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Occurrence and Distribution of Igneous Intrusions in the Nigerian Sector of the Chad Basin: Impact on Hydrocarbon

By

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Abstract

This work seeks to stress the significance of an evaluation of the impacts of volcanic intrusives in the Nigerian sector of the Chad Basin (Bornu Sub-basin) on the hydrocarbon potential. In the Bornu Sub-Basin, intrusive sills and plugs occur interstratified within Cretaceous sediments, particularly the Fika and Gongila Formations. Hand specimen description corroborated by chemical data indicates basic to ultrabasic volcanics, particularly basalts. The emplacement of such shallow level intrusions may impact significantly on the petroleum systems of the sub-basin. The intrusions may increase the geothermal gradient, accelerating thermal maturation and promoting hydrocarbon generation. Forced folding associated with sill emplacement in the shallow subsurface stratigraphically within the Gombe Sandstone could have enhanced the formation of ~~a~~ viable hydrocarbon traps. However, the intrusives might also have led to thermal degradation where excess heat impacts upon organic matter transformation in source rocks. Furthermore, increased magmatism during the Tertiary may have down graded the petrophysical qualities of the reservoir facies within the Bima, Gombe and Gongila Formations.

Introduction

Studies over the years have analyzed various aspects of the petroleum system of the Nigerian sector of the Chad Basin, otherwise known as the Bornu Sub-basin. However, the occurrence, distribution and the possible impacts of the intrusive bodies encountered have been conspicuously de-emphasized.

Physiographic setting around the Chad Basin shows the Biu plateau volcanogenic province occurring in the southern part, with Basement rocks of the Jos Plateau flanking the western edge (Fig. 1). The eastern margin of the basin is bounded by suite of basement rocks constituting the Mandara Mountains.

In many sedimentary basins worldwide, sills of volcanic/plutonic origin have the tendency to become emplaced in lithologies of lower mechanical competences[1] thus impacting thermal effects. Therefore voluminous volcanics are common in many sedimentary basins worldwide e.g the Norton Basin, Alaska as reported by Fisher[2].

In the Bornu Sub-basin, seven sedimentary formations compose the stratigraphy, providing a sediment package that attains 10km around its depocentre Avovbo et al[3]. The lithologies of these

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[1] Hubred, J.H. (2006): Thermal effects of Basaltic sill emplacement in source rocks on maturation and hydrocarbon generation.

[2] Fisher, M.A. (1982): Petroleum geology of Norton basin, Alaska: AAPA Bulletin vol. 66 PP. 286-301.

[3] Avbovbo, A. A., Ayoola, E.O. and Osahon, G.A. (1986): Depositional and structural styles in Chad basin of northeastern Nigeria. AAPG Bull. Vol. 70/12. PP. 1787-1798.

formations are variable from limestone, shale, sandstones etc, some of which are of low mechanical competences, suitable for the emplacement of intrusives.

These intrusives are mainly occurring as parts of short lived continental breakup volcanism Planke et al[4] and the Tertiary volcanic intrusives which are preponderant in the southern fringe of the basin. The former is linked to the west and east African rifting episode, which initiated the evolution of the basin. Elsewhere, this is exemplified by the More and Viking basins offshore Norway, Karoo basin of South Africa, the panama basin of Brazil and on the North West Australian shelf Symonds et al[5].

This work seeks to highlight the occurrence and distribution of these intrusive bodies and their possible impacts on the petroleum system in the Nigerian sector of the Chad Basin.

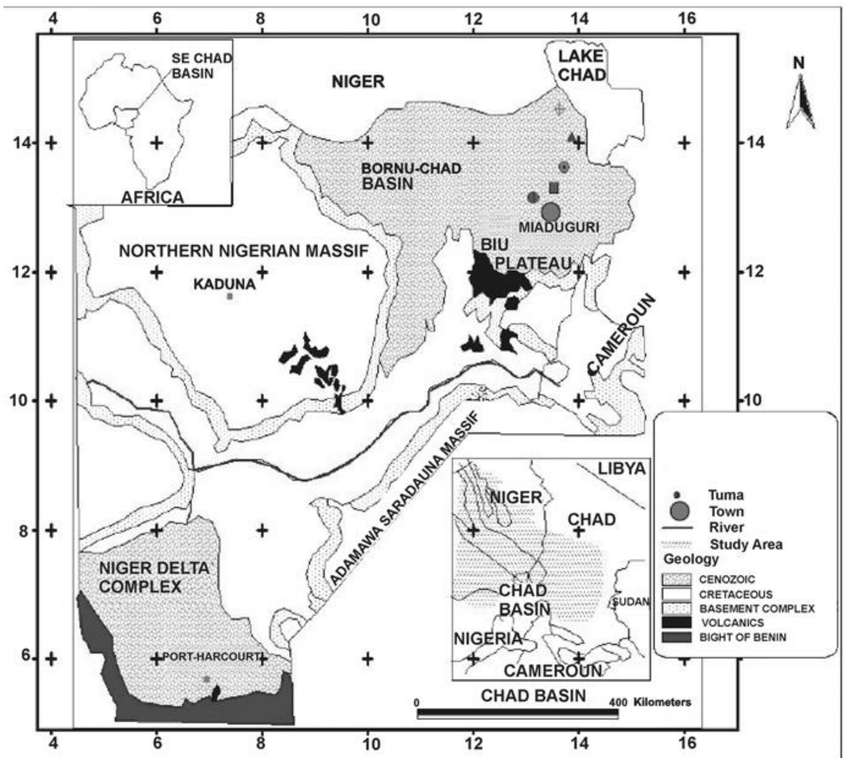

Fig 1: Map of the Nigerian sector of the Chad Basin in the Northeast with the Biu volcanic Province at the southern part of the basin[6].

[4] Planke, S., Malthe-Sorenssen, A. and Jamtveit, B. (1988): Volcanic development of the Western Australian continental margin and its implication for basin development. The Sed. Basins of western Australia. Proceedings of pet. Expt. of Soc. Of Australia symposium. PP. 33-54.

[5] Symonds, P.A., Planke, S., Frey, O. and Skogseid, J. (1998): Volcanic development of the Western Australian continental margin and its implication for basin development. The Sed. Basins of Western Australia. Proceedings of Pet. Expt. of Soc. of Australia Symposium PP. 33-54.

[6] Giruad (1990): Tectono-Sedimentary framework of the early Cretaceous continental Bima formation (Upper Benue Trough, NE Nigeria). Journal of American earth sciences, vol. 10. PP. 341-355.

The Bornu Sub-Basin

The Nigerian sector of the Chad Basin is generally referred to as the Bornu Sub-basin[7,8]. Various mechanisms have been proposed to explain the origin of sediments in the Bornu Sub-basin. Lees[9] and Carter et a1[10] believe that the Cretaceous system of the basin originated as a part of the Benue Trough. It is an extension of the third and failed arm of a triple rift junction system that formed during the Late Jurassic/Early Cretaceous and opened as a subsidiary basin into the emerging Atlantic Ocean.

Furon[11] suggested that the Chad Basin represents the place of dissection of tectonic troughs. Cratchley[12], Cratchley and Jones[13] and Ajaikaye and Burke[14] have shown from geophysical evidence that the Benue Trough is a structural alignment and may have connected with the Chad Basin in the Nigerian sector. The Chad Basin is therefore, genetically linked with the Benue Trough and shows evidence of a rift origin without any strong indication of being fault bounded[15,16,17]. However, Petters[18] is of the opinion that the basin resulted from seafloor spreading along the continental margin of West Africa. He argued that its differentiation during the Mesozoic and Cenozoic was controlled by rifting and subsidence developing into major grabens. Dike[19] interpreted the Bornu Sub-basin as a Late Albian to Early Cenomanian transfer rift of the Northern Benue Trough, the origin of which dates back to the Late Jurassic/Early Cretaceous.

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[7] Olugbemiro, R. O., Ligouis, B. and Abaa, S. I., (1997): Check up Journal of Petroleum Geology

[8] Obaje, N.G., Wehner, H., Scheeder, G., Abubakar, M.B. and Jauro, A., (2004): Hydrocarbon prospectivity of Nigeria's inland basins: From the view point of organic geochemistry and organic petrology. AAPG Bulletin, 88 (3), PP. 325-353.

[9] Lees, G.M. (1952): Foreland folding. Quarterly Journal of Geological Society of London. PP.108.

[10] Carter, J.D., Barber, W. and Tait, E.A.,(1963): The Geology of parts of Adamawa, Bauchi and Bornu provinces in north eastern Nigeria. Geol. Surv. of Nigeria. Bull. Vol. 30.

[11] Furon, R. (1963): Geology of Africa-Oliver and Boyd, London PP. 377.

[12] Cratchley, C.R. (1960): Geophysical Survey of South Western part of the Chad Basin. Paper presented at conference on geology, Kaduna, northern Nigeria.

[13] Cratchely, C.R. and Jones, G.P. (1965): An interpretation of geology and gravity anomalies of the Benue valley, Nigeria. Geophysical paper 1.

[14] Ajakaiye, D.E. and Burke, K. (1973): A Borguer gravity map of Nigeria. Tectonophysics, vol. 16. PP. 103-115.

[15] Carter, J.D., Barber, W. and Tait, E.A.,(1963): The Geology of parts of Adamawa, Bauchi and Bornu provinces in north eastern Nigeria. Geol. Surv. of Nigeria. Bull. Vol. 30.

[16] Matheis, G., (1976): Short review of the geology of the Chad Basin, in C. A. Kogbe, ed, Geology of Nigeria, Elizabethan publishing Company Lagos, Nigeria PP. 289-298.

[17] Benkhelil, J. (1988): Structure et evolution geology namique du basin intracontinental de la Bonoue, Nigeria. Bull. Cent. Rech. Explor. Prod. Elf-Acquitaine vol.12 PP. 29-128.

[18] Peters, S.W. (1981): Stratigraphy of Chad and lullemeden Basins (West Africa). Eclogae Geol. Helv. 74 PP. 139-159.

[19] Dike, E.F.C. (2002b): Some aspects of basin analysis, petroleum geology and hydrogeology of Bornu Basin, NE Nigeria. NAPE International Conference and Exhibition, Eko Meridien Hotel, Lagos. PP. 15.

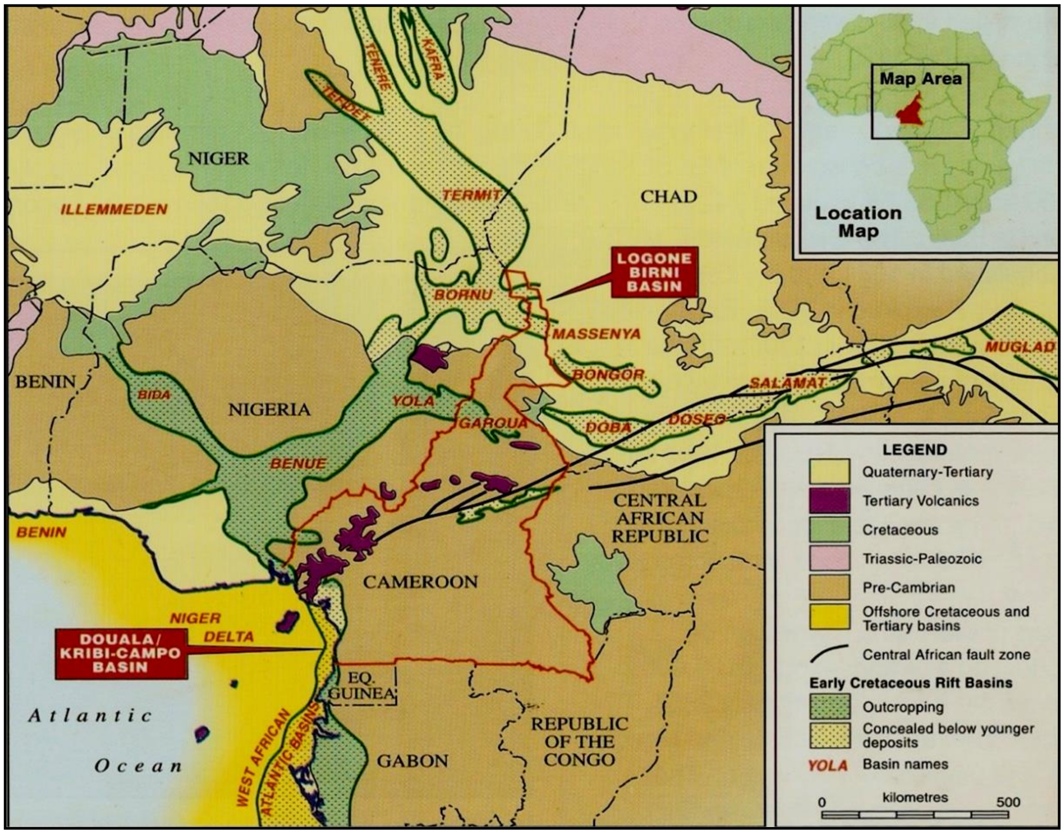

Fig 2: Map of the West and central African rift system (Modified after Genik[20])

The Bornu Sub-basin thus exhibits platform and trough sedimentation in a geotectonic setting related to rifting (Dike[21,22]). This has resulted in a series of continental deposition and marine transgressions and regressions (Table 1). Dike[21,22] and Dike and Bature[23] estimated a total thickness of about 6000m for the formations from NNPC boreholes. Earlier geophysical (seismic) estimates gave an average thickness of over 10,000 m Avbovbo *et al.*,[24]. The following is a generalized sequence of stratigraphic formations in the Bornu Sub-basin.

[20] Genik, G.J. (1991): Regional framework, structural and petroleum aspects of rift basins in Niger, Chad and the Central African Republic. Elsivier Science publishers BV Amsterdam. PP. 169-185.

[21] Dike, E.F.C. (2001): Petroleum exploration for hydrocarbons in the upper Benue trough and Chad Basin. Paper presented at Senate Committee Hearing, Government House Bauchi. PP. 8

[22] Dike, E.F.C. (2002b): Some aspects of basin analysis, petroleum geology and hydrogeology of Bornu Basin, NE Nigeria. NAPE International Conference and Exhibition, Eko Meridien Hotel, Lagos. PP. 15.

[23] Dike, E.F.C. and Bature, P.R. (1999): Subsurface stratigraphy of the Nigerian Chad Basin (Bornu Basin) with some aspects of petroleum geology and hydrogeology.37th Science Association of Nigeria Conference (Abstract volume), Bauchi, PP. 68-69.

[24] Avbovbo, A. A., Ayoola, E.O. and Osahon, G.A. (1986): Depositional and structural styles in Chad basin of northeastern Nigeria. AAPG Bull. Vol. 70/12. PP. 1787-1798.

The Bima Formation

The Cenomanian is marked by the mainly fluviatile sediments as represented by the Bima Sandstone. This syn- rift sequence has not been adequately dated due to the general lack of body fossils. However, reports by the consultants of the NNPC[25], based on palynology, suggest late Albian to early Turonian age.

The Bima Sandstone outcrops in the Bornu Sub-basin and the Northern Benue Trough with reduced thickness along the Zambuk Ridge, a subsurface uplift of the Basement Complex[26]. Its thickness is about 3000m in the Upper Benue Trough according to Carter *et al*[27]. Lithologically, it is composed of gravelly to medium grained, poorly sorted and highly feldspathic sediments. The Bima Sandstone rests on the crystalline Basement Complex and consists of three component members: lower (B1), Middle (B2) and an Upper (B3).

Works based on seismic investigation of the basin[28] have distinguished two lowermost sequences of sand and shale which probably rest on the basement. Although some workers equate these with the Middle and Lower Bima members, Avbovbo *et al*.[28] believe that these members are distinct, mappable depositional entities that should be accorded new formational status. They were then designated as "Pre Bima" Formation. However, the interpretations of the Kinasar 1 well by Dike and Bature[29] and Dike[30] negates the idea of Pre –Bima Formation, postulating that the Middle Bima rests on the basement and in most of the basin the Lower Bima member (B1) may not even be present.

[25] Robertson Group Plc. (1989): The stratigraphy, Sedimentology and Geochemistry of the NNPC Tuma 1, Kanadi 1 and Sa 1 wells drilled in the Nigerian Chad Basin, Borno State, Nigeria. Report No. 4084/1b (Confidential).

[26] Samaila, N.K. (2007): Reservoir potentials of the upper Bima Sandstone in the Yola and Lau-Lamurde Basins, Upper Benue Trough, NE Nigeria. Unpublished PhD thesis, A.T.B.U Bauchi. PP. 201.

[27] Carter, J.D., Barber, W. and Tait, E.A. (1963): The Geology of parts of Adamawa, Bauchi and Bornu provinces in north eastern Nigeria. Geol. Surv. of Nigeria. Bull. Vol. 30.

[28] Avbovbo, A. A., Ayoola, E.O. and Osahon, G.A. (1986): Depositional and structural styles in Chad basin of northeastern Nigeria. AAPG Bull. Vol. 70/12. PP. 1787-1798.

[29] Dike, E.F.C. and Bature, P.R. (1999): Subsurface stratigraphy of the Nigerian Chad Basin (Bornu Basin) with some aspects of petroleum geology and hydrogeology.37th Science Association of Nigeria Conference (Abstract volume), Bauchi, PP. 68-69.

[30] Dike, E.F.C. (2002b): Some aspects of basin analysis, petroleum geology and hydrogeology of Bornu Basin, NE Nigeria. NAPE International Conference and Exhibition, Eko Meridien Hotel, Lagos. PP. 15.

Table 1: Generalized stratigraphic column of northeastern Nigeria (Modified from Carter et al[31]; Avbovbo et al[32])

Age	Formation	Thickness (M)	Description
Quaternary	Chad	400	Clay with sand interbeds
Palaeocene	Kerri-Kerri	130	Predominantly iron-rich sandstone and clay with plinth of laterite
----------	Uncomformity	----------	----------
Maastrichtian	Gombe	315	Sandstone, siltstone and clay beds
Senonian	Fika	430	Dark grey to black shale, gypsiferous with limestone beds
Turonian	Gongila	420	Alternating limestone and shale with sand beds
Albian to Cenomanian	Bima	3050	Poorly sorted, feldspathic sandstone
Albian	Pre-Bima	800	Sand/shale succession
----------	Nonconformity	----------	----------
Precambrian to Cambrian	Basement Complex		

The Gongila Formation

This is a calcareous transitional unit between the purely continental Bima Sandstone and the marine Fika Shale. It accompanied the onset of marine incursion into the basin. It has a basal fossilliferous limestone bed of varied thickness. Although dated Early Turonian, as indicated by the presence of Turonian ammonites[33], it is now known that it is of Late Cenomanian-Early

[31] Carter, J.D., Barber, W. and Tait, E.A. (1963): The Geology of parts of Adamawa, Bauchi and Bornu provinces in north eastern Nigeria. Geol. Surv. of Nigeria. Bull. Vol. 30.

[32] Avbovbo, A. A., Ayoola, E.O. and Osahon, G.A. (1986): Depositional and structural styles in Chad basin of northeastern Nigeria. AAPG Bull. Vol. 70/12. PP. 1787-1798.

[33] Reyment, R.A., (1965): Aspects of the Geology of Nigeria. University of Ibadan Press. PP. 145.

Turonian age in the Northern Benue Trough[34,35]. It consists of alternating beds of sandstone, shale and limestone.

The Fika Formation

This formation consists of blue-black shale, occasionally gypsiferous, with thin limestone intercalations. The marine transgression that started in the Cenomanian reached its peak in the Turonian, during which this shale was deposited. It has an average thickness of 430m and is in many localities intruded by volcanic rocks. It is best exposed around Fika town in Yobe State. Dike and Obaje[36] observed moderate richness in organic matter with lack of thermal maturity, except locally, where volcanic intrusions might have induced maturity.

The Gombe Formation

The Gombe Sandstone was deposited during a regressive phase. It is confined to the western part of Gombe where the outcrop follows a broad belt northwards from Kashere to Gombe and Fika[37]. These are estuarine - deltaic deposits composed of sandstone, siltstone and mudstone[38,39,40]. This formation ranges from fine grained to coarse grained and is mostly poorly sorted. Around Gombe and Fika towns, it is well exposed, typically folded and forms prominent hills. It has an average thickness of about 320m and is Maastrichtian in age and possibly locally Campanian[41].

The Kerri- Kerri Formation

The Kerri-Kerri Formation rests upon the Cretaceous sediments of the Northern Benue Trough. This formation is limited to the southwestern portion of the basin and has not been known to occur east of Potiskum. Drilling has proved that these sediments are absent in the subsurface

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[34] Popoff, M., Wiedman, J., and De Klasz, I. (1986): The Upper Cretaceous Gongila and Pindiga Formations, Northern Nigeria: Subdivisions, Age, Stratigraphic correlations and paleogeographic implications.Eclogae Geol.Helv, 79: PP. 343-363.

[35] Zaborski, P., Ugodulunwa, F., Idornigie, A., Nnabo, P. and Ibe, K. (1997): Stratigraphy and structure of the Cretaceous Gongola Basin, northeastern Nigeria. Bulletin Centre Exploration Production Elf-Aquantaine, 22, PP. 153-185.

[36] Dike, E.F.C. and Obaje, N.G (2002): Hydrocarbon prospectivity of the upper Benue Trough (source rocks-reservoirs evaluation) Paper presented at the 38th NMGS annual international conference, Port Harcourt.

[37] Carter, J.D., Barber, W. and Tait, E.A. (1963): The Geology of parts of Adamawa, Bauchi and Bornu provinces in north eastern Nigeria. Geol. Surv. of Nigeria. Bull. Vol. 30.

[38] Kogbe, C. A. (1976): Palaeogeographic history of Nigeria from Albian times: in Geology of Nigeria. Kogbe, C. A. (Ed.) Elizabeth Publishing co., Lagos. PP. 237-252.

[39] Dike, E.F.C. and Onumara, I.S. (1999): Facies and facies architechture and depositional environments of the Gombe Formation, Gombe and Environs., NE Nigeria. Sci. Assoc. of Nig. Annual conf. Bauchi, Nigeria (Abstracts Vol.).

[40] Abubakar, M.B (2006): Biostratigraphy, Paleoenvironment and organic Geochemistry of the Cretaceous sequences of the Gongola Basin, Upper Benue Trough, Nigeria. An unpublished Ph.D. Thesis, ATBU Bauchi. PP. 293.

[41] Abubakar, M.B (2006): Biostratigraphy, Paleoenvironment and organic Geochemistry of the Cretaceous sequences of the Gongola Basin, upper Benue Trough, Nigeria. An unpublished Ph.D. Thesis, ATBU Bauchi. PP. 293.

around Maiduguri, wedging out between Maiduguri – Damaturu – Gashua area[42,43] but is present as erosional remnant in the southwestern part of the basin.

The Kerri-Kerri Formation is a continental succession deposited under a wide range of conditions. It is composed essentially of sandstones and in most places characterized by a conspicuous reddish-brown coloration. It has been dated as Paleocene and younger[44] and has a thickness of over 320 m[45]. The formation is capped by a thick lateritic horizon which is mostly of oolitic and vesicular texture. The sedimentation of the Kerri-Kerri Formation was followed by a period of uplift and erosion.

Chad Formation

This is a variable succession that includes all Quaternary sediments underlying the surface deposits. The formation is a succession of lacustrine and fluviatile clays and sands of Quaternary/Pleistocene age [46,47,48,49].

Sediments of the Bama Ridge are considered by some authors[50,51] as a constituent of this formation. However, Zarma[52] has shown from heavy mineral and micropalaeontological studies that the ridge is a separate stratigraphic entity. It has an average thickness of 400 m.

With respect to water supply, this formation is of great economic significance. It has a thickness of over 700 m in Maiduguri area and, in zones where the fluvio- lacustrine deposit is complete, water-bearing levels consisting mostly of sands is concentrated in three well defined aquiferous

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[42] Carter, J.D., Barber, W. and Tait, E.A. (1963): The Geology of parts of Adamawa, Bauchi and Bornu provinces in north eastern Nigeria. Geol. Surv. of Nigeria. Bull. Vol. 30.

[43] Dike, E.F.C. (2002b): Some aspects of basin analysis, petroleum geology and hydrogeology of Bornu Basin, NE Nigeria. NAPE International Conference and Exhibition, Eko Meridien Hotel, Lagos. PP. 15.

[44] Adegoke, O. S, Jan du chene, R. E., Agumanu,A. E. and Ajayi,P.O (1978): Palynology and age of the Kerri-Kerri Formation, Nigeria. Rev. Espan. Micropaleont., Vol. 2: PP. 267-283.

[45] Dike, E.F.C. (1993): Stratigraphy and structure of the Kerri Kerri Basin, northeastern Nigeria. Journal of Mining and Geology, 27, 1, PP. 78 -86.

[46] Carter, J.D., Barber, W. and Tait, E.A. (1963): The Geology of parts of Adamawa, Bauchi and Bornu provinces in north eastern Nigeria. Geol. Surv. of Nigeria. Bull. Vol. 30.

[47] Dike, E.F.C. and Bature, P.R. (1999): Subsurface stratigraphy of the Nigerian Chad Basin (Bornu Basin) with some aspects of petroleum geology and hydrogeology.37th Science Association of Nigeria Conference (Abstract volume), Bauchi, PP. 68-69.

[48] Dike, E.F.C. (2002): Sedimentation and tectonics of the Upper Benue Trough and Bornu Basin. Nigerian Mining and Geosciences Society 38th Annual International Conference, Portharcourt, Abstract Vol.

[49] Dike, E.F.C. (2002b): Some aspects of basin analysis, petroleum geology and hydrogeology of Bornu Basin, NE Nigeria. NAPE International Conference and Exhibition, Eko Meridien Hotel, Lagos. PP. 15.

[50] Carter, J.D., Barber, W. and Tait, E.A. (1963): The Geology of parts of Adamawa, Bauchi and Bornu provinces in north eastern Nigeria. Geol. Surv. of Nigeria. Bull. Vol. 30.

[51] Matheis, G., (1976): Short review of the geology of the Chad Basin, in C. A. Kogbe, ed, Geology of Nigeria, Elizabethan publishing Company Lagos, Nigeria PP. 289-298.

[52] Zarma, A.A. (2013): Sedimentology of the Bama ridge deposit (Holocene) in the Borno Subbasin, North Eastern Nigeria. Unpublished Ph.D. Thesis, ATBU Bauchi PP. 229.

horizons[53,54,55]. According to Dike[55], drilling in the basin has given an insight into the basin's subsurface stratigraphy and shows that large volumes of water exist in the formation. According to data from NNPC boreholes in Maiduguri area[55], the Chad Formation rests unconformably on the Fika Formation. This has been explained as due to the local uplift/erosion of the post Maastrichtian sediments which affected the northern Benue Trough prior to the sedimentation of the Chad Formation[56,57]

Results

A geological field study covering an area of about 40,000 km^2 centering on the western and southern fringes has confirmed the presence of volcanic intrusives, occurring mostly as sills and plugs (Fig. 3). Here, depth to basement is relatively shallow as seen from water wells and basement outcrops. All formations constituting the lithostratigraphy of the Chad Basin have been encountered in the studied area: Bima, Gongila, Fika, Gombe, Keri-keri and the fluvio lacustrine Chad Formation.

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[53] Carter, J.D., Barber, W. and Tait, E.A. (1963): The Geology of parts of Adamawa, Bauchi and Bornu provinces in north eastern Nigeria. Geol. Surv. of Nigeria. Bull. Vol. 30.

[54] Dike, E.F.C. and Bature, P.R. (1999): Subsurface stratigraphy of the Nigerian Chad Basin (Bornu Basin) with some aspects of petroleum geology and hydrogeology.37th Science Association of Nigeria Conference (Abstract volume), Bauchi, PP. 68-69.

[55] Dike, E.F.C. (2002b): Some aspects of basin analysis, petroleum geology and hydrogeology of Bornu Basin, NE Nigeria. NAPE International Conference and Exhibition, Eko Meridien Hotel, Lagos. PP. 15.

[56] Dike, E.F.C. (2002): Sedimentation and tectonics of the Upper Benue Trough and Bornu Basin. Nigerian Mining and Geosciences Society 38th Annual International Conference, Portharcourt, Abstract Vol.

[57] Dike, E.F.C. (2002b): Some aspects of basin analysis, petroleum geology and hydrogeology of Bornu Basin, NE Nigeria. NAPE International Conference and Exhibition, Eko Meridien Hotel, Lagos. PP. 15.

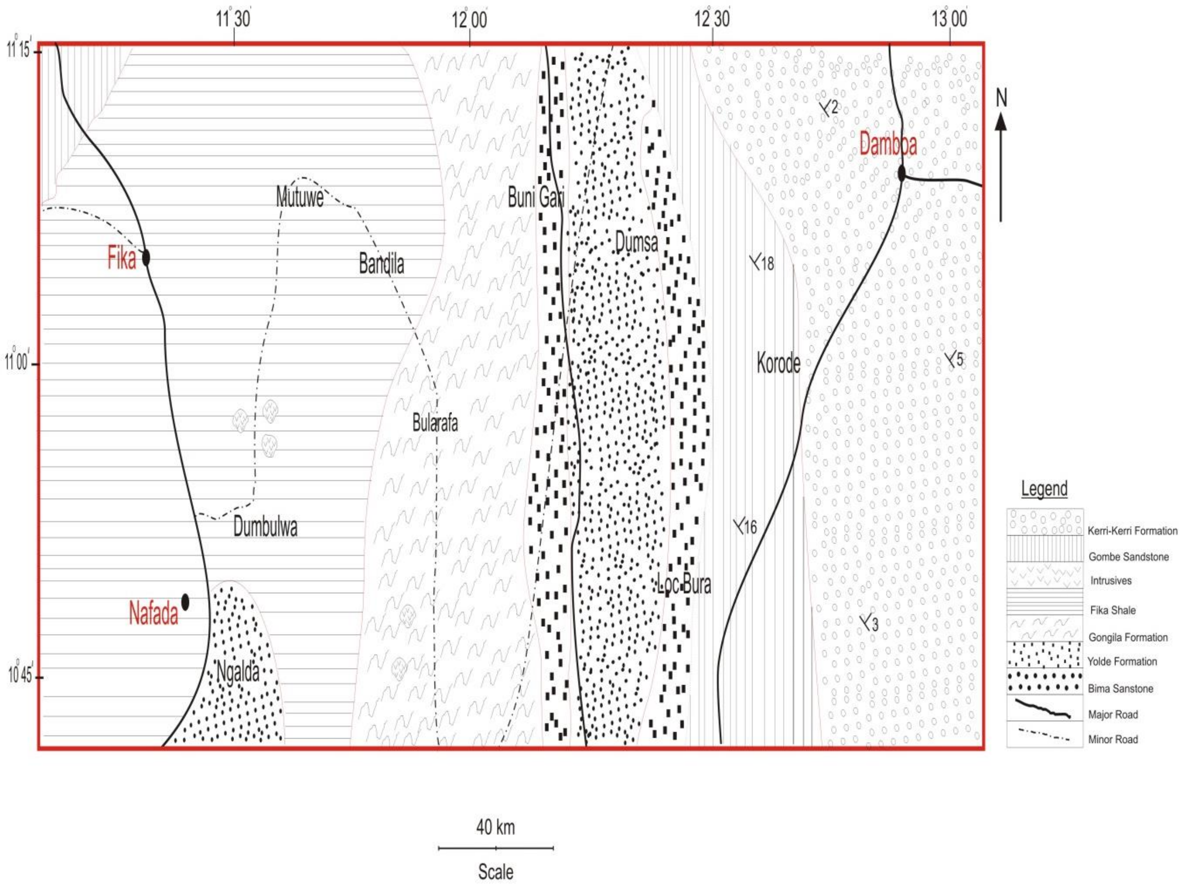

Fig 3: Geological map of the study area at the south western part of the Bornu Sub-Basin

Traversing commenced from the eastern fringe of the area around Maiduguri where the Chad Formation monotonously covered the surface. This is succeeded westwards by the Kerri Kerri Formation around Damboa, the Gombe Formation, Bima Formation, Fika Formation and the calcareous Gongila Formation.

Outcrops of volcanic intrusions of basaltic composition were observed along Mutwe-Dumbulwa road where a cut exposed it through the weaknesses of the surrounding Fika (Shale) Formation (Fig.4). Also sampled were from patches of plugs that have been extruded on to the surface. Ten subsurface samples were obtained from six wells across the three sub-basins. Two of the samples were obtained from the Gubio sub-basin from the Gubio and Ngamma wells. (Table1). The Maiduguri sub-basin has four samples, two each from Sa and Mbeji wells. Similarly, four samples, two each from Albarka and Mbeji wells were utilized in the Baga sub-basin.

Fig 4: Plate showing an outcrop of Fika Shale interstratified with volcanic intrusive Sills along Mutwe-Dumbulwa road.

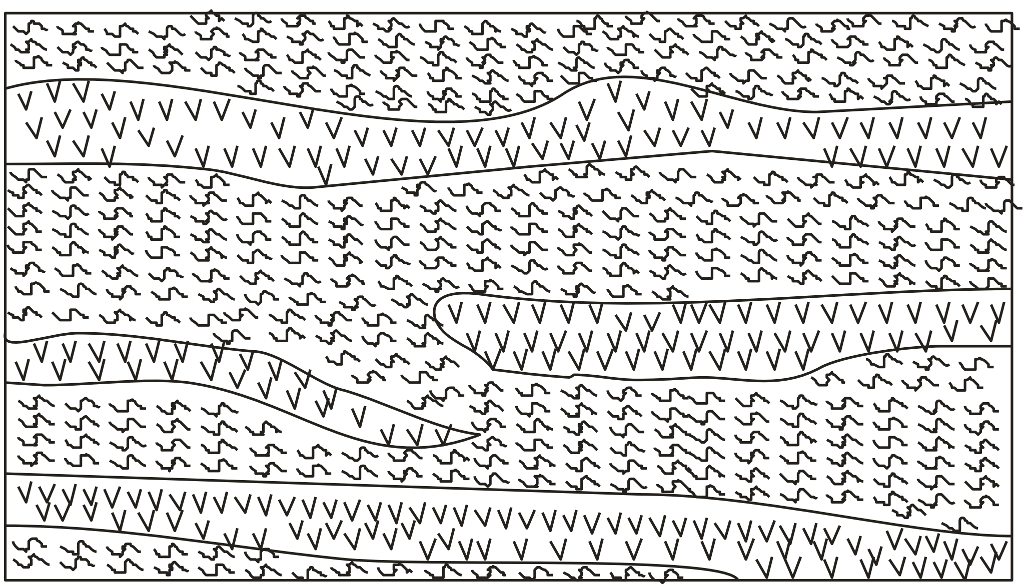

Fig 5: Sketch representation of an outcrop of Fika Shale interstratified with volcanics intrusive sills along Mutwe –Dumbulwa road

Most specimens examined are dark coloured, melanocratic and aphanetic in texture. These were also observed interstratified with sediments, mostly as sills which have permeated horizontally along the bedding/fissility planes. (Fig. 4) Parts of the intruded shale in contact with the intrusion appear darker and more compact, implying thermal effects .Upon close examination with the hand lens, the edges of the intrusion was observed to be texturally distinct with very fine grains.

Data of chemical analyses (Table 1) of the intrusive rock performed by comparing sodium and potassium oxides (After Cox *et al.*[58]) shows an intermediate composition. Thus acidity is not ascribed to these intrusives. The results of Alkali- Silica plot showing the sum of the oxides of Sodium and Potassium, which forms the total Alkalis on one hand and that of silicate on the other hand is presented below (Fig. 6).

[58] Cox K. G., Bell, J. D. and Pankhurst, R. J. (1999): The Interpretation of Igneous Rocks. Allen and Unwin, London. PP 450.

Table 1: Data of chemical analysis of outcrop and subsurface samples of intrusives

(*Outcrop samples are shown in Bold*)

S/N	Location of Sample	Coordinates	Sample Depth (m)	SiO_2	Al_2O_3	Fe_20_3	Mno	Mgo	Cao	Na_2o	K_2o	Tio_2	P_2o_5	Lio	Total
1	**Along Mutwe-Dumbulwa Rd**	**N 11^0 07.70' E 11^0 40.19'**	**0.00**	**49.3**	**13.75**	**11.99**	**0.146**	**8.63**	**8.61**	**2.91**	**0.95**	**2.039**	**0.39**	**2.15**	**100.9**
2	**Along Mutwe-Dumbulwa Rd**	**N 10^0 58.16' E 11^0 55.09'**	**0.00**	**47.62**	**15.06**	**13.12**	**0.370**	**5.83**	**7.72**	**2.85**	**1.36**	**2.215**	**0.55**	**3.49**	**100.2**
3	Gubio SW	N 12^0 26.4' E 12^0 42.0'	1170	47.19	17.74	10.26	0.148	3.32	2.32	1.27	0.95	1.339	0.30	14.8 8	99.45
4	Wadi	N 12^0 11.4' E 13^0 07.8'	1475	52.43	16.33	10.08	0.239	3.40	4.38	3.21	0.92	1.636	0.23	6.69	99.55
5	Wadi	N 12^0 11.4' E 13^0 07.8'	1480	52.51	16.52	9.54	0.109	3.23	4.87	4.07	0.76	1.751	0.24	6.28	99.89
6	Ngamma East	N 12^0 24.0' E 12^0 40.2'	1625	53.19	15.66	8.75	0.124	3.84	5.46	5.65	0.99	2.300	0.24	3.05	98.26
7	Sa	N 12^0 17.4' E 13^0 04.2'	1635	55.15	21.35	7.21	0.035	1.04	0.49	0.76	1.21	1.001	0.24	12.4 3	100.9
8	Sa	N 12^0 17.4' E 13^0 04.2'	1800	50.52	20.18	9.46	0.084	2.28	2.78	1.84	1.07	1.373	0.21	10.0 3	100.8
9	Albarka	N 13^0 14.4' E 13^0 47.4'	2340	44.87	12.70	11.21	0.140	10.8 3	6.87	2.79	0.80	1.944	0.37	7.45	99.98
10	Albarka	N 13^0 14.4' E 13^0 47.4'	2380	54.08	20.74	7.01	0.070	1.59	1.45	1.11	0.94	0.953	0.20	12.0 0	100.1
11	Mbeji	N 13^0 22.2' E 13^0 49.2'	2445	44.16	13.98	10.37	0.132	9.43	6.97	2.85	0.25	1.000	0.13	7.96	97.23
12	Mbeji	N 13^0 22.2' E 13^0 49.2'	2540	49.18	18.91	10.45	0.123	5.43	3.19	1.64	0.71	1.157	0.18	9.00	99.98

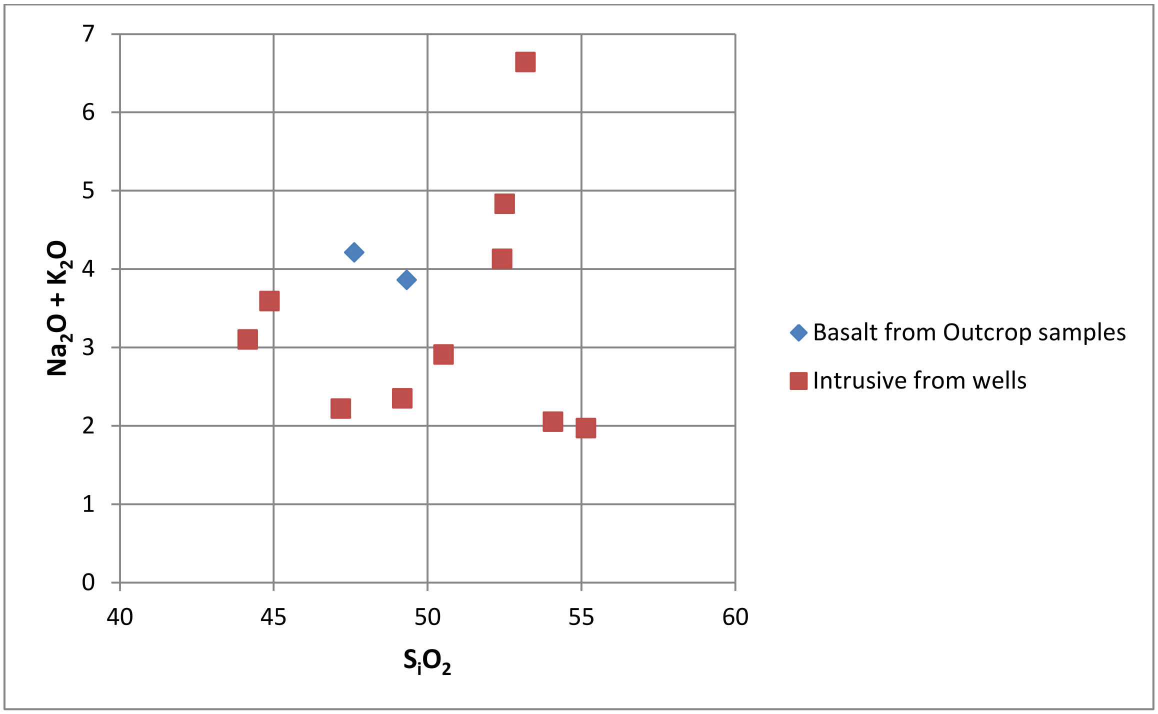

Fig. 6: Nomenclature of intrusive igneous rocks of the Bornu sub-basin using total alkalis versus silica (After Cox *et al*.[59]).

Discussion

Various magmatic processes could inject magma into the Cretaceous sequences of the Chad Basin, as has been observed by various authors, and numerous geological explorations demonstrate that magmatic intrusions may increase the geothermal gradient in sedimentary basins, accelerating the thermal maturation of organic matter in strata, and promoting the hydrocarbon generation[60,61]. They may also be beneficial to the migration and accumulation of oil and gas by providing them with pathways, reservoirs, covering conditions and trapping constructions[62,63,64,65,66]. Much of the existing research on thermal effects of intrusive activity in

59 Ibid

60 Fjeldskaar W, Helset H M, Johansen H (2008): Thermal modeling of magmatic intrusions in the Gjallar Ridge, Norwegian Sea: implications for vitrinite reflectance and hydrocarbon maturation [J]. Basin Research. Vol. 20, PP. 143-159.

61 Jones S F, Wielens H, Williamson M C, Zentilli M. (2007): Impact of magmatism on petroleum systems in the Sverdrup Basin, Canadian Arctic Islands, Nunavut: A numerical modeling study .Journal of Petroleum Geology, 30 (3): 237-255.

62 Feng, Q. and Tang, X. (1997): Magma activity's influence on conditions forming oil and gas pools[J]. Geological Science and Technology Information (In Chinese with English abstract), 1997, 16(4): PP. 59-65.

63 Li Y. (2000): Diabase and hydrocarb on reservoir formation on the northern slope of Gaoyou sag [J]. Journal of Geomechanics (In Chinese with English abstract), 6(2): PP. 17-22.

64 Othman R and Ward C R. (2002): Thermal maturation pattern in the southern Bowen, northern Gunnedah and Surat Basins, northern New South Wales, Australia. International Journal of Coal Geology, 51: PP. 145-167.

petroliferous basins has focused on the direct interactions between igneous intrusions and source rock facies. This is in an attempt to predict their impact on maturation or over maturation[67].

Hubred[68] has postulated that sills and dykes can locally mature source rocks,increase biomarker ratio in extractable compounds and at the same time induce systematic increases in the parameters of kerogen maturation. This is consistent with Planke *et al***.**[69] and Holford *et al.*[70]who put forward from their studies that intrusive volcanic activity can have a major impact on basin history and petroleum systems of sedimentary basins.

Thus, the deformations,uplift and heating associated with intrusives can impact upon source rock maturation,migration pathway, trap/seal formation and even reservoir quality. Peters and Ekweozor[71] in their study of the source rock potentials of the Bornu Sub-basin indicated that surficial areas of the Fika Shale might have been matured owing to the intrusion of basaltic rocks onto its horizons

Although this work focused on the edges of the basin and found the volcanics described above, various other studies have reported the occurrence of intrusives, towards the centre of the basin by using direct and indirect evidences. Avbobvo *et al.*[72] has postulated from seismic interpretations that transpar**e**nt intrusive bodies are virtually restricted to the cretaceous sediment and geographically limited to the deeper areas of the basin. The Fika Formation is intruded by dolerite sills[73,74]. Adekunle however reported the occurrence of diorite sills in several horizons of the Fika and Gongila Formations. Tmax values for the intervals 1700-2300m and 2700-3100m show a range of 430^0c-46^0c, a rather high gradient may be attributable to effects of possible

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65 Othman R, Arouri K R and Ward C R, (2001): Oil generation by igneous intrusions in the northern Gunnedah Basin, Australia. Organic Geochemistry, 32: PP. 1219-1232.

66 Wang Youxiao, Fan Pu and Cheng Xuehui, (1990): Abnormal geothermal influence on hydrocarbon genesis of sedimentary organics, Oil & Gas Geology (In Chinese with English abstract), 11(1): PP. 73-77.

67 Schutter, S.R. (2003): Occurrences of hydrocarbon in and around igneous rocks. Geological society of London vol. 214 PP. 35-68.

68 Hubred, J.H. (2006): Thermal effects of Basltic sill emplacement in source rocks on maturation and hydrocarbon generation.

69 Planke, S., Malthe-Sorenssen, A. and Jamtveit, B. (1988): Volcanic development of the Western Australian continental margin and its implication for basin development. The Sed. Basins of western Australia. Proceedings of pet. Expt. of Soc. of Australia symposium. PP. 33-54.

70 Holford, S.P., Schofield, N., Macdonald, J.D. Duddy, I.R. and Green. P.F. (2012): Siesmic analysis of igneous systems in sedimentary Basins and their impacts on hydrocarbon prospectivity: examples from the southern Australian margin: the APPEA Journal vol. 52 PP. 52.

71 Peters, S.W. and Ekweozor, C.M. (1982): Petroleum geology of Benue Trough and southeastern vahd Basin. Nigeira. AAPG Bull., 66, PP. 1141-1149.

72 Avbovbo, A. A., Ayoola, E.O. and Osahon, G.A. (1986): Depositional and structural styles in Chad basin of northeastern Nigeria. AAPG Bull. Vol. 70/12. PP. 1787-1798.

73 Okosun, E.A. (1995): Review of the geology of the Bornu Basin. Journal of geology and mining vol. 31. PP. 113-172.

74 Alalade, B and Tyson, R.V. (2010): Hydrocarbon potential of the late cretaceous gongila and Fika formations, Bornu (Chad) Basin, NE Nigeria. Jounral of Petroleum geology vol. 33(4) PP. 339-354.

intrusives causing changes in geothermal gradient[75]. Also Vr values for kuchelli-1 ranges between 0.78-1.34 Vr around the depth intervals of 1500 – 3000m indicating the interval as within the oil generative window and perhaps enhanced by increased geothermal temperature due to intrusive volcanics. Thus the basicity of intrusives across the areas studied implies a common genetic setting and perhaps a common magma type, namely the Basic magma.

The porosity values derived for the Chad Basin wells in general ranges between 3 and 38%. However, an increased value for the Fika Shale in some of the wells suggests the effect of intrusion which might have also played a significant role in the brittle and soft nature of the Fika Shale. Adepelumi and Olayoriju[76] opined that this volcanic material inferred might have contributed to the conversion of the source rock, and in the process enhancing its potentials to be gas prone. Given that the injection of a magmatic material into overlying crustal layers of rocks is enhanced by the nature and fluidity of the rock material and that Basaltic magma magma injects and flows faster in mobility, the inference by Adeplumi and Olayoriju[76] might be attributed also to the impact of basic/ultra basic magmatic material, consistent with the results of this work.

Nwankwo and Ekine[77] used the variations in the computed geothermal gradient values of the Chad Basin and further observed from the analyses and interpretation of bottom hole temperature data for about 21oil wells that the gradient range from 3.0 to 4.4^{0}c /100m.This has been correlated to Tertiary intrusives prevalent in the basin, though the basin is rimmed by crystalline basement rock mainly of granitic and gneissic composition with some minor schists.

Obaje *et al.*[78] has reported that towards the end of the tertiary, and until recent times, widespread volcanic activities occurred in the southern and central parts of the Chad Basin. The Gongila Formation has also been inferred to have generated and expelled hydrocarbon by migration or vaporization due to the intrusive activity during tertiary to recent times[79,80]. It has also been observed from quantitative estimation of heat generation and flow for about 9 wells that the values are slightly higher than that obtains for normal sedimentary rocks. It was thus suggested to be a reflection of the influence of volcanic activity, widespread in the central and southern parts of the Bornu Sub-basin.

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75 Chaanda, M.S., Obaje, N.G., Lar, U.A. and Moumouni, A. (2007): Petroleum geochemistry of Kuchalli-1 in the Nigerian Sector of the Chad Basin. Continental Journal of earth science vol. 1. PP. 18-24.

76 Adepelumi, A.A. and Olayoriju, S.I. (2006): Source rock evaluation and petroleum system modeling of Chad Basin, NE Nigeria. AAPA Search and discovery article.

77 Nwankwo, C. and Ekine, A.S. (2009): Geothermal gradients in the Chad Basin, Nigeria. From bottom hole temperature logs. International journal of physical sciences vol. 4(12) PP. 777-783.

78 Obaje, N.G., Wehner, H., Scheeder, G., Abubakar, M.B. and Jauro, A., (2004): Hydrocarbon prospectivity of Nigeria's inland basins: From the view point of organic geochemistry and organic petrology. AAPG Bulletin, 88 (3), PP. 325-353.

79 Burke, K. (1976): The Chad Basin: An active intracontinental Basin. Tectonophysics vol. 36 PP. 197-206.

80 Avbovbo, A. A., Ayoola, E.O. and Osahon, G.A. (1986): Depositional and structural styles in Chad basin of northeastern Nigeria. AAPG Bull. Vol. 70/12. PP. 1787-1798.

Furthermore, the ubiquitous presence of intrusive bodies that are either doleritic or gabbroic has been delineated in the Bornu Basin by Carter *et al*,[81]; stratigraphically above Devonian source rocks during the penatecau magmatic event of the Triassic[82]. This gas been rimmed by crystalline basement rocks of granitic and gneissic composition. In the Salimoes
Basin, Brazil, sills and dykes were widespread and observed to have intruded.

Depths to the OGW observed for wells in the Maiduguri area are relatively shallow and this could reflect the influence of igneous sills. Alalade and Tyson[83]. Nwankwo *et al*[84] estimated from heat flow fluctuations in the Chad Basin in Nigeria using the gamma ray log that the responses indicate the dominance of Chad Formation but show little variations in the Fika Formation. They further noted that the resistivities in the Fika are generally low with high peaks in areas suspected to be associated with intrusives such that the base of the Gongila Formation is mostly recognized by an increase in gamma ray response as it passes into the Bima Formation.

In a similar vein, Nwankwo *et al.*[85] utilized heat flow along with gravity data to evaluate the petroleum potentials and prospects of the Chad Basin in Nigeria. They showed from gravity data that the undulations of the Bouguer gravity map may be attributed to the presence of intrusive rocks and buried sills.

One major challenge that may be associated with exploration for hydrocarbons in the Nigerian sector of the Chad Basin is the presence of intrusive bodies of igneous origin in most of the wells drilled as reported by Nwazeapu[86]. Furthermore the prevalence of Tertiary intrusives in the southern Chad Basin may be linked to the variation in the geothermal gradient[87].

It is apparent from this work that volcanic intrusives are in occurrence in the Bornu sub-basin and are fairly distributed Most are basaltic sills emanating from dykes and observable as weathered plugs on the surfaces of the Fika and Gongila Formations This could have formed through the injection of magmatic material of basic composition perhaps from the Biu volcanic province. The generally low viscosity associated with the fluidal basaltic magma could have enhanced the thermodynamic conditions of extrusion. The soft nature of the Fika Shale coupled

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[82] Wanderly, F.J.R., Evras, J.F., and Vaz, P.T. (2007): Bacias de solimoes-carta Estratigrafica: Revista de Geosciencias de petrobras vol. 15/2 PP. 217-225.

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with fractures developed due to shrinkages in fabric of the Shale has further facilitated the extrusion onto the surface. Calcareous rocks of the Gongila Formation could have developed solution fractures to provide weak routes of passage. Elsewhere, volcanics of doleritic and dioritic compositions is assumed to have originated from magmatic source of intermediate to ultrabasic compositions.

In the central parts of the sub-basin, vertically alligned fractures might have played significant roles in the injection of magmatic material from subsurface spots underlying such zones.It is improbable that the tertiary volcanic events that formed the Biu volcanic province be linked to the sills located hunderds of kilometers at the central part of the sub-basin. Further, heterogeneities in the fabric of rocks across the basin might hinder such huge lateral movements of magmatic material.

Intrusive sills may locally impact negatively on the reservoir quality of the host rock successions, although forced folding, which is associated with sill emplacement in the shallow subsurface, can result in the formation of viable hydrocarbon traps e.g in the Niger Delta oil field, a 10m thick of sill serve as a seal for the accumulation of hydrocarbon. Wells have been drilled below the intrusive to tap the hydrocarbon.

However, igneous intrusives could have a degradational effect on petroleum pools if it occurs after migration[88].Also structural folding of sedimentary sequences if due to magmatic intrusives can lead to degradation or cracking of existing pools. Igneous intrusives could have also caused a remigration or outright degradation of hydrocarbon pools to gas, carbon or graphitic residue.

Therefore, understanding the geometry and evolution of sub-volcanic intrusive networks in volcanogenic basins is thus of interest to the petroleum geologist[89]. Several important studies on the consequences of basaltic intrusions into ancient sediments[90, 91] have revealed that sediments and magmatic rocks were strongly affected later by the overburden pressure of overlying deposits and often by folding and faulting.

Many prospective basins in rifted continental margins including those located along the western Australian continental margins contain extrusive and intrusive rocks generated during rifting and especially during continental breakup.Intrusive igneous systems in basins of rifted margins are typically characterised by networks of interconnected laterally and vertically extensive sheet complexes of sills and dykes that transgress basin stratigraphy. The presence of igneous intrusions thus signify an important geological risk in the exploration of

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hydrocarbon.Constraining the distribution,timing and the intrusive mechanism of the igneous rocks is essential to reduction of exploration risk.According to Fjeldskar *et al.*,[92], two main risks associated with intrusion of igneous rocks into sedimentary basins are the compartmentalization of significant volumes of source and reservoir rocks with consequent reduction of migration efficiency and that igneous related hydrothermal circulation systems can be highly mineralising and detrimental to reservoir quality.It may also be highlighted as implied severally earlier that igneous rocks and its products maybe beneficial to petroleum systems viz the thermal effects of igneous intrusions may in some cases be sufficient to adequately place immature source rocks within the oil generative window.

Total Alkali-Silica diagram(Fig. 6) is considered one of the most useful classification schemes in use for volcanic rocks .The sum of the Na_2O_2 and K_2O constituting the total Alkalis and the SiO_2 were plotted. The plots defined mostly Basalts as basic volcanic rock, with some contributions from ultra basic and intermediate rocks.

Conclusion

In the Bornu Sub-basin, intrusive sills and plugs occur interstratified within Cretaceous sediments, particularly the Fika and Gongila Formations. The emplacement of such shallow level intrusions may impact significantly on the petroleum systems of the sub-basin. These may increase the geothermal gradient, accelerating thermal maturation and promoting hydrocarbon generation. Forced folding associated with sill emplacement in the shallow subsurface around the Gombe Sandstone could have enhanced the formation of a viable hydrocarbon trap. However, the intrusives might also have led to thermal degradation where excess heat impacts upon organic matter transformation in source rocks. Furthermore, increased magmatism of the tertiary may have degraded the petrophysical qualities of the Bima, Gombe and Gongila Sandstones, which are otherwise promising as reservoirs.

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