Introduction

The Palaeogene sedimentary succession in the southern Benue Trough consists of the late Maastrichtian-Paleocene Nsukka Formation (~350 m), Palaeocene Imo Formation (~1,000 m), Eocene Ameki Group (~1,900 m), and Eocene-Oligocene Ogwashi-Asaba Formation (~250 m; Fig. 1). Regional correlation (Short and Stäuble, 1967; Avbovbo, 1978; Fig. 2) shows that the Palaeogene succession can be mapped southward into the Niger Delta where the Imo Formation, Ameki Formation and Ogwashi-Asaba Formation are equivalents of the hydrocarbon-generating Akata Formation, reservoir-containing Agbada Formation and the Benin Formation respectively. With the recent Federal government policy to continue hydrocarbon exploration in the inland basins, the search in the Anambra-Afikpo basin complex, is switching from seismically-defined structures to the more elusive stratigraphic traps in the Paleogene succession. The objective of this research is to provide the first basin-wide lithostratigraphic description and palaeoenvironmental interpretation of the Imo Formation in the southern Benue Trough based on outcrop and subsurface data. The results provide a useful framework for reservoir prediction and improved understanding of the Palaeogene evolution of the southern Nigerian sedimentary basin complex.

Database and Methodology

The outcrop belt of the Imo Formation stretches from the vicinity of Igbariam at the left bank of the Anambra River, through Awka, Okigwe and Akoli, to the Ozuiem and Bende areas of the southern Benue Trough (Fig. 3). Interpretation of outcrop sections described at Awka, Ugwuoba, Okigwe, Umuasua, Lohum, Ozuiem and Bende provided the basis for interpretation of depositional environments, while gamma-ray log and foraminiferal data obtained from an oil well (herein referred to as X-Well) drilled within the study area, supplemented with the outcrop data facilitated sequence stratigraphic interpretation (Fig. 4). The biostratigraphic data has a very good resolution and is
<table>
<thead>
<tr>
<th>AGE</th>
<th>ABAKALIKI-ANAMBRA BASIN</th>
<th>AFIKPO BASIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 my</td>
<td>Oligocene Ogwashi-Asaba Formation</td>
<td>Ogwashi-Asaba Formation</td>
</tr>
<tr>
<td>54.9 my</td>
<td>Eocene Ameki/Nanka Formation/ Nsugbe Sandstone</td>
<td>Ameki Formation</td>
</tr>
<tr>
<td>65 my</td>
<td>Paleocene Imo Formation</td>
<td>Imo Formation</td>
</tr>
<tr>
<td></td>
<td>Nsukka Formation</td>
<td>Nsukka Formation</td>
</tr>
<tr>
<td>73 my</td>
<td>Maastrichtian Ajali Sandstone</td>
<td>Ajali Sandstone</td>
</tr>
<tr>
<td></td>
<td>Mamu Formation</td>
<td>Mamu Formation</td>
</tr>
<tr>
<td>83 my</td>
<td>Campanian Nkporo/Oweli Formation/Enugu Shale</td>
<td>Nkporo Shale/ Afikpo Sandstone</td>
</tr>
<tr>
<td>87.5 my</td>
<td>Santonian Non-deposition</td>
<td></td>
</tr>
<tr>
<td>88.5 my</td>
<td>Coniacian Abugu Group (Agbani Sandstone/Awgu Shale)</td>
<td>Ezakuk Group (incl Amasere Sandstone)</td>
</tr>
<tr>
<td>93 my</td>
<td>Turonian Ezakuk Group</td>
<td>Ezakuk Group</td>
</tr>
<tr>
<td>100 my</td>
<td>Cenomanian- Albian Asu River Group</td>
<td>Asu River Group</td>
</tr>
<tr>
<td>119 my</td>
<td>Aptian Unnamed Units</td>
<td>Basement Complex</td>
</tr>
<tr>
<td>Precambrian</td>
<td>Basement Complex</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Correlation of Early Cretaceous-Tertiary strata in southeastern Nigeria (after Nwajide, 1990)

Fig. 2. NE-SW transect showing the dip-wise facies succession from the Benue Basin across the Anambra Basin to the Niger Delta (after Mural, 1972)
therefore considered very useful in constraining the sequence stratigraphy of the Imo Formation in the study area. Two stratigraphic cross sections (Figs. 5 and 6) were constructed across the study area to provide a correlation framework.

Sequence Stratigraphic Framework of the Imo Formation

The Imo Formation is essentially of Selandian age (Oboh-Ikuenobe, et al., 2005). This interval spans 59.4my-56.5my and corresponds to F3100-F3500 on the Niger Delta chronostratigraphic chart as revised by the SPDC Ltd. in 1998 (Fig. 7). The chronostratigraphic chart shows that the interval contains two 3rd-order depositional sequences associated with the 59.4my, 57.5my and 56.5my 1st-order sequence boundaries and 58.1my, and 56.3my maximum flooding surfaces. The sequence stratigraphic framework of the Imo Formation in the study area is thus based on the identification and interpretation of these sequence boundaries and marine flooding surfaces on biofacies spreadsheets (Fig. 4) or in outcrops, and their basin-wide correlation (Figs. 5 and 6). From oldest to the youngest the surfaces are: (i) the sequence boundaries sb-1, sb-2 and sb-3; (ii) transgressive surfaces of erosion, tse-1, tse-2 and tse-3 that reflect successive rises in relative sea level which provided accommodation for the accumulation of the progradational bay-fill delta in the successive estuarine environments; and (iii) maximum flooding surfaces mxfs-1 and mxfs-2 (Figs. 5 and 6), that reflect the surface of maximum flooding, at the top of the respective transgressive facies.

In the B-C-D cross section (Fig. 5), Sb-1 (59.4my) is located in the Umuasuwa outcrop section and correlated to the Oji-Ugwuoba and Agbobu composite sections (Fig. 6), where tidally-influenced/coastal plain facies overlie shallow marine facies of the Nsukka Formation. This surface is missing in X-Well, possibly faulted out. The other sequence boundaries, sb-2 (57.5my) and sb-3 (56.5my) are readily identified on outcrop where a coarse-grained fluvial and tidally influenced fluvial deposit overlies shoreface-foreshore facies. The two maximum flooding surfaces are located in X-Well, at
2255ft and 1062ft where relatively high faunal abundance and diversity occurs within the F-3500 faunal zone (Fig. 4).

The two transgressive surfaces of erosion (tse-1 and tse-2) are inferred at the top of the tidally-influenced/coastal plain facies and the base of the bay-fill deltas in each of the two respective depositional sequences (Figs. 5, 6 and 8). These transgressive surfaces reflect successive rises in relative sea level that provided accommodation for the accumulation of the progradational bay-fill delta in the successive estuarine environments. **Tse-1** is interpreted as the base of the Imo Formation in the study area. The boundaries are correlated basin-wide (Figs. 5 and 6).

**Lithostratigraphy and Depositional Environments of the Imo Formation**

Four main facies assemblages (depositional facies) are identified within the Imo Formation in the study area: (i) tidally-influenced fluvial facies; (ii) estuarine bay-fill delta; (iii) estuarine and marine shale facies; and (iv) progradational shoreface-foreshore facies assemblages. These facies assemblages determine the reservoir containers, flow units and seals. The characteristics of the facies assemblages are summarized in Table 1 and detailed below.
### Table 1. Summary of characteristics of the major facies assemblages identified in the study area.

<table>
<thead>
<tr>
<th>Facies Assemblage</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>iv</td>
<td>Fine-grained, well sorted sandstones, locally medium-grained, with interbeds of fossiliferous limestone, siltstone and shale. Hummocky cross-stratification, swaley lamination, wave ripple lamination, lenticular bedding, bioturbation, contains bivalve and gastropod shells; trace fossil suite of <em>Skolithos</em> and <em>Glossifungites</em>.</td>
</tr>
<tr>
<td>iii</td>
<td>Mainly bluish-grey shales and black shales with thin interbeds and nodules of coquinas, limestone and sharp-based micaceous siltstones. Hummocky cross-stratification and wave ripple laminations in the sandstones; abundant casts, moulds, and shells of bivalves, gastropods, <em>Skolithos</em> and <em>Cruziana</em> ichnofacies.</td>
</tr>
<tr>
<td>ii</td>
<td>Interbedded fining-upward, well-sorted, and wave rippled laminated, strongly bioturbated sandstone and crudely laminated or mottled / fissile clay and clay Shale; <em>Skolithos</em> ichnofacies.</td>
</tr>
<tr>
<td>i</td>
<td>Profusely cross-bedded, friable sandstone characterised by tidal bundles at lower sections and large scale planar-cross strata up the section. Upper beds may be conglomeratic with distinct pebble horizons; strongly ferruginized; <em>Ophiomorpha</em> and <em>Arenicolites</em>.</td>
</tr>
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</table>

(i) **Tidally-influenced fluvial assemblages**

The tidally-influenced fluvial facies assemblages are the most important potential reservoir sandstone within the Palaeocene Imo Formation in the study area. The depositional facies is recognized based on the coarse grain size, fining-upward textures, and dominance of planar and trough cross-beds (Fig. 9a), presence of clay clasts (Fig. 9b), and tide-generated sedimentary structures including herringbone cross-stratification, flaser bedding, mud drapes and reactivation surfaces (cf. Archer and Kvale, 1989; Leckie and Singh, 1991; Shanley et al., 1992; Hettinger, 1995). The high energy condition typical of this environmental setting is reflected in the presence of *Arenicolites* and *Ophiomorpha* (Pemberton et al., 1992; Figs. 9b & 10). Indications from paleocurrent measurements (arrows in Figs. 5 and 6) show that the sands were brought in by southwesterly flowing fluvial currents and redistributed by a NW-SE directed current to form a shoreline-parallel tidal sand ridge.

The sandstones overlie a *Glossifungites* surface and are largely composed of multi-storey pebbly, coarse-grained sandstones characterized by planar and trough cross-stratification and low angle cross-sets in which pebbles and ferruginized bands occur at various horizons. Strata of this facies association along with the underlying shoreface-foreshore facies form a prominent NW-SE trending ridge that passes through Ebenebe, southwest of Okigwe, Umuasuwa and Ozuitem (Fig. 3). The ridge has net sand that ranges from 10m-40m, and average porosity that is above 20%. The sandstone body may however be locally compartmentalized by thin ironstone layers.

(ii) **Estuarine bay-fill delta facies assemblages**

The bay-fill delta facies assemblages attain a thickness of over 20m, with a net sand thickness of about 10m. This facies is present in all the key sections studied (Figs. 5, 6). It is essentially heterolithic and composed of thin, carbonaceous crudely laminated or mottled, gypsiferous clay and clay-shale that alternate with well-sorted, strongly bioturbated, fining-upward, fine to medium-grained, micaceous, calcareous and fossiliferous sandstone, siltstone and limestone. The units contain wave ripple-lamination, lenticular bedding and flaser bedding, as well as structures belonging to the *Skolithos* ichnofacies and contain whole shell/fragments of bivalves (mainly *Ostrea*) and gastropods.

The presence of gypsiferous and sandy lenticular clays, in association with low diversity burrow types (including *Planolites*, *Thalassinoides* and *Teichichnus*), is indicative of a low energy setting such as in a tidally-influenced estuary (Kamola, 1984; Allen, 1993; Allen and Posamentier, 1993; Oboh-Ikuenobe et al., 2005; Pemberton and Wightman, 1992). The alternation of thin mudstone and fine-grained sandstone/siltstone units containing wave-ripple
Fig. 5. Stratigraphic cross-section E-F-G-H-I across the Imo Formation in Umusunna. Ozuitem-Uzuakoli axis. The locations of the cross sections are shown in Fig. 3.

<table>
<thead>
<tr>
<th>Facies Description</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estuarine central basin and Marine shale facies</td>
<td>Maximum Flooding surface (mxf1-2)</td>
</tr>
<tr>
<td>Estuarine bay-fill delta facies</td>
<td>Sequence boundary (sb-2)</td>
</tr>
<tr>
<td>Tidally-influenced fluvial facies</td>
<td>Flooding surface (tse-2)</td>
</tr>
</tbody>
</table>

**Umuuzike**
- Fine-medium grained, massive sandstone, Tectochirnus, Planolites, S kolithos and Thalassinoides
- Multi-storey poorly-moderately sorted fining-upward pebbly, coarse sandstone, basal ironstone, burrowed, planar and trough cross stratification, abundant ripples clasts.

**Marine Shale facies and progradational shoreface-shelf facies**
- Maximum Flooding surface (mxf1-1)

**Umuasunna**
- Dark grey estuarine heteroliths and thin bands of very fine grained sandstone, Planolites
- Fine-medium grained, sandstone, Tectochirnus, Planolites, S kolithos and Thalassinoides
- Multi-storey fining-upward pebbly, coarse sandstone, basal ironstone, burrowed, planar and trough cross stratification, abundant rip-up clasts.

**Imo Formation**
- Glossating surface, Thalassinoides, Planolites burrows into underlying units

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Fig. 6. Outcrop cross section of the Imo Formation in the Awka-Ogigwe (B-C-O) axis. The locations of the outcrops and lines of section are shown in Figures 3. Arrows indicate paleocurrent directions. The key surfaces are discussed fully in the text.
lamination, lenticular bedding and flaser bedding reflects frequent energy fluctuations consistent with sub tidal and intertidal settings (Prothero and Schwab, 1996). These distal bay-fill delta heteroliths have very low porosities and permeability because of a high percentage of fine sediment and because of mixing by bioturbation.

The deposition of bay-fill delta facies ended with subsequent transgression across the interfluve areas (maximum flooding surface, Figs. 5, 6) that eliminated the estuary and initiated open marine sedimentation in the study area.

(iii) Estuarine central basin and marine shale facies assemblages

The estuarine central basin shale facies assemblages comprise mainly finely laminated bluish-grey shales and black shales with local lenses and interbeds of coquinas, hummocky cross-stratified and wave ripple laminated limestone and sharp-based micaceous siltstones containing abundant casts, moulds, and shells of bivalves, gastropods. The dominant trace fossil is *Planolites*, with local *Teichichnus* burrows associated with sandy layers and lenses. These burrows are of low-diversity and small-sized, indicating a stressed marginal marine setting as is common in the central region of an estuary (Pemberton and Wightman, 1992).

The overlying marine shale facies is fissile, black and contains local lenses of storm-deposited siltstone.

(iv) Progradational shoreface-foreshore facies assemblages

The progradational shoreface-foreshore facies consists of partially amalgamated, yellow to light green colored, strongly bioturbated or wave ripple laminated/hummocky cross-stratified, well-sorted very fine to fine-grained sandstones arranged in upward coarsening and thickening bed sets. In the more basinal areas, it includes shelly sandstone/limestone intervals. Measurements of symmetrical, NW-SE oriented ripple crests indicate that oscillatory currents were NE-SW. The hummocky cross-stratified sets start on a scoured surface that is lined with extra-formational clasts/pebbles. Hummocky cross-stratification is commonly formed above fair weather base by storm-generated waves (Cheel and Leckie, 1993; Myrow and Southard, 1996; Mitgaard, 1996). Extra-formational clasts at the base of the hummocky cross-stratified bed sets are interpreted as transgressive lags deposited over ravinement surfaces (Hettinger, 1995). The intensely burrowed beds and the presence of *Skolithos*
Fig. 9. Trough cross-beds (a) and Arenicolasites (white dots arrowed in b) and a clay-clast (circled in b), within tidally influenced fluvial facies of the Imo Formation at Otuibem and Asika respectively.
reflect a well-oxygenated lower shoreface possibly related to storm-induced turbulent mixing. The upward transition from offshore black shale to coarsening-upward sand bodies characterized by storm-generated sedimentary structures indicates seaward progradation of storm-dominated shoreface parasequences (Walker and Plint, 1992).

The interval is characterized by high diversity trace fossil assemblages with *Paleophycus, Planolites, Teichichnus, Ophiomorpha*, and *Arenicolites*. Inoceramid debris and bivalve whole shell (Fig. 11a) and shell fragments are widespread. It shows an upward transition from better-sorted, largely wave-ripple cross-laminated facies (Fig. 11b) to intervals characterized by herringbone structures, tidal bundles, reactivation surfaces and a trace fossil suite dominated by the *Skolithos* and *Glossifungites* assemblages. Paleocurrent measurements in this uppermost interval indicate a dominant SW mode with a subordinate NE mode.

**Discussion and Conclusions**

The stratigraphic surfaces identified within the Imo Formation are important for understanding the stratigraphic relations of the Imo Formation, sand body geometries and inter-relationships among the sand bodies. For example, the exact boundary between the transgressive Imo Formation and the underlying Nsukka Formation has hitherto, not been clearly defined. The tidally-influenced coastal plain facies of the Nsukka Formation which directly lies above sb-1 is overlain by a thick succession of estuarine clay and clay shale that marks the onset of marine transgression at the end of the Danian Age. The transgressive surface (*tse-1*) that separates the estuarine mudstone from the underlying coastal plain sandstone is here interpreted as the Nsukka Formation-Imo Formation boundary.

Similarly, the exact boundary with the younger Ameki Formation (Eocene) has not been previously
clearly defined. The Eocene Ameki Formation begins with a succession of fine to coarse-grained tidally-influenced fluvial and fluvial sandstones and passes upward through intercalations of clay, shale and limestone, to coarse-grained cross-bedded sandstones and clays (Reyment, 1965; Nwajide, 1979; Arua, 1980; Arua and Rao, 1986). The Imo Formation-Ameki Formation contact, therefore, is probably marked by the transition from fossiliferous/calcereous shoreface facies at the upper levels of the Imo Formation, to the overlying coarse grained tidally-influenced fluvial sandstones that dominate the base of the Ameki Formation (Nwajide, 1979). This level corresponds with sb-3 in Figures 4, 5 and 6.

This study has shown that the Imo Formation contains four major lithofacies assemblages. These are (i) fluvial and tidally-influenced fluvial facies; (ii) estuarine bay-fill delta; (iii) estuarine central basin and marine shale facies; and (iv) progradational shoreface-foreshore facies.

The facies assemblages are arranged to form two basinward-stepping depositional sequences in which two major sandstone members encased by marine shale progressively overstep down-dip. Each of the two sandstone members displays a markedly progradational character, with: (i) a lower abruptly progradational, wave-dominated shoreface facies that is overlain basinward by (ii) tidally-influenced cross-bedded sandstone facies that interfingers basinward with estuarine central basin shale. Stratigraphic correlation shows that the sandstones are laterally continuous and locally compartmentalized by thin ironstone layers, along the outcrop belt of the Imo Formation in the southern Benue Trough. Net sand ranges from 40m-60m, with average porosity that is estimated to be above 20%. The distal bay-fill delta sandstones, on the other hand, are estimated to have very low porosity and permeability because of high percentage of fine sediment and because of mixing by bioturbation. The estuarine central basin and marine shale facies provide for potential bottom seals, lateral seals and top seals for the Imo Formation.

The observed basinward architecture of the Imo Formation is interpreted to have formed in response to conditions of decreasing rate of addition of accommodation space in relation to sediment supply, which followed periods of reduced asymmetrical subsidence of the Anambra platform. The intervening marine shales reflect periods of slightly increasing accommodation and coastal transgression. The depositional processes of the Imo Formation in the southern Benue Trough are therefore, interpreted in terms of two episodes of high frequency sea level changes superimposed on the overall regressive trend that characterized the Tertiary sea in southern Nigeria.
Apart from providing a basis for reservoir prediction within the Paleocene succession, the model presented in this paper should also be a useful contribution toward improved understanding of the Paleogene evolution of the southern Nigerian sedimentary basin complex.

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