn (1949, p. 383) considered the quartz/feldspar ratio as an index of mineralogical maturity; later, he expressed the compositional maturity of a sandstone in terms of the ratio of quartz to feldspar plus lithic grains (1975, p. 212). On the basis of the Q/F ratio, he (1949, p. 383) calculated maturity indices of several types of common sandstones; average sandstone 5.8, average arkose 0.8, average graywacke 2.7, average orthoquartzite over 9.0. These values are, however, difficult to evaluate since to numerical scale for compositional maturity was provided. Weller (1960, p. 341) proposed a scheme of mineralogical maturity of sediments in terms of amounts of ferromagnesian minerals, feldspars, stable heavy minerals and quartz; but he did not provide any quantitative basis for estimating the degree of maturity. Such a quantitative scale is desirable and may be of use to compare various sets of data on compositional maturity of a group of sandstones.

The mineral parameters and their ratios which form the basis of the two most common sandstone classifications (i.e. those of Pettijohn 1975, fig. 7-6,

Table 2. Scale of mineralogical maturity.

Limiting Percentaged of Q & (F+L)	Maturity Index and Maturity stage	Maturity indices of sandstones calculated from published data; rock names based on Folk (1980) and Pettijohn (1975)
Q $\geq$ 95% and (F + L) < 5%	MI $\geq$ 19.0 Supermature	All quartzarenites of Folk, many quartz arenites of Pettijohn. St. Peter Ss (Ordo., Minnesota), Tuscarora Ss (Silu., Pennsylvania), Oriskany Ss (Devo., Pennsylvania) all have MI 19.0; Mansfield Ss (Pennsylvania, Indiana), MI = 79.42; Lauhavuori Ss (Cambrian, Finland), MI = 20.14. <i>Source:</i> Pettijohn 1975. Mauch Chunk Ss (Miss., western Pennsylvania; Hoque, 1968), MI = 26.47 (av. of 23 samples). Ajali Ss (Cret., Nigeria; Hoque & Ezepe 1977), MI > 19.0. Nanka F, (Eocene, Nigeria; Nwajide 1980), MI > 19.0.
Q 95-90% and (F + L) 5-10%	MI 19.0-9.0 Mature	Many quartz arenites and quartz wackes of Pettijohn; many subarkoses and sublitharenites of Folk and Pettijohn. Some Tuscarora (Yeakel 1962), Pocono (Miss.; Pelletier 1958) and Pottsville (Penn.; Meckel 1967) sandstones of Appalachians of the USA are mature with MI ranging from 19.0-9.0
Q 90-75% and (F + L) 10-25%	MI 9.0-3.0 Submature	Many subarkoses, sublitharenites, as well as some feldspathic & lithic graywackes of Pettijohn, many subarkoses and sublitharenites of Folk. Lamotte Ss (Camb., Missouri; Pettijohn 1975, p. 215), Mi = 4.62. Deese Fm (Penn., Oklahoma; Pettijohn 1975, p. 222), MI = 4.33. Mauch Chunk Ss (Miss., western Pennsylvania; Hoque 1968, MI = 4.65 (av. of 28 samples). Makurdi Ss (this report), Mi = 6.29 (av. of 41 samples).
Q 75-50% and (F + L) 25-50%	MI 3.0-1.0 Immature	Many subarkoses, sublitharenites, arkoses, lithic arenites, as well as many feldspathic & lithic graywackes of Pettijohn; many arkoses and litharenites of Folk. Potsdam Ss (Camb., N.Y.), MI = 2.84; Arkoses (Oligo., Auvergne, France), MI = 2.80; Pale & Red Arkoses (Trias., Connecticut), MI = 1.90 & 1.24; Basal Claiborne Ss Eocene, Texas), Mi = 2.73; Oswego Ss (Ordo., Pennsylvania), MI = 1.14; Feldspathic Graywacke (Precamb., Ontario), MI = 1.83 (av. of 3 samples). <i>Source:</i> Pettijohn 1975, pp. 215, 222 & 226.
Q < 50% and (F + L) > 50%	MI < 1.0 Extremely Immature	Many arkoses and lithic arenites of Folk and Pettijohn; many feldspathic and lithic graywackes of Pettijohn. Arkose (Perm., Auvergne), MI = 0.82; Molassesandstein (Tertiary, Germany), MI = 0.67; Lithic graywacke (Devo., Australia), MI = 0.07 (av. of 5 analyses); Kulm graywacke (Harz Mt., Germany), MI = 0.55; Tannar graywacke (Devo-Miss., Harz Mt.) MI = 0.47; Martinsburg graywacke (Ord., Pennsylvania), MI = 0.84. <i>Source:</i> Pettijohn 1975, pp. 215, 222 & 226. Lithic and feldspathic graywackes (New Zealand; Dickinson 1970), MI = 0.11 (av. of 10 western facies) and MI = 0.43 (av. of 10 eastern facies).

p. 211, and Folk 1980, p. 127) can be used for a numerical scale of mineralogical maturity. In such a scheme, a quartz arenite has a mineralogical maturity index (M.I.) of 9.0 or higher; a sandstone with more than 95% quartz may be called supermature (M.I. greater than 19.0), and a sandstone with less than 50% quartz may be called extremely immature (M.I. less than 1.0). Table 2 presents the proposed scheme. Because of variation in the position of boundaries in the compositional triangle, used by Pettijohn (1975) and Folk (1980), several sandstones with different proportions of Q, F, and L may have a similar nomenclature. Such

problems as to whether polycrystalline quartz and chert grains should be considered as rock fragments or be grouped together with quartz (Q-pole) should be resolved before the proposed scale is used. The scheme provides primarily a quantitative basis for a description of mineralogical maturity of a sandstone, and is only implicitly related to provenance and formative processes of a deposit.

The 41 Makurdi samples have an average M.I. of 6.29. For the 27 feldspathic wackes, the average is 6.49, and for the 14 subarkosic arenites, it is 6.00. All are in a submature stage. Table 3 summarizes

Table 3. Maturity indices of Makurdi sandstone.

Parameters	Values	Remarks
A. Clay content	19.44%	High clay content and poor sorting indicate textural immaturity, but polygenetic nature of clay should be considered in the evaluation.
B. Sorting	1.10 phi (std. dev.)	
C. Undulatory quartz	45% of total quartz	Indicates substantial reduction of strained quartz, but overall maturity may still be considered low.
D. Polycrystalline quartz grains	13% of total quartz	Indicates low textural maturity.
E. ZTR index and number of non-opaque haevy mineral species	83.5% and ten species	ZTR index is high, but total number of heavy mineral species should be taken into account in the evaluation of ZTR index. Overall maturity is low
F. Mineralogical maturity index (M.I.) = Q/F + L)	6.29	Submature; but diagenetic reduction of feldspars and lithic grains should be considered.

our observations on textural and mineralogical maturity of Makurdi sandstones based on several of the criteria evaluated in this work.

### Summary of observations

The Makurdi sandstones fall into two groups: feldspathic wackes and subarkosic arenites. Except for differences in their matrix content, the two groups of sandstones have very similar framework mineralogies. It is also concluded that a considerable amount of the clay matrix is diagenetic in origin. An inverse relationship between the incidence of detrital feldspars and the amount of clay matrix is observed. Therefore, the discrimination of sandstones on the basis of matrix content is arbitrary and may not have any primary genetic significance with respect to either provenance or transport system.

Although the ZTR index is generally accepted for identifying mineralogical maturity of sandstone, it should be evaluated in conjunction with the total number of heavy mineral species present in a sample. A sandstone with a high ZTR index as well as a large number of heavy materials may be as immature as one with a low ZTR index. As mineralogy and texture may undergo significant diagenetic modifications, classification of textural and mineralogical maturity on the basis of either clay content or quartz/feldspar ratio may lead to erroneous interpretations. A mineralogical matu-

rity scale, based on the ratio of inert versus labile components (Q/F + L) is proposed to facilitate quantitative description and analysis of mineralogical maturity data of a group of sandstones.

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### References

- Blatt, H. 1967 Original characteristics of clastic quartz – J. Sediment. Petrol. 27: 401-424
- Blatt, H. & J.M. Christie 1963 Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks – J. Sediment. Petrol. 33: 559-579
- Blatt, H., G. Middleton, & R. Murray 1980 Origin of Sedimentary Rocks, 2nd Ed. – Prentice-Hall (New Jersey): 782 pp

- Clarke, F.W. 1924 The Data of Geochemistry – Bull. U.S. Geol. Surv. 770: 841 pp
- Conolly, J.R. 1965 The occurrence of polycrystallinity and undulatory extinction in quartz in sandstones – J. Sediment Petrol. 35: 116-135
- Cummins, W.A. 1962 The graywacke problem – Liverpool and Manchester Geol. J. 3: 51-72
- De Vries Klein, G. 1963 Analysis and review of sandstone classifications in the North American geological literature, 1940-1960 – Bull. Geol. Soc. Am. 74: 555-576
- Dickinson, W.R. 1970 Interpreting detrital modes of graywacke and arkose – J. Sediment. Petrol. 40: 695-707
- 1971 Detrital modes of New Zealand graywackes – Sedimentary Geol. 5: 37-56
- Folk, R.L. 1951 Stages of textural maturity in sedimentary rocks – J. Sediment. Petrol. 21: 127-130
- 1980 Petrology of sedimentary rocks – Hemphill Pub. Co. (Austin): 182 pp
- Franzinelli, E. & P.E. Potter 1983 Petrology, chemistry, and texture of modern river sands, Amazon River system – J. Geol. 91: 23-39
- Goldich, S.S. 1938 A study in rock weathering – J. Geol. 46: 17-58
- Hoque, M. 1968 Sedimentologic and paleocurrent study of Mauch Chunk sandstones (Mississippian), south-central and western Pennsylvania – Bull. Am. Assoc. Pet. Geol. 52: 246-263
- 1976 Significance of textural and petrographic attributes of several Cretaceous sandstones, southern Nigeria – J. Geol. Soc. India 17: 514-521
- Hoque, M. & M.C. Ezepeue 1977 Petrology and paleogeography of the Ajali Sandstone – Nigerian J. Min. Geol. 14: 16-22
- Hubert, J.F. 1962 A zircon-tourmaline-rutile maturity index and the interdependence of the composition of heavy mineral assemblage with the gross composition and texture of sandstone – J. Sediment. Petrol. 32: 440-450
- Hubert, J.F. & W.J. Neal 1967 Mineral composition and dispersal patterns of deep-sea sands in the western North Atlantic petrologic province – Bull. Geol. Soc. Am. 78: 749-772
- Meckel, L.D. 1967 Origin of Pottsville conglomerates (Pennsylvanian) in the central Appalachians – Bull. Geol. Soc. Am. 78: 223-258
- Nwajide, C.S. 1980 Eocene tidal sedimentation in the Anambra basin, southern Nigeria – Sedimentary Geol. 25: 189-207.
- 1982 Petrology and paleogeography of the Makurdi Formation, Benue Trough – Unpub. Ph. D. thesis, University of Nigeria, Nsukka, Nigeria: 307 pp
- Okada, H. 1971 Classification of sandstone: analysis and proposal – J. Geol. 79: 509-525
- Pelletier, B.R. 1958 Pocono paleocurrents in Pennsylvania and Maryland – Bull. Geol. Soc. Am. 69: 1033-1064
- Pettijohn, F.J. 1949 Sedimentary rocks, First Ed. – Harper & Brothers (New York): 526 pp
- 1975 Sedimentary rocks, Third Ed. – Harper & Row (New York). 628 pp
- Pettijohn, F.J., P.E. Potter & R. Siever 1972 Sand and sandstone – Springer-Verlag (New York): 618 pp
- Plumley, W.J. 1948 Black Hills terrace gravels: a study in sediment transport – J. Geol. 56: 526-577
- Potter, P.E. 1978 Petrology and chemistry of modern big river sands – J. Geol. 86: 423-449
- Potter, P.E. & W.A. Pryor 1961 Dispersal centres of Paleozoic later clastics of the upper Mississippi valley and adjacent areas – Bull. Geol. Soc. Am. 72: 1195-1250
- Weller, J.M. 1960 Stratigraphic principles and practice – Harper & Brothers (New York): 725 pp
- Yeakel, L.S. Jr. 1962 Tuscarora, Juniata, and Bald Eagle paleocurrents and paleogeography in the central Appalachians – Bull. Geol. Soc. Am. 73: 1515-1540