

Depositional Control on Hydrocarbon Accumulations in Deepwater Nigeria*

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Introduction

Seafloor geomorphology controls deepwater sand deposition that, combined with structural configurations, controls hydrocarbon accumulation. Structural control of hydrocarbon accumulations is very well known, but depositional control seems to be very important in some deepwater exploration areas. This is demonstrated by a case study on Nigeria deepwater discoveries.

Many discoveries have been made in anticlinal structures in the Nigeria deepwater. The anticlines are located from the shale-diapir province, through the inner thrust belt and translational province, to the outer toe-thrust belt. One of the most interesting observations is that most of the discoveries were made on the downslope (basinward) side of the anticlines.

Two possible explanations, among others, become obvious. One is that sand deposition preferentially occurs on the downslope side of the structures at the time of deposition synchronous with structural growth (generated by shale diapirism or thrusting). This is the result of relatively greater accommodation space and/or hydraulic jump of turbidity current flow across seafloor topographic highs. The second one is that hydrocarbon migration and charge preferentially occur, along a regional depositional slope, in an updip (landward) direction. This extended abstract is aimed to expand the discussion of the two explanations.

Examples of hydrocarbon discoveries in the deepwater Nigeria on the downslope side of anticlinal structures (shale-cored diapirs or thrust-generated anticlines) include Bonga, Bonga Southwest, Akpo, Uge, N'Golo, and Obo North. A common characteristic of all the structures is that reservoir sand deposition was synchronous with structural growth. The structures occurred as seafloor topographic highs during the time of sand deposition. Turbidite elements of the reservoir sands consist primarily of channel fill and associated frontal splays (e.g., lobate sheet sands).

There are other discoveries, such as Agbami, in the deepwater Nigeria, which do not exhibit this pattern. A detailed examination of those discoveries reveals that the reservoir sands were deposited prior to structural growth, and therefore the structures did not affect

sand distribution. Moreover, turbidite elements of the reservoir are mainly basinal-plain terminal sheet-sand lobes.

Depositional Control on Sand Distribution

Deepwater gravity sedimentation in general and sand deposition in particular is greatly influenced by seafloor topography with sediment being largely focused into topographic lows. On a continental slope, sedimentation of turbidite and associated gravity flow deposits are controlled by local base level and accommodation space which, in turn, is controlled by the slope equilibrium profile (Pirmez, 2000; Prather, 2003).

Erosion/incision occurs in areas above the profile, and deposition occurs in areas below the profile.

Growth of shale-core diapirs, due to either deep-seated duplexing/thrusting as a result of downslope gravity gliding along detachment surfaces or differential sediment loading, generate subtle seafloor topographic highs, thus leading the depositional surface to deviate from the equilibrium profile and creating local areas of erosion and accommodation space for deposition. Pre-existing or syn-growth channels along the continental slope across these seafloor highs have to adjust themselves. Channel thalwegs will be subject to either down-cutting (deepening) and possible headward erosion across these highs (if thalweg elevation is above the equilibrium profile) or aggradation (shoaling) on the downslope flank of the highs and the adjacent structural low area (where thalweg is beneath the equilibrium profile).

Turbidity current flows emanating down from a seafloor topographic high is forced to undergo a hydraulic jump from a Froude-supercritical flow regime to a highly Froude-subcritical regime. This results in a deep, placid, slow-moving turbidity current farther downstream (Parker, 2003), leading to deposition of sands that cannot be carried farther downstream. Skaloud and Cassidy (1998) used the hydraulic jump theory to explain the sand deposition on the downslope flanks of both Bonga and N'golo field. This process can explain sand distribution in some of the fields mentioned previously. The depositional model is illustrated in Figure 1.

It is possible that sands can be carried by a single turbidity current across multiple structural highs and deposit them in the form of terminal lobe if the channel thalweg is more or less close to the equilibrium profile and flow thickness is less than the channel depth. During periods of active structural growth, such equilibrium condition will be disrupted and sand deposition should occur, although non-uniformly, across different channel segments across multiple structures. A modern example is shown in Figure 2.

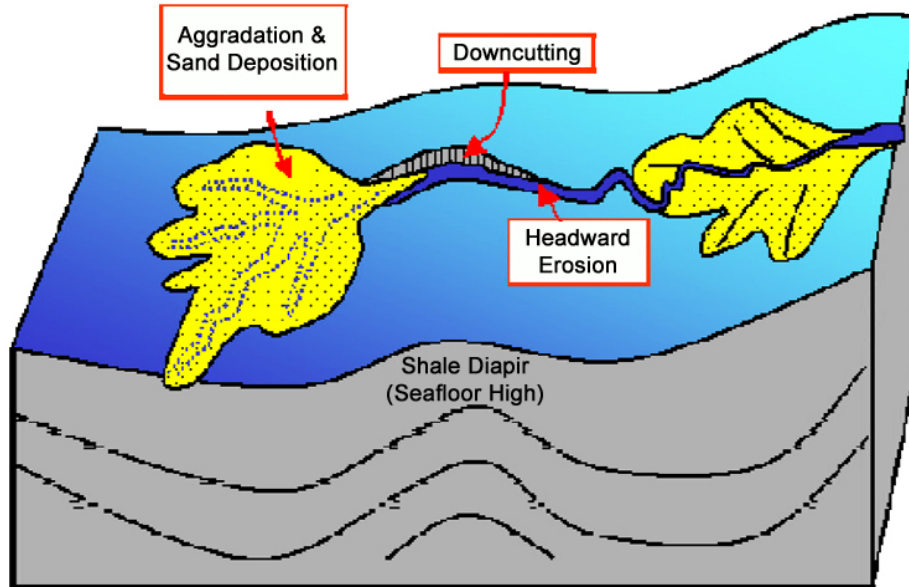


Figure 1. A simple depositional model for sand deposition as ponded lobes on the downslope side of anticlinal structure.

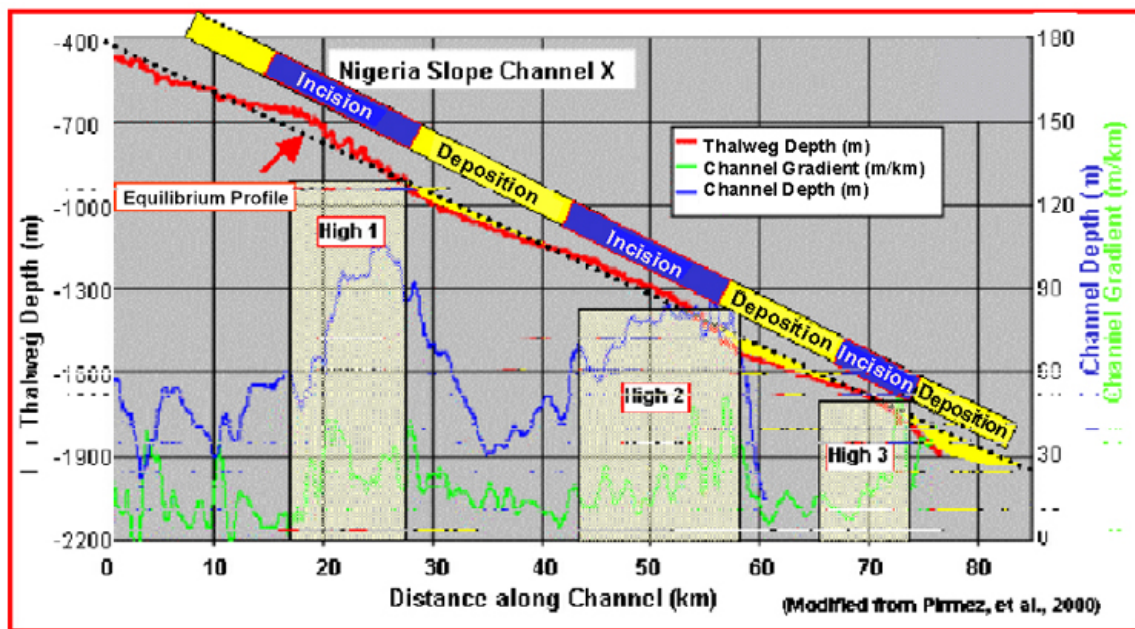
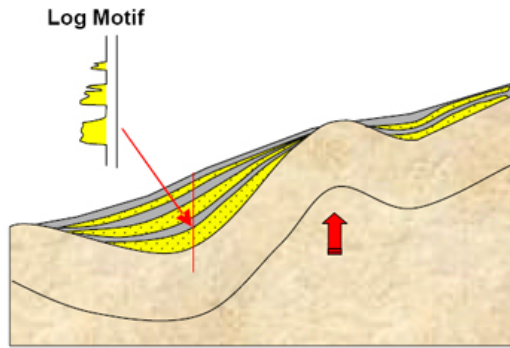


Figure 2. A present-day Nigeria slope channel and its geomorphological parameters. The channel thalweg depth is in red, thalweg depth in blue and the channel gradient in light green. The presumed slope depositional equilibrium profile is shown in dotted pink. The channel extends across three seafloor topographic highs (i.e., High 1, High 2 and High 3) associated with either shale-cored diapirs or thrust-generated anticlinal structures. Note the thalweg elevation for the channel segment directly across these highs is above the equilibrium profile, suggesting potential for further down cutting and headward erosion. The deepest part of the channel thalweg, as shown by the channel thalweg depth curve (blue), occurs at approximately the intersection point between the thalweg elevation and the equilibrium profile curves. Channel depth gradually decreases down-dip from the intersection point as a result of deposition within the channel thalweg. Sand deposition across the channel should be expected to occur primarily on the downslope sides of the highs because of (1) a relatively greater accommodation spaces, and (2) hydraulic jumps within turbidity current flows emanating from the highs. (Modified from Pirmez, et al., 2000.)

Sands are expected to be predominantly deposited on the downslope sides of structural highs due to a greater accommodation space (below the regional depositional equilibrium profile). Hydraulic jump of turbidity current flows emanating down from these structural highs is the dominant hydrodynamic process for sand deposition. The upslope flank of the structural high as manifested by the channel thalweg profile is generally above the equilibrium profile. Consequently, little sand will be deposited there and on the top of the highs, assuming turbidity current flow thickness is less than the channel depth. Even if sands are deposited across the top and upslope flanks of the highs during periods when structural growth rate is far less than sedimentation rate across the entire channel stretch, they may not be well preserved because subsequent structural growth and turbidity current flows may lead to erosion. For thick sand deposition within a particular channel segment downslope of a structural high, it requires a greater accommodation space and higher preservation potential, other factors being equal. This can occur when structural growth rate is significantly greater than the background sedimentation rate, such that a high topographic relief of the seafloor is created. This could create a ponded mini-basin upslope of the structural high, where sands could be deposited (Prather, 2003). Once the mini-basin is filled to such a level that the thalweg elevation plus a presumed turbidity current flow thickness exceeds the elevation of the regional equilibrium profile, sand will start to be funneled down the structural high into the downslope part of the channel and be potentially deposited in the next basinward mini-basin. This will be the time for relatively thick sand deposition, until the downslope mini-basin is filled. Therefore, the timing of thick sand deposition in a slope setting is either synchronous or soon after individual active structural growth episodes.

The overall succession of the sand package generally exhibits a thinning-upward trend (Figure 3). If sedimentation rate keeps up with structural growth and no significant accommodation space is available along the channel stretch, only thin but possibly more sands will be deposited due to a less degree of amalgamation. It is also possible that more unconfined lobate-shaped sandbodies will be deposited due to relatively shallow thalweg depth and ease of overbank flow stripping. It is clear from the above discussion that the downslope flanks of shale-cored structural highs are loci for sand deposition as long as structural growth continues and sedimentation rate is not high enough to smooth out its seafloor topographic relief. The thickness and number of sands are dependent upon, other factors being equal, the relative rate between structural growth and sedimentation. High rate of structural growth creates more opportunities for thick sand deposition on the downslope flank of the structure, but a greater degree of erosion at the top of the structures.

A: Structural growth rate >> sedimentation rate



B: Structural growth rate

• or < sedimentation rate

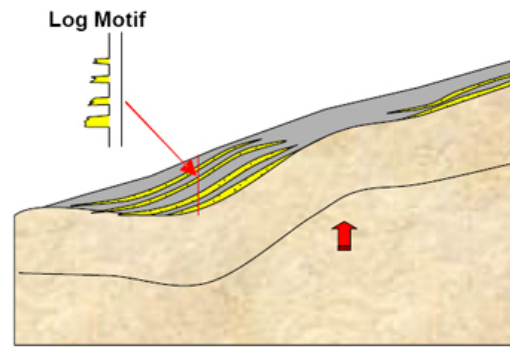


Figure 3. The impact of structural growth rate and sedimentation rate on sand thickness and the number of sands on the downslope side mini-basin. Assuming other factors being equal, thicker but fewer sands occur where structural growth rate is significantly greater than sedimentation rate (A), and thinner and more sands will be deposited if structural growth rate is close to or less than sedimentation rate (B).

Hydrocarbon Migration/Charge

In addition to the depositional control over hydrocarbon accumulation pattern, it is also important to note that hydrocarbon migration and charge also play a critical role. Two most important factors are worthy of consideration. First, hydrocarbon migration from source-rock kitchen generally occurs in an updip direction. Secondly, the fetch area from source-rock kitchen is generally much greater for its updip shale-cored anticlinal structures than that for its downdip structures (Figure 4). Therefore, charge volume for a given structure is relatively limited from the updip side source rock kitchen and the bulk of hydrocarbon charge is from the source-rock kitchen on the downdip side of the structure. Regardless of sand distribution differences, as long as sands are not uniformly distributed across a given structure, hydrocarbon migration direction and charge volume alone should lead to more accumulations on the downslope side.

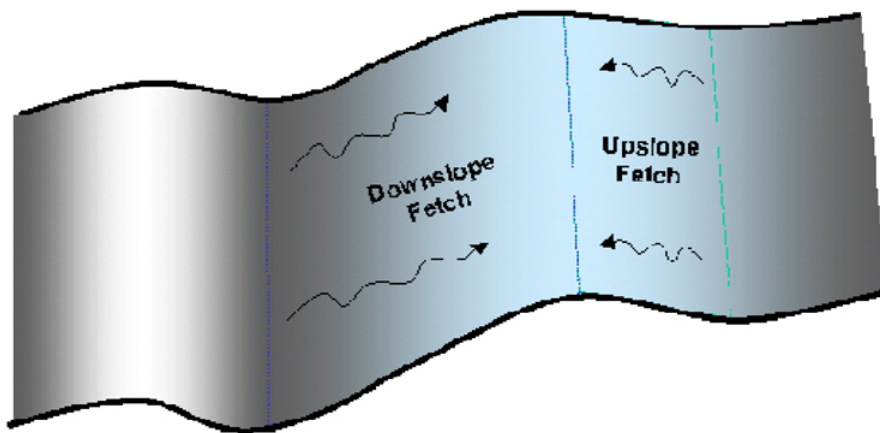


Figure 4. Schematic diagram illustrating the relative sizes of the fetch areas from source-rock kitchens on both the updip and the downdip sides of an anticlinal structure. In a slope setting, the fetch area on the downslope side of a given anticlinal structure is generally much greater than that on the updip side of the same structure.

Comment

The finding of the hydrocarbon accumulation pattern in the deepwater Nigeria can potentially be applied to other deepwater exploration regions such as the Gulf of Mexico and offshore Angola, where the target stratigraphic intervals were deposited synchronously with or shortly after structural growth. However, it does not apply to the stratigraphic intervals or areas where sand deposition was not affected by structural growth (e.g., a basin-floor fan setting in a basinal plain without any growing seafloor structures).

Conclusions

1. Several hydrocarbon discoveries in deepwater Nigeria suggest that hydrocarbon accumulations preferentially occur on the downslope flank of shale-cored structural highs.
2. The hydrocarbon accumulation pattern is primarily controlled by preferential sand deposition on the downslope sides of the structures.
3. Hydrocarbon migration direction and charge volume may also play an important role for the observed hydrocarbon accumulation pattern.
4. The finding of hydrocarbon accumulation pattern can be applied to other deepwater basins where structural growth is synchronous with sand deposition.

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