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Environment of ore formation and anchizonal metamorphism in Pb-Zn-fluorite-barite deposits of the Benue Trough, Nigeria

Samuel O. Akande,[1] Andreas Hoffknecht[2] & Bernd-D. Erdtmann[2]
[1] *Department of Geology and Mineral Sciences, University of Ilorin, P.M.B. 1515, Ilorin, Nigeria;*
[2] *Technische Universität Berlin, Institut für Geologie und Paläontologie, Sekr. ACK. 14, Ackerstraße 71–76, D-1000 Berlin 65, Germany*

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Abstract

Lead-zinc-fluorite-barite vein ore-bodies occur in the Benue Trough within the Lower Cretaceous (Albian) sequence of this intracontinental rift structure. The veins are distributed in a series of N/S and NW/SE fracture systems cross-cutting the Trough axis. Ore-hosting sediments range from deep marine carbonaceous shale in the lower Benue area to platform carbonates (middle Benue) and fluvial to deltaic sandstones in the upper Benue area. These sediments are invaded by mafic to felsic intrusives which are either pre or post-ore.

Fluid-inclusion temperatures of vein minerals range from about 105° C to over 200° C and ore-fluid salinities vary from 14 to 25 equivalent weight % NaCl. Reflectance (Rm) of finely dispersed vitrinite in the ore-hosting sediments reaches up to 4.3% at vein centres in the lower Benue, decreasing to ca. 2.6% at about 2 km from known veins. In the middle Benue, Rm values vary from 0.9 to 1.7%. This suggests that ore-hosting shales in the lower Benue are slightly metamorphosed having been heated to an estimated temperature of about 240° C before the Santonian peak of tectonism. Illite-crystallinity indices on these shales in places suggest anchi to epimetamorphic contact aureoles adjacent to intrusive bodies.

Our data suggest that the Benue ore-bodies were formed by hot, evaporitic, basinal brines set into motion by the high geothermal gradient accompanying continental rifting. Anchimetamorphic conditions were reached in shales of the lower Benue area where the largest ore-bodies occur.

Introduction

The Benue Trough of Nigeria is an intracratonic rift structure which extends from the northern limit of the Niger delta to the southern margin of the Chad basin (Benkhelil 1982). It is partitioned geographically into the lower, middle and upper Benue Trough from the southern Ishiagu to the northern Gombe-Zurak districts (Fig. 1). The Trough is believed to have formed as a result of the Early Cretaceous continental rifting and opening of the Atlantic Ocean (Grant 1971). Its evolution is described by several authors, following the geosynclinal hypothesis of King (1950), the graben model of Stonely (1966), the spreading ridge hypothesis (Burke et al., 1970) and the aulacogen model of Olade (1976). The rift model has been supported by geophysical data obtained in the last two decades (Cratchley and Jones 1965; Adighije 1976; Ofoegbu 1984). Most recently, structural studies by Benkhelil (1982, 1987, 1989) suggest that sinistral wrenching was a dominant tectonic process re-

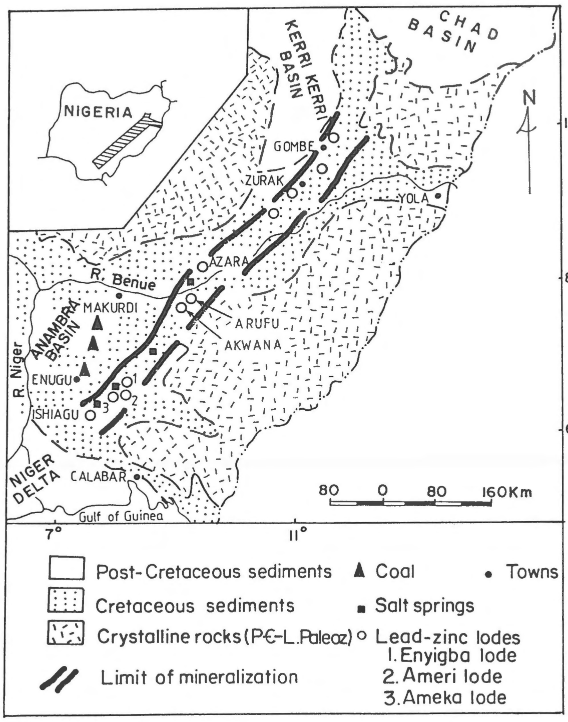


Fig. 1. Regional geological setting of the Benue Trough based on the map of the Geological Survey of Nigeria (1974). Inset shows the position of the Trough in the eastern part of Nigeria.

sponsible for the structural arrangement and geometry of the sub-basins in the lower, middle and upper Benue regions.

The Benue Trough contains more than 5000 m of Cretaceous sediments with concentrations of mafic to felsic dykes, sills and extrusives and of important lead-zinc-barite-fluorite mineralization in the gently folded Albian sediments exposed on its axis. Mineralization occurs as fracture-controlled bodies in the lower, middle and upper Benue areas (Fig. 1). These ore-bodies have produced concentrates of lead and zinc metal intermittently since the beginning of this century. Unfortunately, production records are not available and reserve estimates are lacking. Mining records between 1946 and 1974 put total production at 14000 tons of lead and 5000 tons of zinc, mostly from the lower Benue veins.

Recent exploration assessments by the Nigerian Mining Corporation put barite reserves in the middle Benue as 700,000 tons and efforts are being made to estimate tonnages of the larger lead-zinc veins in the lower Benue.

Among the important features which can aid current exploration efforts are the controls of mineralization, the environment of ore formation, the nature of the ore-forming fluids and the ore-host relationships in the different parts of the Trough. We have carried out geological, fluid-inclusion and vitrinite-reflectance studies of the ores and host sediments in the Trough in order to document and characterize the ore-forming environments. The objective is to derive a geological model that can guide exploration efforts in the light of these parameters. This paper describes the depositional environments of the ore-hosting sediments, the ore-mineralogical associations and the textures of these associations. Temperatures of ore formation are deduced from mineralogical-textural, fluid-inclusion, stable-isotope and vitrinite-reflectance data and a regional synthesis of the ore-forming environment is presented.

Regional stratigraphic setting

The origin of the Benue Trough reflects basement fragmentation, subsidence and rifting during the Early Cretaceous continental separation of Africa and South America (Grant 1971; Burke and Whiteman 1973; Olade 1976). Sinistral wrenching and en-echelon development of sub-basins along transcurrent faults was recently proposed as the mechanism for the Trough evolution (Benkhelil 1982, 1989). The resulting sub-basins are filled with more than 5000 m-thick Cretaceous sediments from the Aptian to Maastrichtian while Tertiary sediments are restricted to the Niger delta in the southwest and the Chad basin in the northeast.

At the onset, continental sediments, mostly siltstones and arkosic sandstones, of possibly Aptian age were deposited unconformably over the gneisses, schists and migmatites of the Pre-Cambrian to Lower Paleozoic basement complex. The continental sediments, recorded mostly in the upper Benue sub-basins, are overlain by the first cycle of marine sediments of the Albian transgression (Allix et al. 1981). This succession, the Asu River

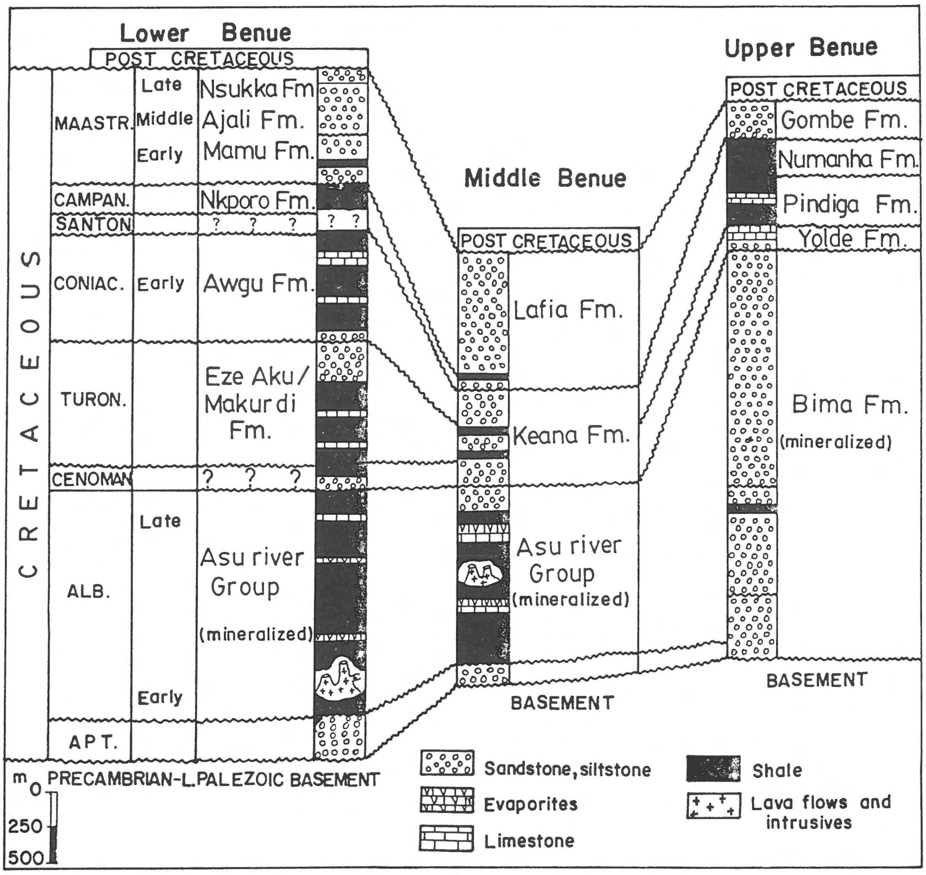


Fig. 2. Generalized Cretaceous stratigraphy in the lower, middle and upper Benue Trough; simplified from Reyment (1965).

Group, consists of about 2000 m of shale, siltstone and limestone and of lavaflows, dykes and sills which are also known to be of Albian age (Reyment 1965) (Fig. 2). It is moreover intruded by Cenomanian and Santonian dykes and sills. It is well developed throughout the Trough and generally crops out in the core of anticlinal structures e.g. the Abakaliki anticline in the lower Benue axis. Shales of the Asu River Group host the lead-zinc veins in the lower Benue area whereas their limestone and sandstone equivalents are hosts for fluorite-barite veins with or without lead and zinc in the middle and upper Benue areas.

The Cenomanian was a period of uplift and non-deposition in most parts of the Trough except on the south-eastern Calabar flank. At this time, the Albian sediments in the Trough axis were slightly deformed, fractured, brecciated and intruded by mafic dykes and sills (Nwachukwu 1972, Benkhelil 1989). In the Turonian, the Asu River Group was covered by sediments of the Eze Aku Formation as a result of renewed transgression. This formation consists of black carbonaceous shales, of limestone and of siltstone which grades into sandstone, e.g. the Makurdi and Keana sandstone formations in the lower and middle Benue areas respectively. The transgression maximum of the Turonian led to the linkage of the Gulf of Guinea with Tethys water across the Sahara, the Niger and the Lake Chad basins (Benkhelil 1989). Several sequences of shales were deposited in the lower Benue from the end of the Turonian to the Campanian (Fig. 2). Shallower seas in the upper Benue deposited the limestone and shale successions of the Pindiga and Numanha Formations at about the same period (Allix 1983). The stratigraphic record suggests that the peak of the transgression at the end of the Turonian was succeeded by a Coniacian regression when the sea withdrew from most parts of the Trough.

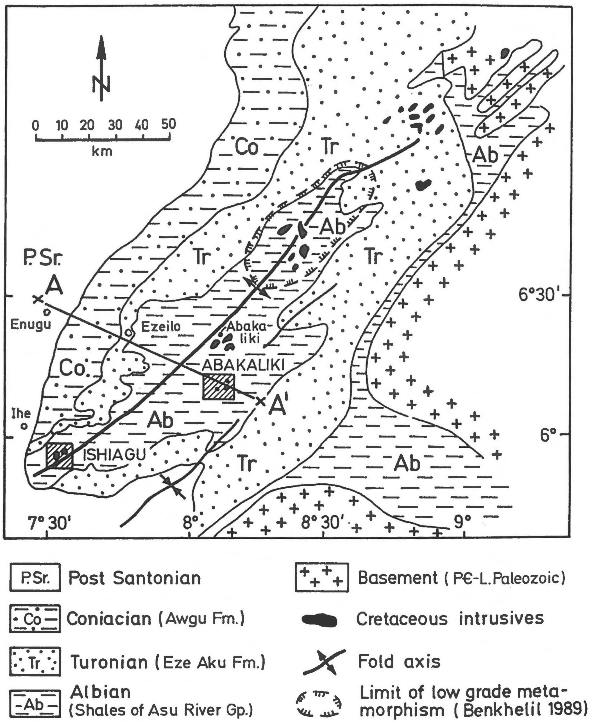
A major Santonian tectonism affected the Albian to Coniacian sediments, producing numerous folds, faults and fractures. This was accompanied by mafic to intermediate volcanic activity which led to the emplacement of dykes, sills, lavas and tuffs (Short and Stäuble 1967, Murat 1972, Benkhelil 1989). The same tectonic event appears to have deformed the Benue ore-bodies. Subsequently, most parts of the lower and middle Benue Trough were uplifted and considerable amounts of sediments (at least 1000 m) were eroded (Agagu & Adighije 1983). Sedimentation during the Campanian and Maastrichtian was dominantly continental to shallow marine in the sub-basins of the Benue Trough (e.g. the Anambra sub-basin). Tertiary and Quaternary sediments are confined to the southern Niger delta and the northern Chad and Kerikeri basins (Fig. 1). Sediment thicknesses of up to 12,000 m comprising the Cretaceous, Tertiary and Quaternary have been recorded in the modern Niger delta (Agagu & Adighije 1983).

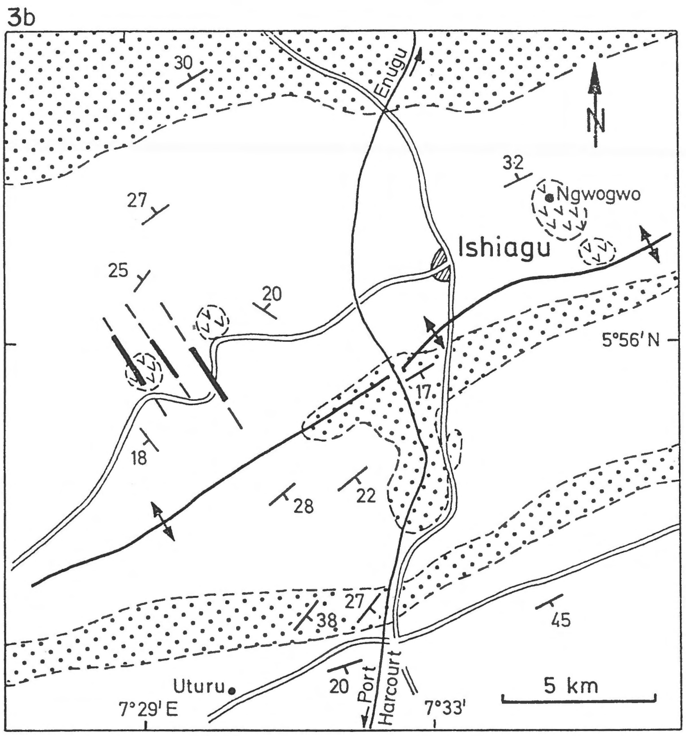
Mineralization

Ore-bodies of lead-zinc, fluorite or barite occur in the lower, middle and upper Benue areas as discordant, fracture-controlled veins in the Albian Asu River Group sediments. Fault systems controlling these ores trend dominantly NW/SE, N/S and E/W and in the lower Benue they localized igneous intrusions.

Lower Benue veins

The largest ore-bodies in the Trough are distributed in the Abakaliki and Ishiagu districts on the main axis of a major anticlinal structure, the Abakaliki anticlinorium (Fig. 3A). Here, vein ore-bodies occur in gently dipping Albian carbonaceous shales of the Asu River Group (Figs 3B, 7). Mineralization is unknown in the overlying Turonian Eze Aku shale exposed in parts of the district. Vein ore-bodies are generally fillings of a series of steeply dipping, open fractures which cut the regional fold axis of the Abakaliki anticline (Fig. 3A). The veins generally trend N/S and NW/SE and have strike lengths between 30 and 120 m and in the Enyigba vein up to 2 km (Fig. 3C). Width of veins varies from 2 to 20 m. At Ishiagu (Fig. 3B), altered diorite intrusive bodies are cut by mineralized veins within a similar fracture system. This suggests that some of the earlier (Albian) mafic intrusions predate mineralization. Indeed, mineralized veins cutting through porphyritic diorite have been encountered in the Onuahia and Ajirija-Ihietutu hills near Ishiagu. On the other hand, some of the dykes and sills dilate the ore bodies in part of the Ishiagu open pit. Vein-wall rock contacts here are sharp and commonly brecciated. The average ore grade is about 12% combined Pb + Zn with a Pb/Zn ratio of approximately 2:1. Fluorite and barite are absent. Vein constituents in this part of the Trough include siderite, galena, sphalerite, marcasite, chalcopyrite, bornite, enargite and quartz. Ore constituents are massive and highly recrystallized. In many instances, the shale host to veins is slickensided, fractured and brecciated. Brecciated shale fragments are cemented together by anastomosing veins of siderite, especially along the vein walls and siderite in turn is commonly cemented by massive sphalerite. Sphalerite and galena (the major vein constituents) are generally coarse crystalline, exhibit triple-junction configuration and may contain inclusions of pyrite and chalcopyrite. In the Enyigba vein (the largest ore-body) sphalerite and galena are commonly associated with chalcopyrite, highly twinned bornite, enargite, chalcosite, digenite, tennantite-tetrahedrite, bournonite, boulangerite and a variety of bismuth-bearing copper sulphide minerals. These copper sulphide ores and the associated sulphosalts occur as intergrowths in close spatial associations with sphalerite and galena suggesting a genetic relationship. The sulphide minerals are oxidized near the surface and covered by smithsonite, cerussite, malachite, anglesite, and azurite. The sequence of events, deduced from the cross-cutting relationships in the vein and wall rock, suggests near-vertical faulting, breccia for-





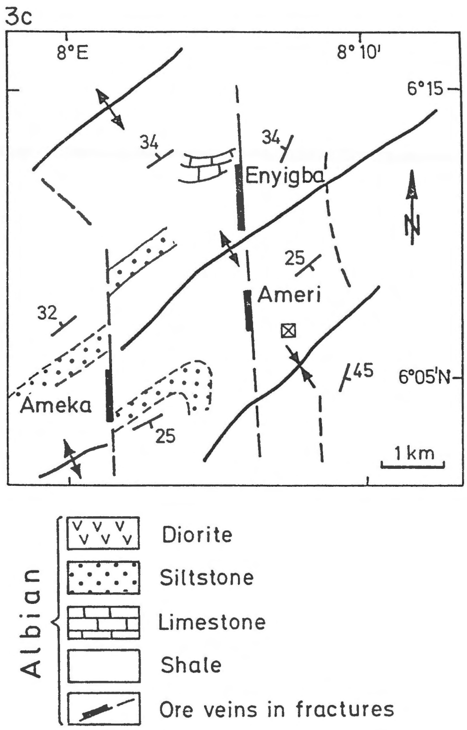


Fig. 3. (A); Geological setting in the lower Benue showing the position of the Abakaliki and Ishiagu Pb-Zn districts (Figs. 3B, C), the limit of low-grade metamorphism defined in Benkhelil (1989) and the line of section A-A' in Fig. 7.
(B); Local geology and vein distribution in the Ishiagu district.
(C); Local geology and vein distribution in the Abakaliki district. Note the Enyigba, Ameri and Ameka veins.

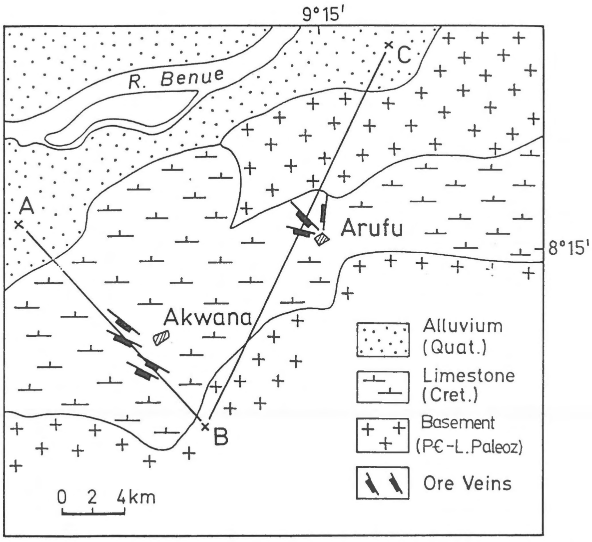


Fig. 4. Geological setting of the middle Benue area showing the distribution of the Arufu and Akwana veins. A-B-C is line of section for Fig. 8.

mation and the initial cementation of the shale fragments by siderite-rich ore fluid. This was succeeded by the formation of pyrite and quartz, the formation of sphalerite, galena, chalcopyrite, bornite and tetrahedrite and late-stage marcasite. Near-surface weathering of the ore-stage sulphides led to the formation of malachite, azurite, anglesite, cerussite and smithsonite as coatings on the primary vein constituents (Akande & Mucke 1989).

Middle Benue veins

The Arufu and Akwana veins are hosted in the Albian Arufu limestone (Fig. 4) and the barite veins at Azara in arkosic sandstone. Both sequences are lateral equivalents of the Albian Asu River Group (Reyment 1965, Ofodile 1975). Unlike the thick sequences of shales in the lower Benue axis, the Arufu limestone and the sandstone equivalent in the middle Benue area were deposited on the margins of the Trough. Limestone lithologies at Arufu and Akwana include recrystallized micrite, peloidal wackestone, oncoidal packstone, oolitic grainstone and breccia. Porosity types in these lithologies include interstitial, intragranular, sheltered, moldic, vuggy and channel types. Vein constituents are in places distributed within these porosities. We interpret the carbonate lithologies as platform deposits formed in shallow water environments ranging from shoals through restricted lagoons. Both the Arufu limestones and the sandstones were potential Albian aquifers (in the middle Benue). Filled primary porosity in the limestone is approximately 10%.

Vein ore-bodies in the middle Benue are generally very steep, having widths of 0,5–10 m and lengths of approximately 100 m along strike. Contacts with wall rock are sharp and ore grades vary between 3 and 5% combined lead and zinc. Vein constituents include galena, sphalerite, tetrahedrite, and occasionally native silver. These minerals are contained in a gangue of fluorite, quartz and calcite representing up to 95% of the constituents. At Azara, barite is the primary vein constituent in a gangue of siderite. The massive barite ore is highly recrystallized and may occur as lath-shaped crystals in fracture-related vugs.

The limestone wall rock at Arufu and Akwana is highly silicified and this alteration appears to be related to mineralization. The intensity of alteration diminishes at ca. 20 m away from the veins (Akande et al. 1988). Paragenetic relationships suggest pre-ore silicification of limestone and growth of marcasite and calcite, ore-stage precipitation of barite, fluorite, quartz, calcite, sphalerite, galena, chalcopyrite, tetrahedrite and native silver and finally post-ore weathering of the primary sulphide minerals into malachite, limonite, smithsonite and pyromorphite (Akande et al. 1988).

Upper Benue veins

The Gombe and Zurak veins are hosted in the Bima sandstones. The Bima Formation is a lateral equivalent of the Albian Asu River Group (Reyment 1965). It consists of cross-bedded sandstone and siltstone sequences overlying the basement. Vein ore-bodies were worked intermittently at Zurak for lead-zinc and silver since the early part of this century. The veins are generally N/S trending, having widths between 1 and 3 m and lengths of approximately 60 m along strike. They generally have sharp wall rock contacts and ore grades vary between 5 and 9% combined lead and zinc.

Ore minerals include galena, sphalerite, hematite and native silver in quartz matrix. The ore minerals are frequently covered by cerussite and smithsonite as a result of near-surface weathering. Quartz veins with sub-economic concentrations of galena and hematite are common in the Bima sandstones in the Gombe and Zurak areas.

Geothermometry

Temperatures of the ore formation, the nature of the ore-forming fluid and thermal maturity levels of the ore-hosting sediments were determined by fluid-inclusion microthermometry of vein-mineral assemblages and by vitrinite-reflectance studies of finely dispersed vitrinite particles in the ore-hosting sediments.

i Fluid inclusion microthermometry

Experimental
Homogenization and melting temperatures were measured on more than 400 primary, pseudosecondary and secondary inclusions (> 5 μm in diameter) in sphalerite, quartz, calcite, fluorite and barite in the Benue veins. The measurements were done on doubly polished plates using a U.S.G.S. gas-flow heating-freezing stage and a calibrated Chaixmeca stage. The inclusions studied were selected based on the criteria and recommendations of Roedder (1976). Reproducibility is better than 1.5° C up to 300° C. The salinity data reported are based on the freezing-point depression in the H_2O-NaCl system (Porter et al. 1978).

Results
At Ishiagu, Enyigba and Ameri (lower Benue), homogenization temperatures (Th) of primary inclusions in sphalerite range from 104 to 172° C (average 141° C, Fig. 5). These temperatures overlap

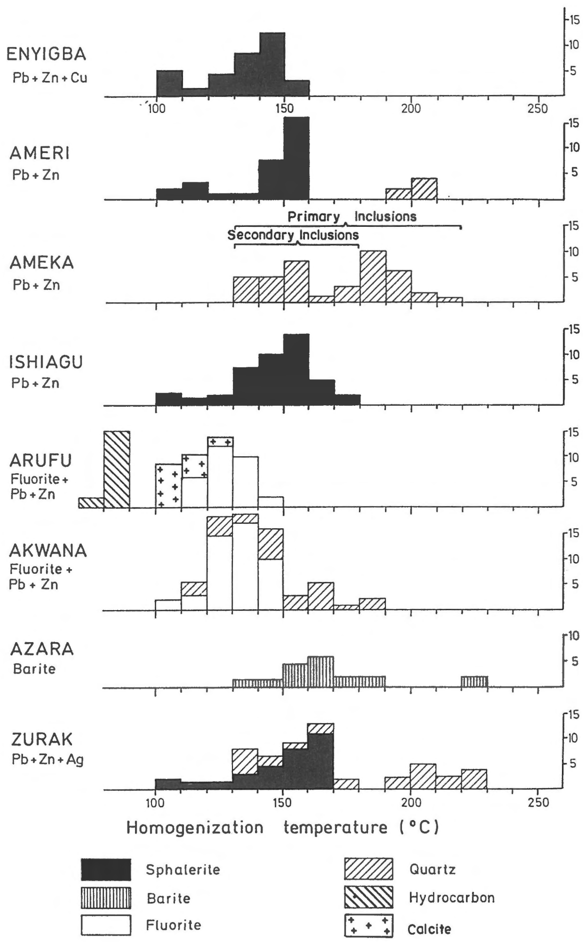


Fig. 5. Homogenization temperatures of fluid-inclusions from the Benue Trough vein minerals. Except where indicated otherwise, these measurements are from primary inclusions.

the 131 to 214° C field for the primary inclusions in quartz in the Ameka vein. However, secondary inclusions in this group of quartz homogenized from 130 to 172° C (average 147° C). During freezing, the Ishiagu, Enyigba and Ameri inclusions indicated salinities from 20.5 to 25 equivalent wt. percent NaCl.

At Arufu, Akwana and Azara (middle Benue) homogenization temperatures for primary inclusions in fluorite, calcite and barite range from 102 up to 229° C but secondary hydrocarbon inclusions in calcite (Arufu) homogenized at about 80° C (Fig. 5). Freezing experiments on the Arufu, Akwana and Azara inclusions indicated fluid salinities from 14 to 24 equivalent wt. percent NaCl.

At Zurak (upper Benue), primary inclusions homogenize between 105 to 167° C in sphalerite and from 131 to 224° C in quartz. Salinities between 16 and 20 equivalent wt. percent NaCl are indicated in this group of inclusions.

The low initial temperatures of ice melting (i.e. the eutectic temperature (Te-ice) of −41 to −62° C) in most of the inclusions suggest the presence of large amounts of $CaCl_2$ in the ore fluids. Depths of formation of the ore-bodies are poorly known. Stratigraphic information suggests about 1000 m minimum cover at the time of ore formation. A depth of formation of ca. 1 km would require a pressure correction of 30° C to be added to the homogenization temperature (Th) if the load was lithostatic. This will bring the ore-fluid maximum temperatures to ca. 244° C for the lower Benue veins, about 218° C in the Arufu-Akwana district (middle Benue), 259° C in Azara (middle Benue), and up to 254° C in the upper Benue veins if we consider the primary inclusions in the early vein minerals. These temperatures decrease through the paragenetic evolution of minerals in each district.

ii Organic maturity

Experimental

The maturation of organic matter, like fluid inclusions, can give indications of the conditions of burial metamorphism reached in sedimentary successions. Since vitrinite reflectance is not subjected to retrograde effects (Bostick 1973) we have integrated this tool in the present study.

Samples of Albian to Maastrichtian sediments were collected from mine workings, quarries and fresh outcrops. These extend from the western margin of the Trough to the central axis, where base-metal mineralization occurs.

The samples were crushed (<2 mm) and impregnated in epoxy and polished for quantitative reflected-light microscopy. Organic petrology studies were carried out on a REICHERT JUNG POLYVAR photo-microscope equipped with stabilized halogen and HBO lamps, a photomultiplier and a computer unit. Random reflectance (Rm) was measured on vitrinite using monochromatic (546 nm) nonpolarized light in conjunction with a 40 × Pol. oil immersion objective. The photomultiplier was calibrated with standards of known reflectance (1.23; 3.16; 7.47%). Data collection and evaluation was carried out using COAL-program by REICHERT JUNG. Macerals were identified using white light and blue light excitation at 546 nm and 460 nm respectively.

Results

Organic matter is comparatively sparse in the ore-hosting sediments of the Benue Trough although the black carbonaceous shales hosting the lower Benue veins contain a fair amount (averaging 3 vol. %). Most of the vitrinite reflectance data come from these ore-hosting shales. Nevertheless, some measurements were carried out in the middle Benue sediments and in a few Maastrichtian shales and coals from the western margin of the lower Benue area. The dispersed sedimentary organic matter generally consists of kerogen Type I, mainly alginite, kerogen Type III, huminite/vitrinite, and kerogen Type IV, i.e. inertinite. The coal contains high amounts of kerogen Type II, i.e. sporinite, cutinite, resinite and bituminite, but rarely kerogen Type I.

Lower Maastrichtian shales from Ihe on the western margin of the lower Benue (Fig. 3a) display the greatest variety of macerals. Rm 0.67% indicates low organic maturity equivalent to sub-bituminous A to high-volatile bituminous C rank of coal. The Lower Maastrichtian coal from Enugu does not exceed sub-bituminous A rank (Rm 0.55%). Fluorescence properties support the low maturity level evaluated from reflectance measurements. Alginite is the most common maceral in the shales. The bulk of this alginite consists of telalginite, i.e. the genus *Leiosphaeridia*. The accompanying constituents consist of small indeterminable fragments of porate and bacculate acritarchs. The alginites are thin-walled (<5 μm), lenticular in shape and commonly show internally folded cell walls. Under blue light excitation, they display yellow to yellow-orange fluorescence. The maximum intensity (I max) at 532–540 nm and the Red/Green

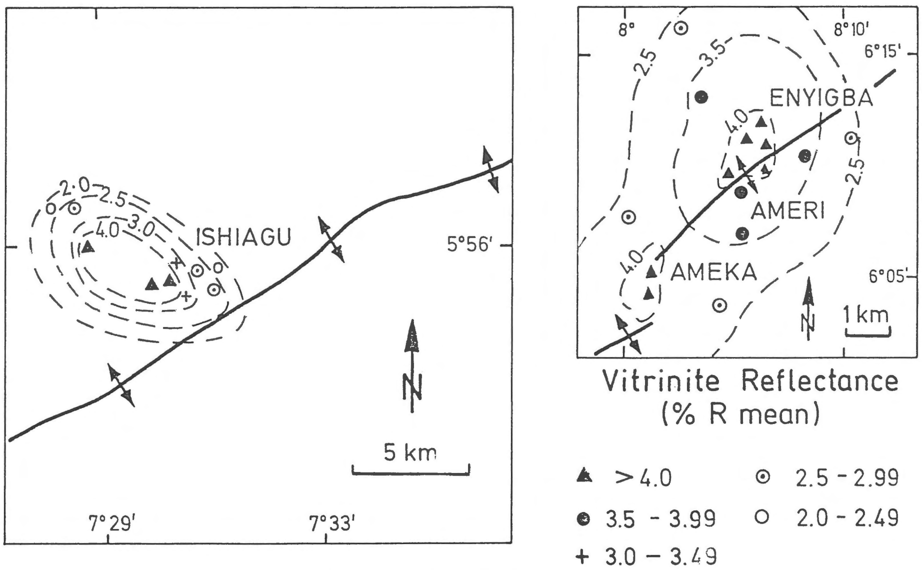


Fig. 6. Isoreflectance contours of vitrinite around the Ishiagu and Abakaliki vein ore-bodies (lower Benue).

quotient (Q) between 0.56–0.77 of the yellow fluorescence spectra are in good agreement with the average Rm 0.67% (Robert 1989). Pollen and spores are virtually absent. Homogeneous bituminites in the shale (bituminite II sensu Techmüller & Ottenjann 1977) are round or kidney-shaped and display a yellow-orange fluorescence. They are virtually transparent or display reddish colours in white light. Kerogen Type III and type IV consist of vitrinite, possibly bituminite III, semifusinite and fusinite. It is not always possible to distinguish clearly bituminite III from vitrinite and vitrinite from semifusinite. In these cases the result may be a broad scatter of reflectance values.

Turonian shales from Ezeilo (Fig. 3a) contain less liptinite than shales from Ihe. Bitumens are also rare whereas micrinite appears more frequently. Vitrinite reflectance (Rm) varies between 0.91 and 1.2%.

At Ishiagu, kerogen generally consists of finely dispersed vitrinite and in few cases of lenses and thin bands of vitrinite. The lenses and thin bands of vitrinite are partly replaced by carbonate. They may be more than 30 μm in length. Vitrinite particles range from 3–10 μm in width. Vitrinite reflectance varies from 2.46 to 4.27% Rm (Fig. 6). Reflectance values are comparatively uniform at the vein centres but they rapidly decrease with increasing distance. Bireflectance is very low. Fusinite is rare and only few vitrinitic macerals seem to originate from liptinite i.e. thin walled (< 1 μm) spherical macerals showing greater bireflectance than vitrinites.

At Enyigba and Ameri, vitrinite reflectance ranges from 2.66 to 4.31% whereas at Ameka Rm is between 2.83 to 4.37% (Fig. 6). Observed reflectance data from the exposed Cretaceous successions (NW/SE section) across the Abakaliki anticline indicate a consistent increase of vitrinite reflectance values from the younger Maastrichtian sequences, i.e. shales from Ihe and Ezeilo and coals from Enugu, to the older sequences exposed at the core of the anticline, i.e. the Albian shale (Fig. 7). Reflectance values of this section range from 0.45 on the Trough margin to 4.31% Rm at the anticlinal axis where most ore bodies and intrusives are concentrated. The high (> 4.0% Rm) values rapidly decrease to less than 3% Rm a few kilometres away from the ore bodies (Fig. 7).

Similar relations are observed in the middle Benue, although maturity levels are considerably lower and stratigraphic control is less precise than in the lower Benue. At Arufu and Akwana reflectance values increase towards the mineralizations.

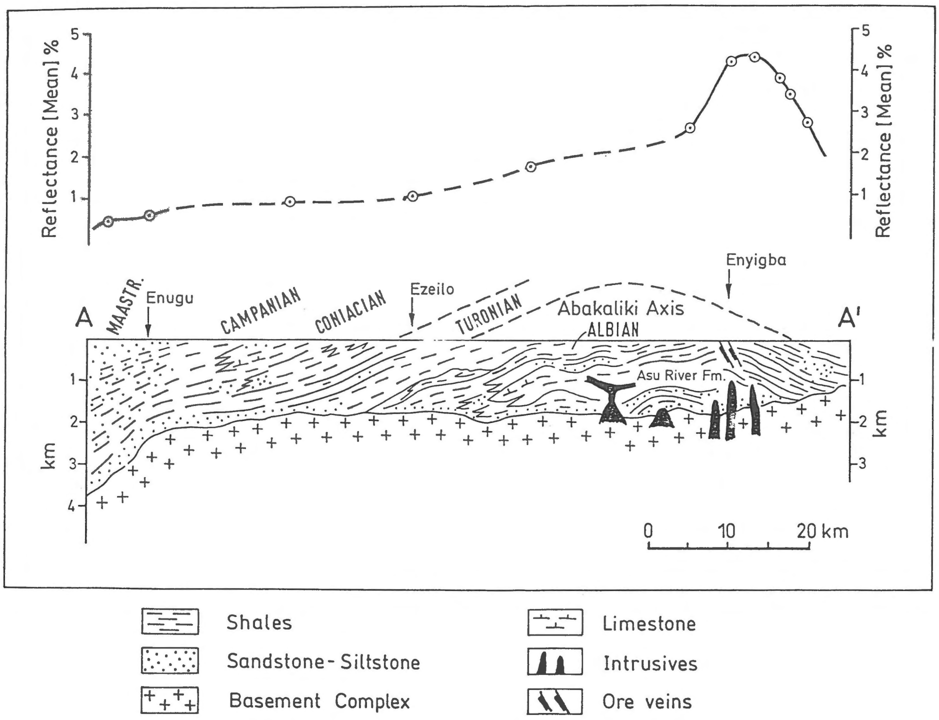


Fig. 7. Vitrinite reflectance distribution in section A-A' Enugu-Enyigba (lower Benue). Line of section as in Fig. 3A.

Ranges from 0.61 to 1.21% Rm (Arufu) and 0.85 to 1.96% Rm (Akwana) were measured within the ore-hosting sediments (Fig. 8); the higher values were reached near the vein centres.

iii Illite crystallinity studies on the Albian shale

The abundance of dykes, sills and lava flows within Albian sediments in the Benue Trough has led to low-grade metamorphic transformations of the ore-hosting sediments and their lateral equivalents, particularly in the lower Benue area. Studies of a NW/SE section across an intrusive body (the Workum syenite, 50 km NE of Abakaliki) indicate illite crystallinity index values from 1.5 to > 8 mm (Benkhelil 1987, 1989). Most of these values are between 2.5 and 4 mm and indicate anchimetamorphism. The onset of the anchi and epizone are put at ca. 4.0 mm and 2.5 mm respectively (Benkhelil 1987, Fig. 17). Some of the values are smaller than 2.5 mm and fall within the epizone. Illite crystallinity values are greater than 4 mm away from the intrusive body. From Benkhelil's pioneer study, an ellips-shaped area of low-grade metamorphism centred on the intrusive body was defined (Fig. 3a).

Mineralogical studies of schists/slates in the Workum area indicate the presence of andalusite porphyroblasts (chiastolite) around the intrusion and quartz, chlorite, calcite, muscovite and epidote as matrix components. The slates consist of cleavage-oriented chlorite porphyroblasts in some places (Benkhelil 1989). An earlier contact metamorphism (associated with the formation of andalusite) is dated as Albian (104 Ma) whereas the later low-grade regional metamorphism described as syntectonic was associated with the Santonian tectonic event. This is shown by a K/Ar date of 83 Ma on illite from the Workum hills (Benkhelil 1989).

Discussion and conclusions

Our study of the ores and host rocks and data from a number of temperature-measuring techniques,

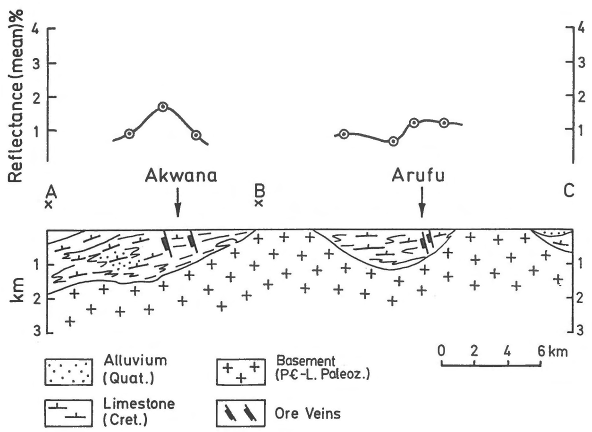


Fig. 8. Vitrinite reflectance values across the Akwana and Arufu vein ore-bodies (middle Benue). Line of section as in Fig. 4.

put constraints on the environment of the ore formation in the Benue Trough. The geotectonic framework of the Trough supports its evolution from mantle upwelling, doming, crustal thinning and rifting prior to the deposition of over 5000 m Cretaceous sediments in the Trough. The Benue mineralization was formed in faulted and folded Albian Asu River Group sediments and their equivalents in the different geographical regions. Depositional environments of the ore-hosting sediments range from deep marine carbonaceous shale sequences in the lower Benue, to shallow water platform carbonates in the middle Benue and fluvial to deltaic sandstone-siltstone in the upper Benue area. Geochronological data on the Benue intrusives (Benkhelil 1989) suggest that these sediments were affected by high heat flows during the period Albian to Santonian (30 Ma). The intrusive dykes and sills caused contact metamorphism of the Albian shales in the lower Benue (Benkhelil 1989). Recent magnetic surveys in the lower Benue indicate that the mineralized veins in the Abakaliki and Ishiagu districts are underlain by highly magnetic intrusive bodies (A. Sowa, personal communications). The anomalous fluid-inclusion maximum temperatures in excess of 200° C (after pressure correction) throughout the Trough and the elevated levels of organic maturity around and at the vein centres suggest that the veins were sites of thermal anomalies and anchizonal metamorphism during the mineralization event.

Organic maturity and illite crystallinity studies of Duba & Williams-Jones (1983) in southwestern Gaspe, Quebec, Canada, led to the recognition of a large paleothermal anomaly enclosing several sediment-hosted copper deposits. These authors suggest that the ore-hosting sediments in their study area underwent burial metamorphism to anchimetamorphic grade and the ore zones could be outlined on the basis of the vitrinite reflectance and illite crystallinity in the sedimentary successions. Our geothermometric and reflectance data are consistent with the illite crystallinity indices of Benkhelil (1989) for the lower Benue Trough area. The two sets of data suggest that the Benue thermal anomalies coincide with base-metal vein mineralization, intrusions and the major axis of the folding and cleavage development.

Textural and mineralogical studies of vein constituents indicate that the veins are deformed, brecciated and recrystallized with the development of strong inversion twinning in bornite. The deformation patterns observed lend credence to the Santonian deformation of the vein constituents. Strong inversion twinning in bornite in the Enyigba vein suggests a minimum temperature of ca. 225° C (A. Mucke, personal communication) during the recrystallization process.

The relatively uniform fluid-inclusion temperatures between 218–259° C in the vein centres throughout the Benue do not completely agree with vitrinite reflectance data patterns. During the Albian to Santonian (30 Ma) effective heating time, the ore-hosting sediments in the lower Benue would have been heated to temperatures between 200–240° C whereas the middle Benue lithologies would have been heated to only a maximum of 170° C on the basis of their respective maturation levels (using Karweil's (1956) diagram). Kisch (1987, Fig. 7.8) suggests that effective heating time necessary for the attainment of 'stabilization of rank' is likely to be longer for low than for high temperatures. This may indicate a short effective heating time for the lower Benue, perhaps 1 Ma. Ranks from the middle Benue would also require a relatively short effective heating time, if we consid-

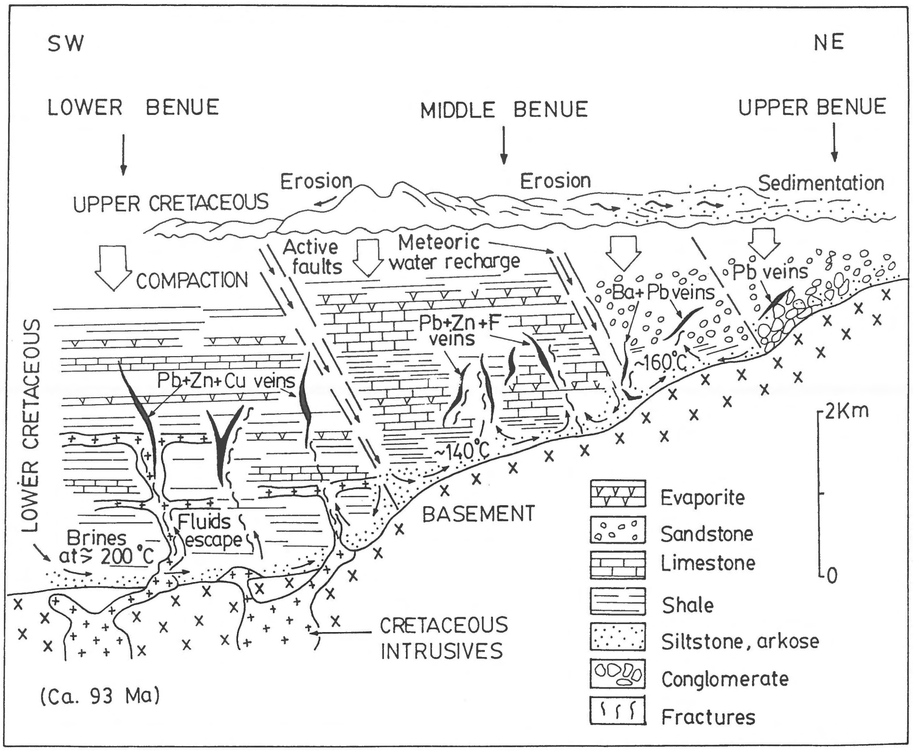


Fig. 9. Schematic representation of the basinal brine expulsion model for the Benue Trough mineralization. Pb-Zn-fluorite-barite veins were formed in near-vertical fractures from fluids driven by compaction and high geothermal gradient during the Cenomanian. Intrusives shown are Albian and Cenomanian. Santonian intrusions took place subsequently.

er the sediment temperature estimates as the maximum temperatures attained by the host rocks during ore formation. By applying Kisch's (1987) estimates of maximum temperature and time, we suggest that the Benue ores formed in a relatively short-lived (less than 2 Ma) event. Furthermore it is apparent that in the lower Benue high temperatures reigned over a longer time than in the middle Benue. This suggests a higher geothermal gradient in the lower Benue. Reflectance values of 2.46% Rm in the lower Benue ore-hosting shales indicate a maturity level which is in good agreement with fluid inclusion temperatures after pressure correction (ca. 244° C). If we follow Kisch (1987), who suggests temperatures in the range of 200–250° C and reflectance Rm of 2.3–3.1% for the onset of the anchizone, these shales, therefore, would have reached an anchimetamorphic grade at least at ca. 2 km from the veins. However, the high reflectance value (> 4% Rm) at the centres of the veins suggests considerably higher temperatures than those measured in the inclusion fluids. We suggest that the fluid-inclusion temperatures are averages of the minimum temperatures attained in the vein-forming environment.

Previous genetic models for the Benue ore fluids include magmatic hydrothermal origin (Farrington, 1952), formation from juvenile and connate brines (Ofodile, 1975), and circulating connate brine sources (Olade & Morton 1985). The close spatial association of igneous intrusions with most of the Benue veins and the fluid-inclusion and stable-isotope evidence led Akande et al. (1989) to favour the circulating brine model. However, the opening of new pits and quarries in the Ishiagu area, has provided evidence for the mutually crosscutting relationships of the ore bodies and intrusive wall rocks. Indeed the coincidence of thermal anomalies with base metal vein ores and exposed intrusives in the lower Benue suggests that igneous contributions to vein constituents cannot be completely ruled out (Fig. 9).

Recent observations in newly developed pits at Ishiagu show that faults similar to those which control diorite intrusives in the deposit localized the veins. We suggest that some of the vein components, especially the As, Cu, Bi contents of the sulphide minerals, may have been contributed to the ore solution, from deep-seated intrusive bodies whereas the basement rocks and their weathered equivalents appear to have contributed the principal metal ions in this solution (Maurin & Lancelot 1987, Akande et al. 1989). Sulphur-isotope equilibrium fractionation temperatures between coexisting sphalerite and galena (Enyigba vein) suggest a maximum value of 236° C for the ore fluid (Akande et al. 1989). This value is comparable with the maximum estimated temperatures to which the sediments in the lower Benue were heated. The sulphide minerals appear to have re-equilibrated during recrystallization and have therefore approached equilibrium conditions.

Although the tectonic framework and sedimentation history of the Benue Trough favour synsedimentary exhalative metal deposition when compared to other rift-related, giant base-metal deposits like Mt. Isa, Hilton and McArthur River in the Middle Proterozoic sequence of northern Australia, the Devonian Meggen deposit in the Rhenish Massif in Germany and the Lower Carboniferous Irish base-metal sulphide deposits (Navan, Tynagh, Silvermines; Russel et al. 1981, Russel 1983, Sawkins 1984), the Benue ores show no synsedimentary features and there is a general lack of stratiform mineralization. We postulate that the ore fluids are hot saline brines formed from the deeper, highly compacted parts of the Benue Trough, that were expelled into fractures accompanying fluid overpressures. Brine movement under a high geothermal gradient could have been gravity driven (Garven & Freeze 1984 a, b) in response to the Early Cenomanian uplift in the Benue Trough.

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