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Paleoenvironments, source rock potential and thermal maturity of the Upper Benue rift basins, Nigeria: implications for hydrocarbon exploration

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Abstract—The Upper Benue rift comprising the Gongola and Yola Basins in Nigeria consist of the Aptian–Albian Bima Formation, the Yolde Formation (Cenomanian–Turonian), Gongila/Pindiga/Dukul Formation (Turonian–Coniacian) and Gombe Formation (Campanian–Maastrichtian). To evaluate the maturity and source rocks potential, vitrinite reflectance, Rock-Eval pyrolysis and infrared spectroscopy were carried out on 52 shale samples collected from boreholes, mine quarries and outcrop sections. In the Gongola Basin, mean random vitrinite reflectance (R_{om}) values range from 0.45% in the Gombe Formation to 0.69% in the Pindiga Formation and to 0.82% in the Bima Formation. Reflectance values in the Yola Basin also increase with stratigraphic age ranging from 0.73% in the Dukul Formation to 0.94% in the Yolde Formation and up to 1.37% in the Bima Formation. Total organic carbon (TOC) values in the Pindiga and Gongila Shales are between 0.4 to 2.4% averaging 0.75%. TOC contents from 0.10 to 12.9 averaging 1.2% are contained in the Yolde Formation of the Yola Basin. T_{max} values from the pyrolysis of shales in the Gongola Basin range from 419 to 435°C whereas for shales in the Yola Basin they range from 431 to 442°C. Plots of HI vs T_{max} for kerogen classification indicate the prevalence of Type III kerogens in the Gongila and Pindiga Shales although there are some indications of Type II–III kerogens in the Yolde Shales of the Yola Basin. Our preliminary data suggest that Cretaceous successions in the Gongola Basin are thermally immature to marginally mature whereas source rocks in the Yola Basin are thermally mature with respect to hydrocarbon generation. The predominance of Type III kerogens in the Gongola Basin suggest their potential to generate gas in the deeply buried sections. The Dukul and Yolde formations with Type II–III kerogens may have generated some quantities of oil and gas in the deeper non-emergent sections. © 1998 Elsevier Science Ltd. All rights reserved

Key words—Benue Trough, source rocks, kerogen, pyrolysis, infrared spectroscopy, maturity

INTRODUCTION

The Benue rift basin is a sediment-filled northeast trending structure in Nigeria (Cratchley and Jones, 1965; Burke *et al.*, 1970). It is divided geographically into the lower, middle and upper Benue regions (Fig. 1) and has been a subject of several publications and discussions (see King, 1950; Grant, 1971; Burke and Whiteman, 1973; Olade, 1975; Odebode, 1988). Although the associated basins are thought to have formed from extensional processes, recent studies by Benkhelil (1982, 1987, 1989) suggest the importance of sinistral wrenching as a dominant process for the structural readjustment and geometry of the different subbasins. Two subbasins, the NNE/SSW trending Gongola and the E/W trending Yola Basins, are delineated in the Upper Benue Trough (Fig. 2). In the present study, paleoenvironments of the Cretaceous formations based on the sedimentological descriptions and palynofacies analysis of outcrop sections, are investigated. The source rock potential and thermal maturity are evaluated on the basis of total organic carbon, Rock-Eval pyrolysis, infrared spectroscopy and vitrinite reflectance measurements on 52 samples from shallow water boreholes, mine quarries and outcrop sections.

REGIONAL STRATIGRAPHIC SETTING

Cretaceous successions in the Upper Benue Trough are flanked by the Precambrian–L. Paleozoic basement gneisses and granite which occur as inlier on occasion (e.g the Kaltungo inlier Fig. 2). The Precambrian basement rocks are overlain by the Albian Bima Sandstone as the oldest Cretaceous sediment in the region. This is overlain

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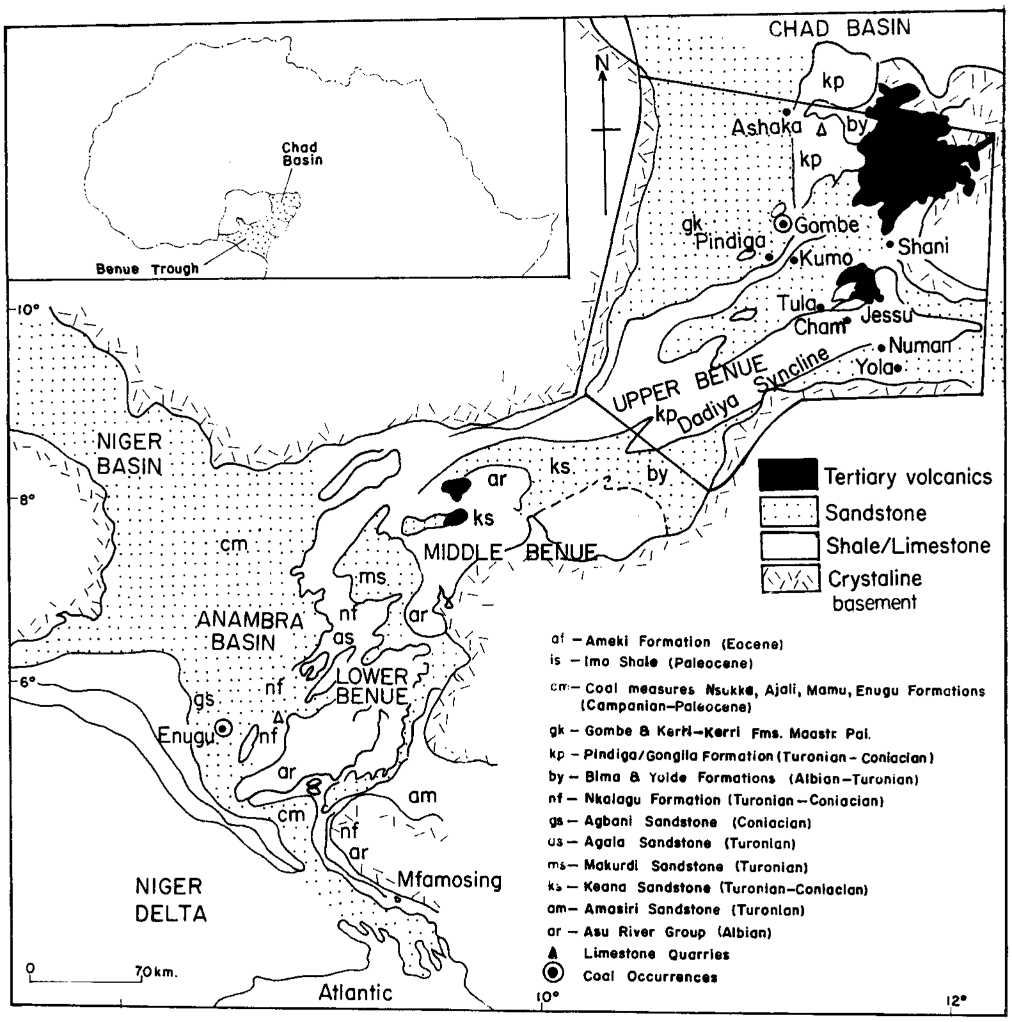

Fig. 1. Geological map showing the Upper Benue region. Inset shows the position of the Benue Trough in Nigeria.

by the transitional Yolde Formation (Cenomanian–Turonian), and succeeded by the marine Turonian to Coniacian Pindiga Formation, Gongila Formation in the Gongola Basin and its lateral equivalents; the Dukul, Jessu and Numanha formations in the Yola Basin (Fig. 3). These successions are overlain by the Campanian–Maastrichtian Gombe Sandstone in the Gongola Basin and the Lamja Sandstone (lateral equivalents) in the Yola Basin. The Tertiary Kerri-Kerri Formation capped the succession west of Gombe in the Gongola Basin.

Lithostratigraphy and depositional environments

Gombe Sandstone (Campanian to Maastrichtian). The Gombe Sandstone [Fig. 4(a)] consists of poorly to moderately sorted sandstone facies that are interbedded with gray argillaceous beds. Siltstone interbeds in this formation are intercalated with oolitic ironstone. The interbedded dark gray shales and siltstone increased in thickness towards the lower part of the boreholes GSN 1504 and 4041. Outcrop sections of the Gombe Formation were measured in Gombe town. The presence of terrestrially derived palynomorphs such as *Longiapertites*, *Echitriporites*, *Proteacidites* (Lawal and Moulade, 1986) was confirmed in the argillaceous units. The lithological features and rare marine palynomorphs suggest a fluvio-lacustrine environment of deposition for this formation.

Pindiga formation (Turonian to Coniacian). This formation consists of shales intercalated with limestone beds in the Gombe and Kumo areas [Fig. 4(a) and (b)]. Limestone beds in the Pindiga sections are highly fossiliferous containing oyster shells, bivalves and ammonites (Zarboski, 1993). The shales are light gray to brownish in colour and contain thin gypsiferous layers at the lower parts. Thickness of the Pindiga Formation ranges between 80 to 160 m in outcrops and boreholes investigated in the Gon-

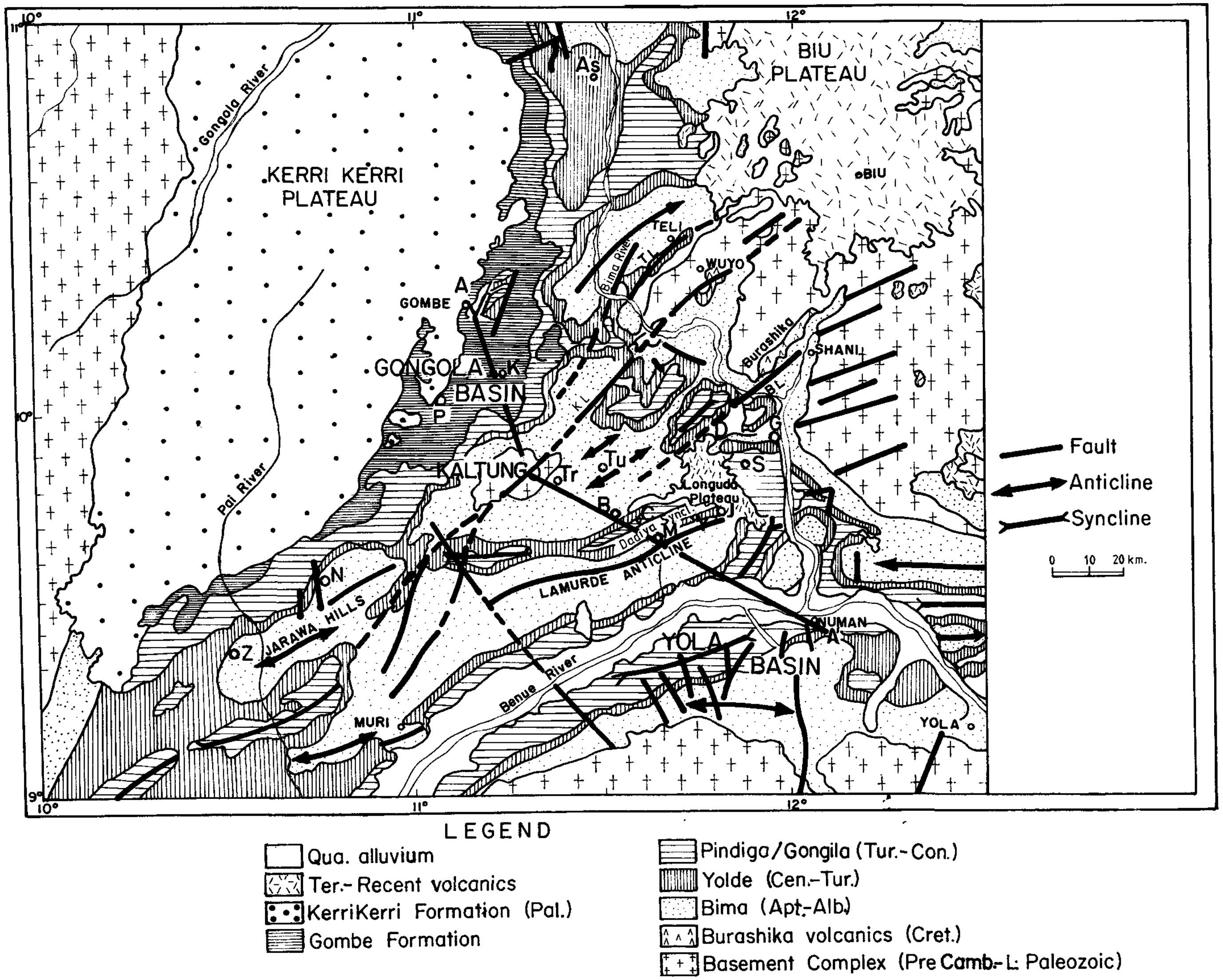

Fig. 2. Simplified geological map of the Upper Benue rift basins (boxed area of Fig. 1) highlighting the N/S trending Gongola Basin and the E/W trending Yola Basin (modified from Maurin *et al.*, 1986). Abbreviation of study locations include As, Ashaka; P, Pindiga; K, Kumo; Tu, Tula; B, Bambam; C, Cham; J, Jessu; Y, Yolde; M, Mona; S, Sekule; D, Dukul and G, Guyuk.

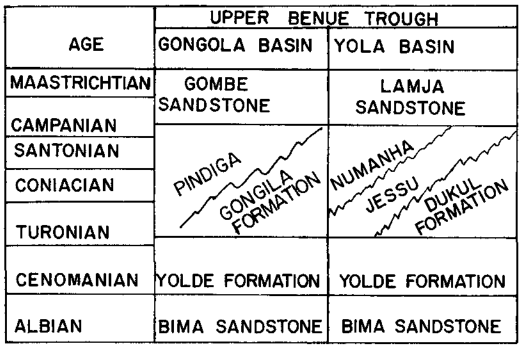

Fig. 3. Generalized stratigraphic subdivisions in the Upper Benue Trough.

gola Basin. The Pindiga Shales commonly contain some marine dinocysts (*Deflandrea* sp. and *Hystrichosphaerina* sp.). The associated marine dinoflagellates suggest that the Pindiga Formation was deposited in a marginal marine to inner shelf environment.

Gongila formation (Turonian to Coniacian). The Gongila Formation exposed in the Ashaka cement quarry is a lateral equivalent of the Pindiga Formation (Fig. 3). It attains a total thickness of 22 m on outcrop scale consisting of alternating sets of massive to nodular limestones at the base, marly bed (about 3 m) and thick shale units, intercalated with thin limestone beds in the upper part within the Gongola Basin. The limestone is bioturbated and highly fossiliferous with abundant ammonites. The associated calcareous lithologic units and presence of marine microflora similar to the forms contained in the Pindiga Shales suggest that the Pindiga and Gongila formations are lateral equivalents.

Dukul formation (Turonian to Coniacian). The Dukul Formation consists mainly of gray shales and thin silty beds [Fig. 4(c)] in the borehole GSN 1612 investigated in the Yola Basin. At Kutari and Lakun villages near Cham, dark gray shales of this formation are interbedded with limestone. The shales are commonly laminated and in places contain some bivalves. The limestone interbeds are medium to coarse grained and generally gray in colour, bioturbated and massive. Both the outcrop and well samples contain marine palynomorphs including, *Oligosphaeridium*, *Florentina* sp. and *Exoschosphaeridium* sp. The palaeontological data and sedimentologic features support an open marine depositional environment for this formation.

Yolde formation (Cenomanian to Turonian). The Yolde Formation consists of interbeds of shale, siltstone, sandstone and calcareous mudstone. About 140 m of these sediments were intersected by the GSN 1612 well in the Yola Basin [Fig. 4(c)]. The shale units, are in places laminated and contain plant remains. Outcrop sections of the Yolde Formation measured at Bambam and Cham area consist of sandstone facies ranging from massive, parallel to cross-stratified units, calcareous sands and shale facies. The sandstones are lithified, medium to coarse and well sorted although in some intervals, clasts of shale are common. In places, the calcareous sandstone unit is bioturbated. The shales are relatively thin with an average thickness of 0.3 m. The Yolde Formation is interpreted as ranging from a continental to a nearshore marine regime. Identifiable coarsening upward cycles support a deltaic system of deposition. The thin siltstone and shale layers with plant remains correspond to swamp sub-facies of deltaic plain, the sandstone units to a delta front and the basal mudstones constitute the prodelta facies (Ojo *et al.*, 1995).

EXPERIMENTAL

Vitrinite reflectance measurements

Selected samples were crushed to less than 2 mm and impregnated in epoxy for quantitative reflected light microscopy. In the samples with sparse organic constituents, kerogen concentrates were prepared, mounted and polished. Organic petrology studies were carried out on a Reichert Jung Polyvar photomicroscope equipped with halogen and HBO lamps, a photomultiplier and computer unit at the "Zentraleinrichtung für Elektronenmikroskopie" (ZELMI) at the Technische Universität Berlin, Germany. Mean random reflectance of vitrinite in oil (R_{om}%, cf. Bustin *et al.*, 1983) was calculated from the reflectance of at least 30 grains of vitrinite measured in random orientation using monochromatic (546 nm) non-polarised light in conjunction with a ×40 oil immersion objective. Calibration of the microscope photometer was achieved using standards of known reflectance (1.23 and 3.16%). Measured R_{om} values of the reflectance standards confirmed the photomultiplier to be consistently linear within the range of the measurements.

Data collection and evaluation were done using the coal programme by Reichert Jung and macerals were identified through the use of white light and blue light excitation at 546 and 460 nm, respectively. The mean reflectance as compared to the median or modal reflectance appears to be an adequate measure of thermal maturity in this study (Tissot and Welte, 1984; Pollastro and Barker, 1986).

Rock-eval pyrolysis

Total organic carbon content (TOC) was measured on pulverized samples at 1000°C under intense oxygen flow by combusting in Carmograph-8 equipment. The hydrocarbon generative potential, the maturity and type of the kerogen and the hydrogen index were determined by Rock-Eval II

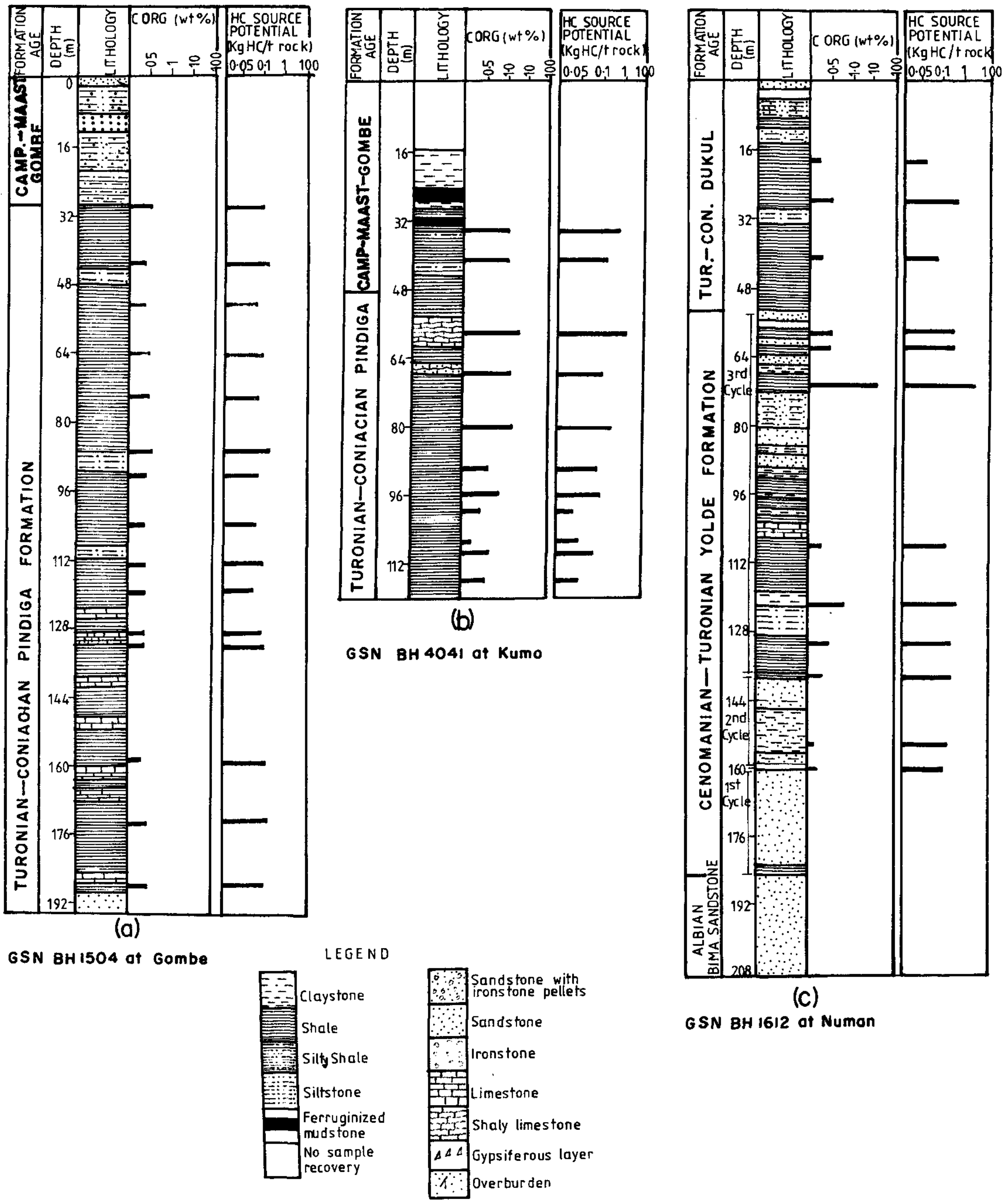

Fig. 4. Lithologic sections and source rock potential of boreholes in Gombe, Kumo and Numan areas; (a) GSN 1504 borehole at Gombe, (b) GSN 4041 borehole at Kumo and (c) GSN 1612 borehole at Numan.

pyroanalyser (Espitalié *et al.*, 1977). Pyrolysis of 30–40 mg of samples at 300°C for 4 min was followed by programmed pyrolysis at 25°C/min to 550°C, in an atmosphere of helium. These analyses were carried out at the Department of Mineralogy, Geochemistry and Petrography, Attila Jozsef University, Szeged, Hungary.

The residue of the thermal degradation (unconverted kerogen) was characterized by Rock-Eval pyrolysis and by the CR/CT ratio measured according to the ASTM standard (Cummins and Robinson, 1972).

Infrared spectroscopy

Infrared spectra of demineralized kerogen concentrates were measured between 200–4000 cm^{-1} using the KBr-pellet technique described in Ganz (1986) at the Organic Geochemical Laboratory of

Table 1. Rock-Eval pyrolysis, vitrinite reflectance and infrared spectroscopy data of samples from the Kumo (GSN 4041) borehole

Formation	Sample No.	TOC (wt%)	HI*	GPI	S1**	S2**	S1 + S2***	T_{max} (°C)	R_{om}%	A factor	C factor	HGP
Gombe	KM 3	1.46	65	0.03	0.03	0.96	0.99	433	0.52	0.41	0.4	5.99
Gombe	KM 4	1.20	22	0.04	0.01	0.27	0.28	422	0.49	0.38	0.43	4.56
Pindiga	KM 9	2.45	76	0.01	0.02	1.88	1.90	435	0.55	0.39	0.38	9.56
Pindiga	KM 11	1.63	13	0.05	0.01	0.22	0.23	415	0.44	0.39	0.46	6.36
Pindiga	KM 13	1.56	19	0.03	0.01	0.31	0.32	416	0.46	0.47	0.45	6.86
Pindiga	KM 16	0.60	15	–	–	0.09	0.09	423	0.48	–	–	–
Pindiga	KM 17	0.74	13	0.17	0.02	0.10	0.12	422	0.47	–	–	–
Pindiga	KM 18	0.39	10	0.00	–	0.04	0.04	426	0.41	0.36	0.46	1.4
Pindiga	KM 19	0.28	14	0.25	0.01	0.04	0.05	–	0.46	0.24	0.43	0.67
Pindiga	KM 21	0.65	13	–	–	0.09	0.09	425	0.48	0.35	0.43	1.92
Pindiga	KM 23	0.54	9	0.17	0.01	0.05	0.06	419	0.43	–	–	–
Pindiga	KM 25	0.21	–	0.08	0.01	0.11	0.12	–	0.52	0.33	0.39	0.69

*In mg HC/g TOC.
**In mg HC/g rock.
***In kg HC/ton rock.
HGP = A factor × TOC × 10.
A factor = $I(2930\ \mathrm{cm}^{-1}) + I(2860\ \mathrm{cm}^{-1})/I(2930\ \mathrm{cm}^{-1}) + I(2860\ \mathrm{cm}^{-1}) + (1630\ \mathrm{cm}^{-1})$ and C factor = $I(1710\ \mathrm{cm}^{-1})/I(1710\ \mathrm{cm}^{-1}) + I(1630\ \mathrm{cm}^{-1})$, where I is the intensity corresponding to peak heights at their respective wave numbers.

the Institut für Angewandte Geowissenschaften II, Technische Universität Berlin, Germany. The infrared spectra typically display distinct peaks at 2860 and 2930 cm^{-1} (CH_2 and CH_3 aliphatic groups), at 1710 cm–^{1} (carboxyl and carbonyl groups) and at 1630 cm^{-1} (aromatic C=C bonds) Ganz (1986). The ratios of relative intensities of the peaks corresponding to aliphatic/aliphatic + aromatic bonds (A factor) and carboxyl–carbonyl/carboxyl–carbonyl + aromatic bonds (C factor) can be used for interpreting kerogen types and changes in kerogen composition during coalification. A diagram similar to the van Krevelen diagram has been introduced for this purpose (Ganz and Robinson, 1985; Ganz, 1986). Hydrocarbon generation potentials (HGP) presented in Tables 1–3 are estimated from the expression HGP = A factor × TOC × 10 (Ganz and Kalkreuth, 1987).

RESULTS AND DISCUSSIONS

Organic geochemical investigations

The Rock-Eval pyrolysis technique used in this study is a fast method which allows the processing of a large number of samples and preparation of well logs (Espitalié *et al.*, 1977; Clementz *et al.*, 1979). Geochemical logs of the three boreholes penetrating the source rock facies are presented in Fig. 4 showing the organic carbon content and the hydrocarbon generation potential. The source rocks show a range of TOC values between 0.10–12.9% (Tables 1–3). The Gombe, Pindiga and Yolde formations with average TOC values (1.3, 0.63 and 0.46%, respectively, except the one with 12.9%) may be considered as good source rocks in view of the concentration level of organic matter rating above the minimum threshold value of 0.5% for a

Table 2. Rock-Eval pyrolysis, vitrinite reflectance and infrared spectroscopy data of samples from the Ashaka quarry and Gombe (GSN 1504) borehole

Formation	Sample No.	TOC (wt%)	HI*	GPI	S1**	S2**	S1 + S2***	T_{max} (°C)	R_{om}%	A factor	C factor	HGP
Pindiga	GB 1	0.57	15	0.10	0.01	0.09	0.10	426	0.52	–	–	–
Pindiga	GB 3	0.60	24	0.17	0.02	0.10	0.12	423	0.46	0.29	0.44	1.19
Pindiga	GB 6	0.35	22	–	–	0.08	0.08	428	0.49	–	–	–
Pindiga	GB 8	0.46	17	0.30	0.03	0.08	0.11	421	0.44	0.37	0.47	1.70
Pindiga	GB 10	0.47	23	0.08	0.01	0.08	0.12	422	–	–	–	–
Pindiga	GB 13	0.49	36	0.10	0.02	0.18	0.20	424	0.49	–	–	–
Pindiga	GB 14	0.45	16	0.12	0.01	0.07	0.08	419	0.43	0.31	0.45	1.33
Pindiga	GB 16	0.32	21	0.12	0.01	0.07	0.08	425	0.51	–	–	–
Pindiga	GB 17	0.48	29	0.07	0.01	0.14	0.15	419	0.44	0.35	0.42	1.68
Pindiga	GB 19	0.43	16	0.12	0.01	0.07	0.08	419	0.63	0.28	0.34	1.2
Pindiga	GB 21	0.42	19	0.20	0.02	0.08	0.10	425	0.47	0.37	0.46	1.55
Pindiga	GB 22	0.40	37	–	–	0.15	0.15	420	0.48	–	–	–
Pindiga	GB 26	0.38	39	0.06	0.01	0.15	0.16	423	0.46	0.33	0.45	1.32
Pindiga	GB 28	0.46	30	0.12	0.02	0.14	0.16	424	0.48	0.32	0.39	1.47
Pindiga	GB 31	0.40	27	0.08	0.01	0.11	0.12	424	0.53	0.33	0.36	1.32
Gongila	AS 1	0.41	24	–	–	0.10	0.10	423	0.49	0.26	0.41	1.07
Gongila	AS 4	0.26	15	–	–	0.04	0.04	431	0.65	0.29	0.42	0.75

*In mg HC/g TOC.
**In mg HC/g rock.
***In kg HC/ton rock.
HGP = A factor × TOC × 10.

Table 3. Rock-Eval pyrolysis, vitrinite reflectance and infrared spectroscopy data of samples from the Numan (GSN 1612) borehole

Formation	Sample No.	TOC (wt%)	HI*	GPI	S1**	S2**	S1 + S2***	T_{max} (°C)	R_{om}%	A factor	C factor	HGP
Dukul	NA 2	0.25	24	–	–	0.06	0.06	–	0.73	0.38	0.26	0.95
Dukul	NA 4	0.53	41	0.60	0.33	0.22	0.55	431	0.65	0.39	0.31	2.07
Dukul	NA 6	0.33	24	–	–	0.08	0.08	442	0.75	0.35	0.25	1.16
Yolde	NA 8	0.58	18	0.44	0.08	0.11	0.19	442	0.74	0.35	0.32	2.03
Yolde	NA 10	0.56	48	0.12	0.03	0.24	0.27	442	0.71	0.36	0.32	2.06
Yolde	NA 12	12.9	171	0.02	4.48	22	26.48	438	0.71	0.52	0.29	67
Yolde	NA 17	0.33	27	0.10	0.01	0.09	0.10	437	0.64	0.32	0.34	1.06
Yolde	NA 22	0.89	55	0.12	0.06	0.49	0.55	437	0.69	0.6	0.29	3.54
Yolde	NA 23	0.58	48	0.07	0.02	0.28	0.30	438	0.77	0.33	0.29	2.03
Yolde	NA 25	0.39	55	0.05	0.01	0.20	0.21	442	0.76	–	–	–
Yolde	NA 27	0.10	30	0.03	–	0.11	–	–	0.74	0.33	0.30	0.33
Yolde	NA 29	0.21	42	0.20	0.02	0.09	0.11	–	0.73	0.35	0.28	0.74

*In mg HC/g TOC.
**In mg HC/g rock.
***In kg HC/ton rock.
HGP = A factor × TOC × 10.

potential source rock (Hunt, 1979; Tissot and Welte, 1984). The average TOC values of the Pindiga Formation are 0.44 and 0.9% in Gombe and Kumo areas, respectively, suggesting that the hydrocarbon potential for the Pindiga lithofacies in the Kumo area is better than in the Gombe area. The higher organic matter content of the non-marine swamp facies of the Yolde Formation in the Yola Basin may be due to proximity to organic source (Bustin, 1988) in this environment. Despite the organic richness, however, the hydrogen index values are generally low ranging from 9 to 76 mg HC/g TOC except for the one of 171 mg HC/g TOC (Tables 1–3). The average HI value is highest in the Yolde Shales (Table 3). The plots of HI vs TOC (Jackson *et al.*, 1985) indicate a gas-prone source rock for the Gombe, Pindiga and Yolde formations while a poor source is suggested for Gongila and Dukul formations (Fig. 5) in the Gongola and Yola Basins. The poor source beds were probably deposited in oxic conditions (Demaison and Moore, 1980; Olugbemiro *et al.*, 1997).

The organofacies of the formations show substantial contribution from terrestrial sources. This is indicated by the plot of HI vs T_{max} (Fig. 6), where all the samples plot on the Type III (gas prone) kerogen field (Espitalié *et al.*, 1984), except for the swamp facies of the Yolde Formation in the Yola Basin with some indications of Type II kerogen. The predominance of Type III kerogen is further supported by the plot of A factor vs C factor from infrared data (Fig. 7, Tables 1–3) which classify the Gombe, Gongila and Pindiga formations as having mostly Type III kerogens. The Yolde Formation in the plot contains both Type II and III kerogens (Ganz, 1986; Ganz and Kalkreuth, 1987). The plots indicate that the Cretaceous samples have relatively higher contents of carboxyl groups and moderate aliphatic values (Akaegbobi, 1995). This confirms substantial contribution of terrestrially derived organic matter to the sediments of the Gongola Basin as a result of rapid run off into the basin from the adjacent land areas.

Measured T_{max} values ranging from 415 to 442°C and vitrinite reflectance values of 0.41 to $1.03R_{om}$% (Tables 1–3) for the Cretaceous sediments show immature to mature source beds (Ramanampisoa and Radke, 1992; Hetenyi, 1992; Plummer, 1994). The Dukul and the Yolde formations in the Yola Basin are within the oil generating window while the Pindiga and Gongila formations in the Gongola Basin are immature to marginally mature with respect to oil generation (Fig. 7). Estimated vitrinite reflectance equivalents (VRE%) (0.4 to 0.5%) from the plot of A vs C factors also support the immaturity to marginally mature status for the Pindiga and Gongila Shales of the Gongola Basin (Fig. 7). Vitrinite reflectance equivalents (VRE%) from the plots (Fig. 7) indicate maturity status for the Dukul and Yolde formations in the Yola Basin (Price, 1983; Tissot and Welte, 1984).

Hydrocarbon potential

The conventional source-rock investigation using TOC, Rock-Eval pyrolysis and infrared data of selected source rock intervals of the Cretaceous succession in the upper Benue Trough indicate a generally low to moderate amount of organic matter (Fig. 4). In the regional context, the amount of organic matter barely meets the minimum pre-requisite for petroleum source beds. Thus they can be rated as poor to fair oil source rocks. Source rock horizons of the Pindiga Formation in the Kumo area (Gongola Basin, Fig. 2) have relatively higher contents of organic matter. The higher TOC value in Kumo area may be due to its originally higher organic input. It is observed that dispersed organic matter in the source rock facies is composed mainly of Type III (gas prone) kerogen. This indicates a predominantly terrestrial source for the organic matter constituents. However, a certain interval of the deltaic plain (swamp subfacies) of the Yolde Formation in the Numan area contains Type II

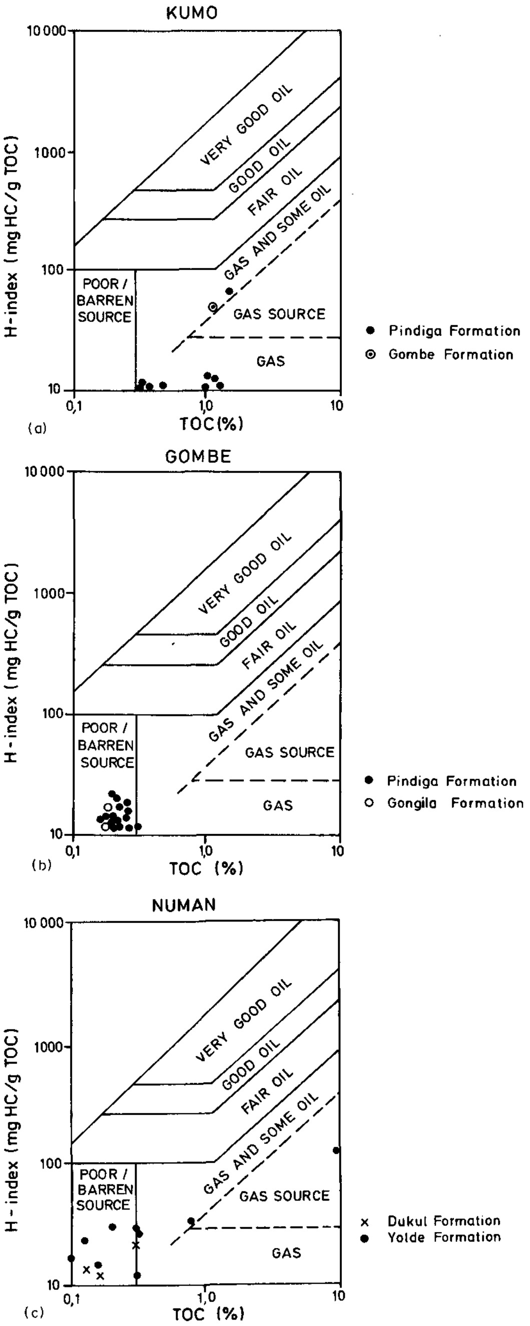

Fig. 5. Source richness plot of samples from (a) Kumo (GSN 4041) borehole, (b) Ashaka quarry (Gongila Formation only) and Gombe (GSN 1504) borehole and (c) Numan (GSN 1612) borehole.

kerogen. This same interval has a distinctly high TOC value of 12.9 wt% [Fig. 4(c)]. The predominant Type III kerogen in the two basins indicates that source beds in the region are generally gas prone and can only be expected to provide low yields of hydrocarbons from this kerogen type (Espitalié *et al.*, 1985). The relatively higher abundance of carboxyl groups and moderate aliphatic values (Akaegbobi, 1995) also suggest gaseous hydrocarbon potential. Generally, the genetic potential (S_1+S_2) of the source rocks is low, less than 1.0 kg HC/ton rock except for the organic-rich swamp facies of the Yolde Formation with a genetic potential of about 26.5 kg HC/ton rock (Fig. 4). The low S_1 values of less than 0.4 mg HC/g rock indicate barely free hydrocarbons in the potential source rocks. Thus, impregnation with migrated oil is unlikely (Ramanampisoa and Radke, 1992). Powell *et al.* (1991) reported that Rock-Eval pyrolysis may not fully define the oil proneness of a source rock dominated by terrestrially sourced organic matter. Our study suggests that the distribution and types of organic matter in the Upper Benue rift basins are largely controlled by the basin morphology and paleogeography despite the development of an extensive regional anoxic marine environment suggested for the Upper Cenomanian to Santonian times in the Benue Trough (Petters and Ekweozor, 1982). The source-rock intervals of the Gombe, Pindiga, Gongila, Dukul and Yolde formations investigated are poor in organic matter of marine origin but dominated by terrestrially derived types. This indicates that the predicted anoxic environment throughout the mid-Cretaceous was not sustained and there is a prevalence of an oxic depositional environment.

Thermal maturation from T_{max} and vitrinite reflectance data indicate that the organic matter in the Gongola Basin is immature to marginally mature. Indeed, the Turonian–Coniacian Pindiga Formation in the Gongola Basin is in the diagenetic stage of maturity. In the Yola Basin, the Turonian–Coniacian Dukul Formation and the Cenomanian–Turonian Yolde Formation are within the oil generating window. This suggests that geothermal heat associated with volcanic events in the Yola Basin is significant in causing additional reheating of the Cretaceous sediments thereby enhancing maturity. It is also possible that higher rates of sedimentation and more rapid burial existed in the Yola Basin. These possibilities are being tested in our future work in the prospectivity of the Yola Basin.

SUMMARY AND CONCLUSION

The samples described in this study are representative of the Gombe, Pindiga, Gongila, Dukul, and Yolde formations. These contain most of the possible source rocks in Gongola and Yola Basins of the Upper Benue rift. The Cretaceous sediments were deposited in a wide range of environments with the Albian Bima Sandstone in a continental condition dominated by a fluvial system. The Cenomanian–Turonian Yolde Formation is interpreted as shoreline marine deposit while the Turonian–Coniacian Pindiga, Gongila, Dukul formations were probably deposited in an

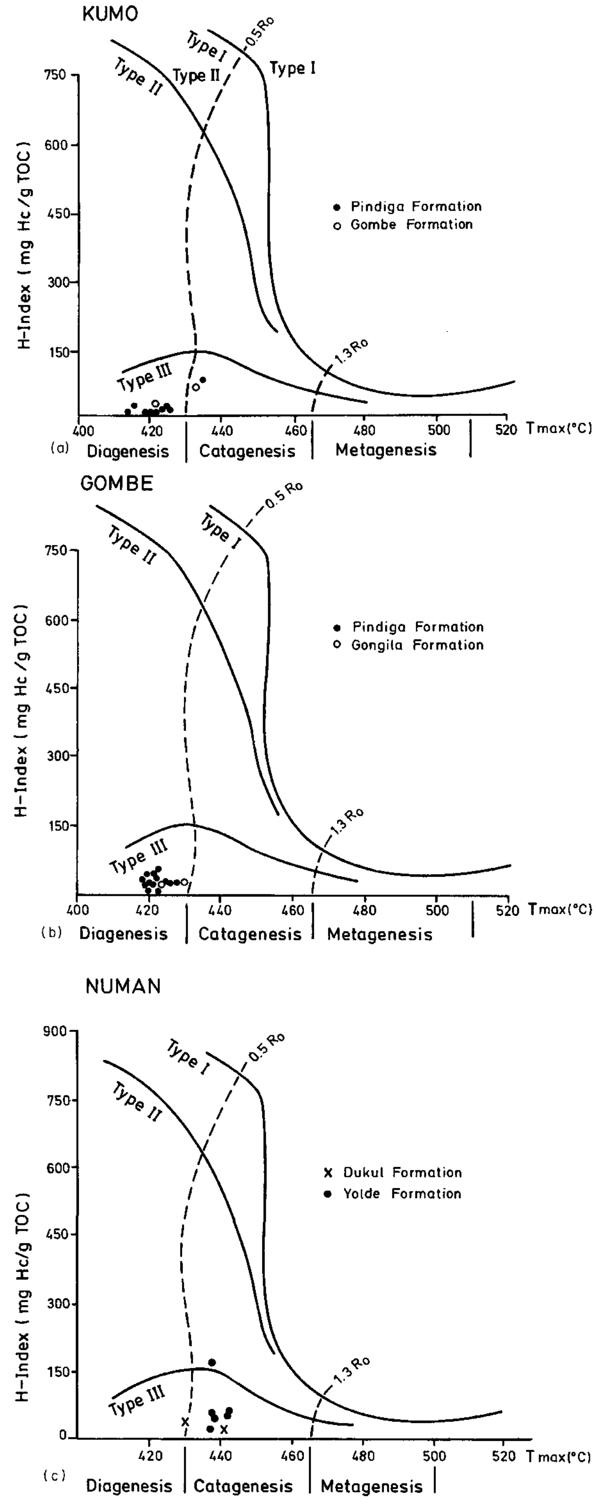

Fig. 6. Composite HI–T_{max} diagram for the interpretation of kerogen type and maturity of (a) data from Kumo (GSN 4041) borehole, (b) data from Ashaka quarry (Gongila Formation only) and Gombe (GSN 1504) borehole and (c) data from Numan (GSN1612) borehole.

inner shelf marine environment. The Campanian–Maastrichtian Gombe Sandstone is thought to be a fluvio-lacustrine deposit.

Source rock facies in these successions contain low to fair concentrations of organic matter. They are considered to be a poor to fair oil and gas

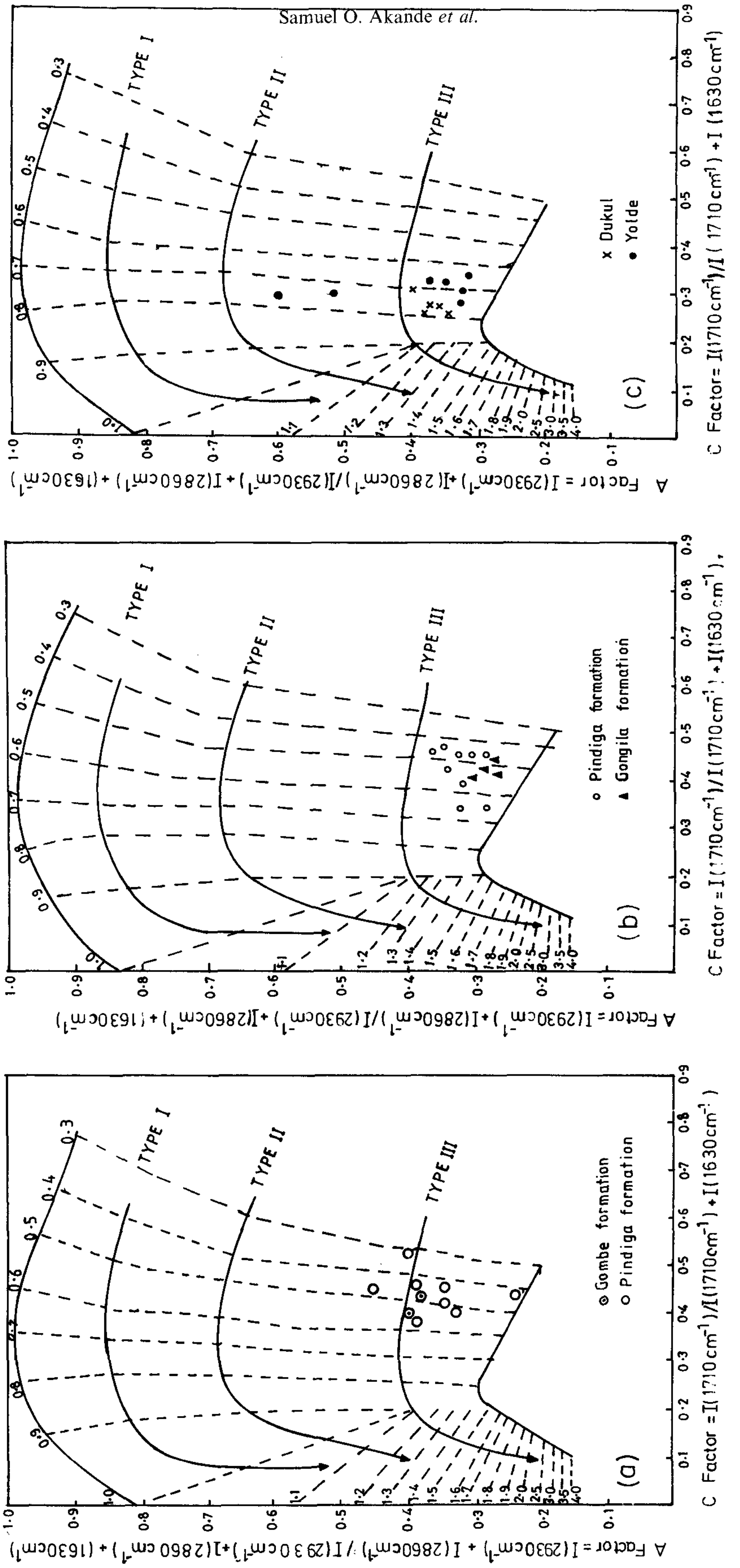

Fig. 7. Classification of Kerogen-types according to A and C factors obtained from infrared spectroscopy of samples from (a) Kumo (GSN 4041), (b) Ashaka quarry (Gongila Formation only) and Gombe (GSN 1504) borehole and (c) Numan (GSN 1612) borehole (adapted from Ganz, 1986).

source rock. Generally, the genetic potential of the source-rocks is low and free hydrocarbons are barely present. The highest TOC and HI values occur in the upper deltaic plain (swamp) sediments of the Yolde Formation in the Yola Basin. The generally lower HI < 50 (mg HC/g TOC) in the Pindiga and Dukul formations suggests dilution of autochtonous organic matter and probably an oxic condition in a shallow marine setting. Source-rock facies are dominated by terrestrially derived organic matter (Type III kerogen) and therefore may have gas potential. The Pindiga Shales are immature. However, the source rocks of the Dukul and Yolde formations in the Yola Basin are within the oil generating level of maturity. Since the present data are to be considered preliminary, the source capabilities and thermal maturity especially of the Bima formation will be tested in future research when deeper boreholes become available from the proposed drilling programme of the oil and gas exploration companies.

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