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THE NATURE AND STRATIGRAPHIC SIGNIFICANCE OF ALBIAN PALEOKARST UNCONFORMITY, CALABAR FLANK, SOUTH-EASTERN NIGERIA.

ADEROGBA, ADEDOTUN ABAYOMI
Department of Geology, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria
Email: adedotun_aderogba@yahoo.com

ABSTRACT

At the top of Mfamosing Limestone is a major stratigraphic break which is a regionally widespread, mappable unconformity in Calabar Flank. This unconformity occurs between Albian Mfamosing Limestone and the overlying Cenomanian-Turonian Ekenkpon Shale. This unconformity developed on a shallow-marine shelf carbonate platform that strikes in a NW-SE direction in Calabar Flank. Deductions from petrographic studies show that during late-Albian sealevel lowstand, the carbonates were exposed to subaerial environments leading to the development of karst. This karst system is characterized by an irregular erosional surface, meter-size dissolution cavities, collapse breccias, sinkholes, boring and solution-enlarged, vertical joints. The strata closer to the unconformity have abundant intercrystalline and vug porosity while strata further away from the unconformity have only intercrystalline pores. Porosity and permeability enhancement occurs in areas where vugs are directly connected, and in areas where vugs connect through zones of solution-enlarged joints. The high depositional porosity which started the paragenesis was later replaced by meteoric calcite cement during karstification.

Key Words: *Diagenesis, Karstification, Porosity, Permeability, Reservoir Properties*

Introduction

This work is about the unconformity which separates the Mfamosing Limestone from the Ekenkpon Shale in the Calabar Flank. This unconformity is a regional erosional surface that formed as the Albian carbonates were subaerially exposed to oxidizing meteoric (freshwater) diagenesis during a relative sealevel fall. This paleokarst surface is part of a regionally extensive karst plain that formed on top of the Albian carbonates all around the paleo-Gulf of Guinea. Eustatic changes during this period caused subaerial erosion to occur, leading to the development of a spectrum of surface and subsurface karst features.

Features which demonstrate the subaerial nature of this paleokarst include: 1) a regionally widespread mappable unconformity; and 2) various subsurface solution features ranging from fossil molds, vugs, breccias, collapsed strata, solution-enlarged joints, small caves and internal sediments. These paleokarst features are more pronounced in strata close to this unconformity, and its effect decrease away from it. The Mfamosing paleokarst unconformity is well exposed in many localities in the Calabar Flank.

Geological Setting

During Cretaceous times, Calabar Flank was a shallow, southward-deepening stable shelf located at the southeastern end of the proto-Gulf of Guinea. The shape of this unique basin suggests that it must be connected with the Benue Trough and South Atlantic Ocean. The basin is characterized by crustal block faults trending in a NW-SE direction. This faulting system resulted in the formation of a horst and graben structure called the Itu High and Ikang Trough. The Ikang Trough was the site of clastic sedimentation while the Itu High was a stable carbonate platform [1].

The Calabar Flank displays a stratigraphic sequence that records progressive tectonic stages of a typical rifted continental margin. By early Cretaceous times (Neocomanian-Aptian) a small rift basin had evolved. Syn-rift fluvio-deltaic conglomerates and sandstones of the Awi Formation [2] occupy the structural lows within the rift system. The first marine transgression of the proto-South Atlantic began to invade the Calabar rift system during the Albian times. This initial transgression was gradual and slow, so that from mid-to-late Albian, a carbonate platform developed south of Oban Massif. Tectonic activities during the late Albian-early Cenomanian in the Benue Trough [3;4;5] and [6] together with the widening of the South Atlantic Ocean basin caused the carbonate platform to subside, and a sequence of argillaceous marine sediments of the Ekenkpon Shale to be deposited.

Stratigraphic Relationships between Mfamosing and Ekenkpon Formations

The Albian Mfamosing Limestone was deposited in warm, shallow, normal marine environments. The strata formed a narrow belt around the southern rims of the Oban Massif. Detailed outcrop examination shows that the depositional pattern is not completely homogenous but randomly heterogeneous along its entire depositional strike. At the type section of the formation near Mfamosing village, the thickness of the succession is about 50m [1].

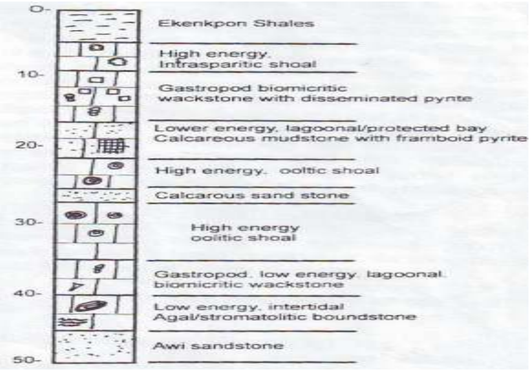

FIGURE 1: Stratigraphic section of the Mfamosing Limestone.

Sequence stratigraphic principles and models have been used to interpret the Mfamosing sedimentation. Important studies to date that used sequence stratigraphic terminology in the Calabar Flank to describe and interpret the depositional environments of the Mfamosing Limestone are those of Reijers and Petters, [1;7], Reijers, [8;9] and Aderogba, [10]. According to Reijers and Petters, [7] the Mfamosing strata started as an early aggradational sequence around the fringing of Oban Massif. The succession begins with the algal stromatolitic boundstones and packstones/grainstones. This microfacies reflects deposition in shallow-marine environments.

After the deposition of these highstand deposits the sealevel fell. Exposure of these carbonates resulted in the formation of a microkarst on the tidal flats and shoreface microfacies. Subaerial exposure of the landward portion of Mfamosing Limestone led to the development of chalky limestone in peritidal carbonate horizons [12;13]

After this period of syndepositional exposure, the upper part of the succession was formed during a renewal sealevel rise. The microfacies succession during this period indicates a shallow-marine nearshore condition. This carbonate sedimentation continued until another time of sealevel fall. Eustatic sealevel fall that marked the end of Mfamosing sedimentation resulted in subaerial exposure and major karstification of the limestone. Karstic solution erosion continued until the deposition of Ekenkpon Shale.

The Ekenkpon Shale consists of two types of depositional sequences. These are informally referred to as the lower hard shale and upper soft shale (Aderogba), [10]. The lower hard shale sequence was probably deposited during the late Albian-early Cenomanian transgression in the Calabar Flank. This was at the very beginning of the second transgressive cycle in the southern Nigerian sedimentary basins. These sediments were deposited under anoxic water conditions [14] or below the zone of bioturbation and oxygenated pore water. Characteristically, these sediments contain pyrite nodules and pyritized framboidal shell remains which could serve as a marker horizon for correlation purposes.

The upper soft shale sequence is separated from the lower hard shale sequence by an intraformational unconformity [16;17;19]. The upper soft shale sequence was probably deposited during the early Turonian trans-Saharan transgression into the southern Nigerian sedimentary basins. This sequence consists of dark-grey, weakly resistant shaly, silty, sandy and oyster shell beds intercalated with thin beds of resistant marly limestone and calcareous sandstone bands. Deposition of the early Turonian dark-grey, organic-rich soft shale took place in inner neritic to marginal marine conditions.

Following, the early Turonian trans-Saharan transgression, a mid-Turonian regression was initiated and erosional truncation of the Ekenkpon Shale occurred. The lowermost part of the New Netim Marl was deposited within a broad shallow valley that cut into the previously deposited sediments of the Ekenkpon Shale.

Aim of Study

The aim of this work is to show how these karstic features have provided the plumbing system that controlled diagenesis and base metal emplacement in the Albian strata of the Calabar Flank. It specifically examines the complex interplay of subaerial erosional and diagenetic events, (including karstification, pyritization, meteoric calcitization) on the depositional patterns of the limestone.

Method of Study

The karst features and surfaces recognized in this work are the following:

Planar Erosional Surfaces (Figure 3)

Although, the Mfamosing strata represent an overall transgressive sequence, it records at least a minor and a major regressive event. These events are characterized by: 1) a local microkarst horizon associated with shallowing-upward peritidal carbonate cycle, and 2) a major paleokarst unconformity of regional extent.

FIGURE 2: Location map where samples were taken.

Figure 3: Photo is showing the planar erosional surface above the Mfamosing Limestone.

Syndepositional exposure of nearshore peritidal carbonates result in the formation of minor microkarst surfaces. These microkarst surfaces occur individually in intertidal and supratidal carbonates. This phenomenon is sometimes expressed in outcrops as chalky limestone horizons. On the other hand, the paleokarst unconformity on top of the Mfamosing Limestone is a major stratigraphic break. This surface in close look appears to be a planar surface with little or no relief. It is commonly featureless. The preserved thickness of Mfamosing strata beneath the paleokarst unconformity around the southern rims of Oban Massif generally ranges from zero to 50m at the surface [20] while it is about 450m at the subsurface [1]. Although, there are extreme local variations, the carbonate strata thicken towards the south from Oban Massif. Local variations may be due to uplift and erosional removal of the Mfamosing strata close to Oban Massif.

Interpretation

The regional distribution of this unconformity suggest eustatic sealevel fall. This unconformity probably spanned about 1-3 million years [10]. Subaerial emergence, even though of short duration, formed distinctive karstic features in the Mfamosing strata. Local, syndepositional erosional horizons are interpreted as microkarst formed during subaerial exposure of peritidal carbonates. The sharp erosional contact and the preservation of chalky limestone and other dissolution features below this surface suggest subaerial exposure.

Sinkholes and Caves (Figure 4)

Sinkholes are subsurface solution features localized in form of cavernous channelways, sometimes occurring above small caves. Many are vertical to bedding, while some are horizontal at depth. Some are filled with mud-supported or clast-supported lithoclast breccias. The principal fill materials of most sinkholes are siliciclastics material.

Figure 4: Photo is showing sinkhole deposits in the Mfamosing Limestone.

Interpretation

Sinkholes represent phreatic zone solution features formed by dissolution of the limestone by flowing oxidizing meteoric groundwater[21]. The flowing groundwater moving through the limestone was probably undersaturated with respect to calcite and aragonite, therefore, causing dissolution of the limestone.

Breccias and Internal Sediments (Figure 5)

Intraformational breccias are common between 10-35m below the unconformity surface. Most breccias are composed predominantly of clasts of limestone while most matrix consist of siliciclastics material. Sometimes, the clasts are angular or subrounded in shape. Fractures may have controlled the development and distribution of these features. Sediment-fills include all material in caves and sinkholes such as sand, silt, shale, clay and rock fragments.

Figure 5: Photo is showing breccia and internal sediments in the Mfamosing Limestone.

Interpretation

Localization of breccias below the unconformity suggests meteoric freshwater dissolution of the limestone. This limestone has been brecciated as a result of karstification. But, the degree of brecciation differs from place to place.

Enlarged Joints and Fractures (Figure 6)

Joints and fractures are special and common features in the Mfamosing Limestone. They could be vertical or horizontal. They are mostly common in the upper 30m of the carbonate sequence. They are commonly filled with pyrite, calcite and siliciclastics materials. Most solution-enlarged joints are filled with pyrite and calcite. The enlarged fractures often shows evidence of corrosion of wall. They may occur in any direction.

Figure 6: Photo is showing joints and fractures in the Mfamosing Limestone.

Interpretation

Most early joints may probably be formed during early stages of karst development in the vadose zone[22]. Solution-enlarged joints are mostly formed during burial. Leaching by undersaturated meteoric or basinal fluids along previous fractures enlarged these fractures.

Molds and Vugs (Figure 7)

These are the common manifestation of karstic dissolution. They are common in the upper 35m. A distinctive rock type that has a high concentration of vugs is the chalky limestone. Some vugs are partly or completely filled with equant calcite cement and other minerals.

Figure 7 : Photo is showing vugs of different sizes in a hand held slab of the Mfamosing Limestone.

Interpretation

Fossil molds and vugs are formed by the dissolution of carbonate minerals (e.g. aragonite). The presence of these easily dissolved minerals (e.g. ooids, mollusks, marine cements) provided advantageous conditions for the formation of vuggy pores.

Results

The effects of subaerial exposure and the development of paleokarst unconformity in Albian Mfamosing Limestone have been very profound. First, it was this subaerial exposure episode that texturally altered and mineralogically changed some horizons in the limestone into a diagenetic facies rather than initial depositional facies. Extensive surface and subsurface karst facies were formed as the carbonates were subaerially exposed to oxidizing meteoric (freshwater) diagenesis during a relative sealevel fall. These paleokarst facies are more pronounced in strata close to the unconformity, while its effect decreases away from it.

Second, it was the subaerial exposure event that transformed the limestone into a major karst plumbing system. It is widely acknowledged that something must have happened in order to allow the entry of solvents into limestone. For karstic dissolution to occur in limestone, the strata must be exposed to fluid that is undersaturated with respect to calcium carbonate. This was made possible at the paleokarst unconformity, as the newly-deposited carbonate sediment was brought in contact with rainwater which is undersaturated in respect to calcite. Groundwater solutions charged with carbonic acid and organic acids are known as the greatest agents in the dissolution of limestone.

Third, this exposure event led to the development of secondary dissolution porosity in this Albian limestone with little or no primary (interparticle and intraparticle) porosity remaining. The development of abundant pore systems very close to the paleokarst unconformity indicates that the surface resulted from intense meteoric leaching and karstification. The secondary pore spaces that newly emerged in the limestone after the exposure event includes: moldic pores, fenestral pores, vuggy pores, cavernous pores, interbreccia pores, and solution-enlarged fracture pores.

Lastly, another important aspect of this subaerial exposure event is that karstification and later burial diagenetic processes are responsible for making the limestone a potential site for economic mineral accumulation. It appears that karstification and subaerial exposure are of great importance in the preparation of fluid-transporting and the ore-hosting structures in the Mfamosing Limestone. Major solution features related to this period of subaerial exposure appear to control the distribution of pyrite mineralization in this limestone.

Discussion

Mfamosing Limestone has been subjected to several episodes of diagenetic modifications during progressive burial from nearshore (eogenetic) through relative deep subsurface (mesogenetic) into surface (telogenetic) environments. Deposition of Mfamosing strata occurred in a shallow, marine shelf platform. Only minimal diagenetic alteration occurred at this stage [20]. Cementation was the principal processes. Evidence for syndepositional marine diagenesis includes: micrite rims developed on fossils (e.g. algae and gastropod); and the first generation, isopachous rim cement. At this initial stage, massive botryoidal cements are formed during this stage of influx of marine waters. These precipitates were composed originally of aragonite and high-Mg calcite [21;22;4;23;24]

After Mfamosing sedimentation accumulated to a certain depth, leaching, cementation and compaction became important in shallow burial stage. Pervasive matrix leaching and cementation are common especially in subaerially exposed nearshore deposited rocks. Leaching in these horizons was contemporaneous with marine phreatic cementation along the oceanward margin. Mechanical compaction features such as collapse and broken fossils also are common [25;26;27;28;29;30;31;32].

Following syndepositional marine stage, the Mfamosing Limestone was exposed to subaerial environments leading to the development of karst. Karstic dissolution was initiated by movement of meteoric water through the limestone [33]. Flushing by meteoric waters caused marked changes in the texture and mineralogy of the Mfamosing strata. The rapidly flowing oxidizing meteoric groundwater moving through the limestone probably was CO_2 charged and undersaturated with respect to calcite and aragonite. This may have caused extensive karstic dissolution of the limestone. Heavy leaching and dissolution developed into karstification. This meteoric freshwater leaching created an extensive network of moldic pores and vugs.

Karstic dissolution of aragonite and possibly high-Mg calcite by shallow phreatic meteoric waters resulted in local supersaturation of pore fluids with respect to calcite. As a result, nonferroan calcite cements were precipitated as $CaCO_3$ saturated oxidizing meteoric groundwaters percolating through fissures, fractures, channelways, sinkholes and caves created during karstic dissolution [34;35;36;23;37]. By Late Albian times, the Mfamosing Limestone platform was slowly subsiding. Burial diagenesis probably commenced in early Cenomanian, with the deposition of Ekenkpon Shale and younger formations. Mechanical and chemical compaction became very important diagenetic process during this period. During burial, the unlithified carbonate muds and grainstones were compressed destroying porosity. Intense pressure solution seams and high-amplitude stylolites occurred at contacts between carbonate and clastics. As a result, the released calcium carbonate was precipitated as cement filling near-by porous zones [38;39;40;41;42].

A considerable amount of post-stylolization diagenetic processes also occurred in Mfamosing Limestone. This includes dissolution and cementation. Evidence for dissolution consists of development of porosity along and immediately adjacent to stylolites. $CaCO_3$ undersaturated burial fluids migrated along stylolites, thereby, widening stylolites. Base metal sulfides and their associated gauque minerals (calcite, dolomite, quartz and fluorite) were precipitated from hot, basinal fluids during burial. Metalliferous basinal hot brine derived during the compaction of overlying shale formation, was precipitated as cement in the limestone.

The Mfamosing Limestone is presently undergoing a second period of karst formation [43;44]. As a result of Pliocene uplift, the Mfamosing Limestone is brought against in contact with freshwater oxidizing fluids. Rapidly flowing meteoric groundwater moving through the conduit pore are undersaturated with respect to calcite. This is causing extensive dissolution and the formation of caves. The results of this late subaerial stage are similar to that of the earlier diagenetic subaerial stage.

Conclusion

The Mfamosing Limestone is a shallow-marine carbonate platform that was karstified as a result of subaerial exposure. During late-Albian sealevel lowstand, the carbonates were exposed to subaerial environments leading to the development of karst. This karstic system is characterized by an irregular erosional surface, meter-size dissolution cavities, collapse breccias, sinkholes, boring and solution-enlarged, vertical joints. The regional distribution of this unconformity suggest eustatic sealevel fall. The distribution of porosity in these Albian strata was affected by subaerial exposure and burial diagenesis. The original depositional fabric and the related primary pore system were overprinted by karstic and burial dissolution processes.

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