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Recognising Top of Overpressure Zone From Resistivity And Penetration Rate Data: NW Niger Delta, Nigeria.

C. Unuevho
Department of Geology, Federal University of Technology, Minna.

Abstract
The NW Niger Delta contains overpressure zones in the lower portion of its Agbada Formation, where prolific petroleum bearing sands exit. The bit has often penetrated the sands within the overpressure zone without warning and contingency preparation. This sometimes in the past resulted in loss of drilling rigs, logging equipment, oil wells and human life. Minor problems have included hole caving and stuck pipe. For petroleum development activities to continue safely and at reduced total well cost, the top of the overpressure zone must be recognized early and contingency drilling mud prepared in time at the well-site. Reversal in trend of resistivity and penetration rate value in shales, augmented by increased content of methane, ethane, propane and butane in gas librated from shales, clearly reveals the top of the overpressure zone. This top is a pressure seal constituted by a thick marine shale associated with calcite precipitation. This shale is the shallowest regional marine transgressive shale, and is lithostratigraphically Uvigelinella-5. When mud-log data and LWD (logging while drilling) resistivity data are analysed integratedly, the top of the overpressure zone will be predicted and recognized in real time at the well-site.

Introduction.

The Niger Delta is a clastic sedimentary basin at the northeastern margin of the Gulf of Guinea in West Coast of Africa (Fig. 1). The NW Niger Delta is constituted by the western portion of the basin's Northern Depobelt (Fig. 2). In this area, thick Cenozoic sediments overlie thin deeper water Cretaceous sediments, which in turn overlie the basement non-conformably (fig. 3). Its lithostratigraphic formations are Benin Formation (continuous fresh water bearing gravels and sands occasionally punctuated with shales and lignite fragments), Agbada Formation (sandstones and marine shales interbedded in rhythmic offlap sequences, with onlap marine sands separating successive offlaps) and Akata Formation (continuous marine shales with minor deep water sand and siltstones). Upper Cretaceous black shales underlie the Akata Formation, and have been described as deeper water Akate Facies by Schlumbarger (1985) and Ozumba (1997).

Petroleum reservoirs are in the Agbada Formation, which contains overpressure zones in the NW part of the basin (fig. 4). Enormous problems and losses arise when drilling bit penetrates the permeable portions within overpressure zones without forewarning for contingency preparations.

Early warning of overpressure risk will help quick modification of casing and drilling mud programme for optimal result. To improve on well-site safety and drilling economics, this work focuses on the recognition of the top of overpressure zones primarily from resistivity and penetration rate data, and secondarily from liberated gas and lithology data.

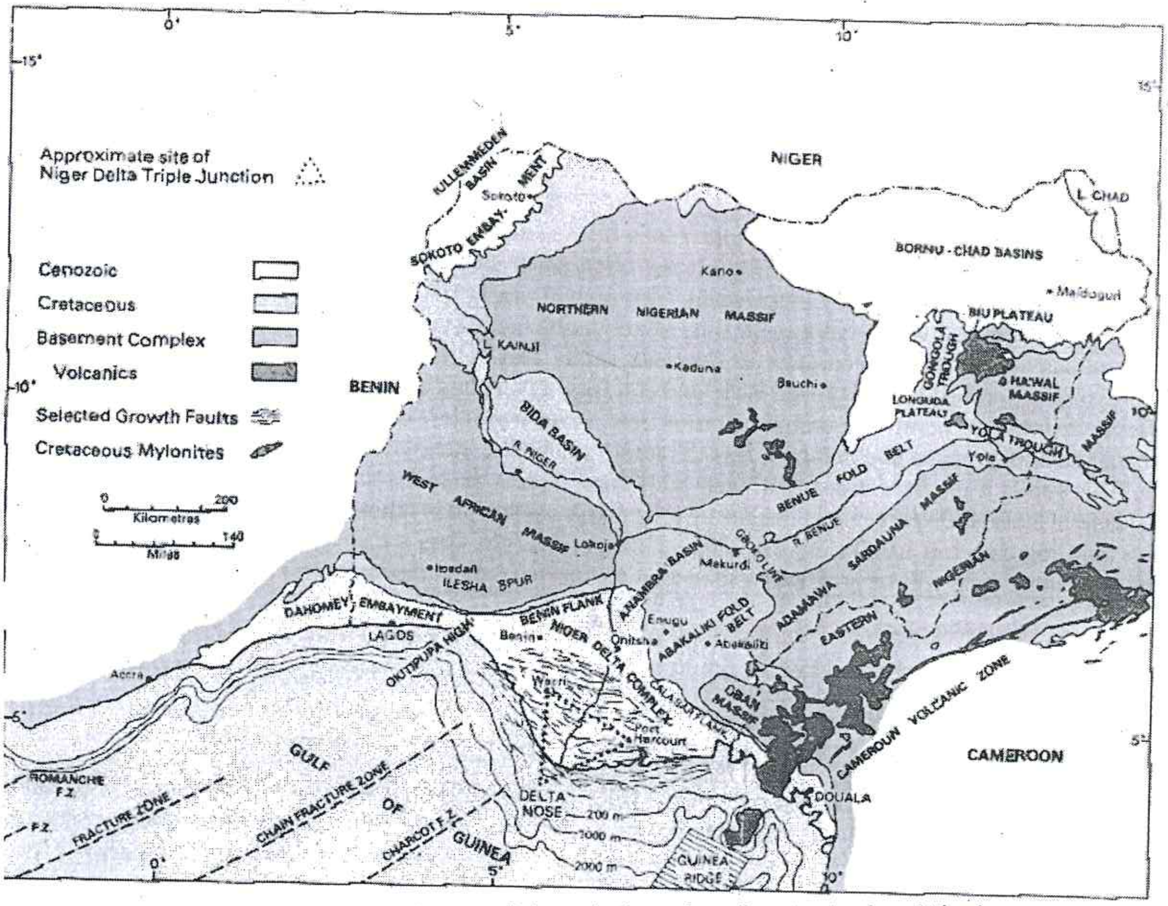


Fig. 1: Generalized geological map showing Niger Delta and other main sedimentary basins of Nigeria After Whiteman, 1982

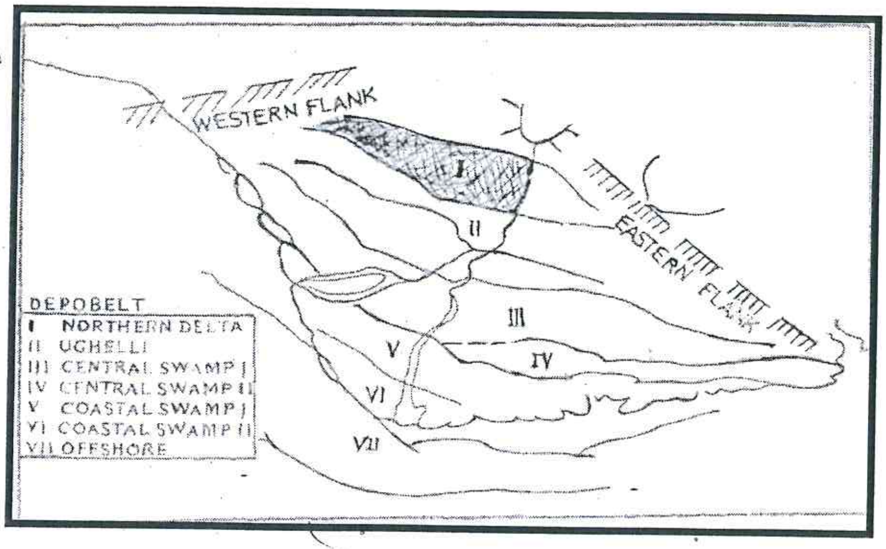


Fig. 2: Schematic map showing NW Niger Delta as the western portion of the Northern Depobelt.

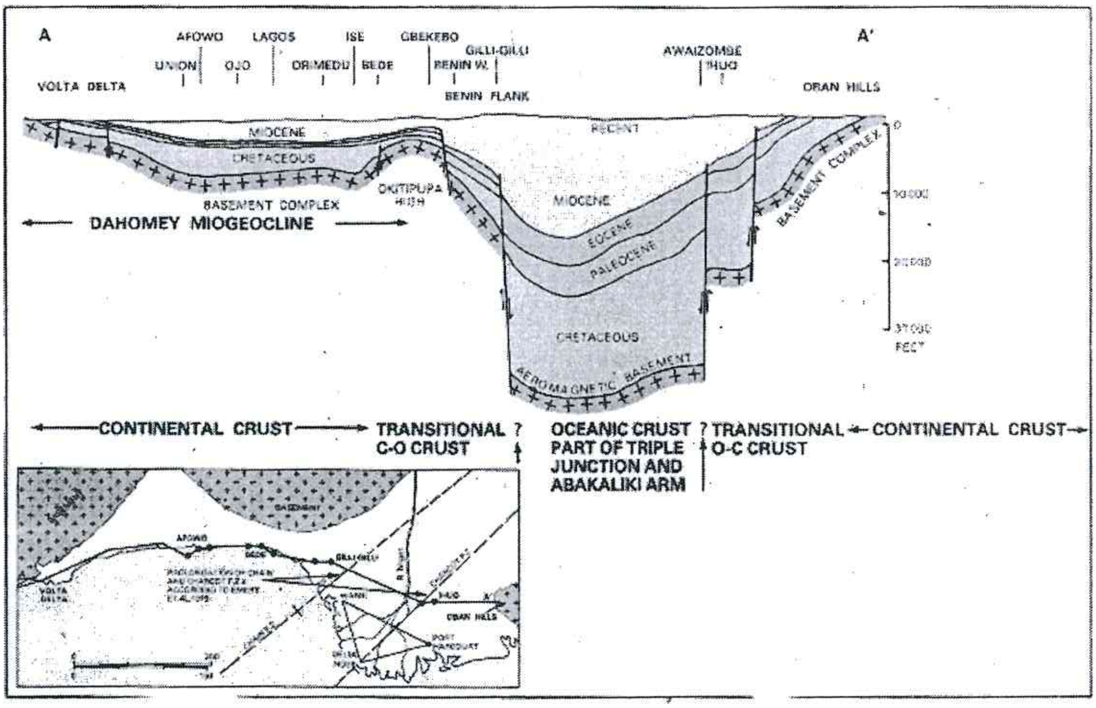


Fig. 3: NW Niger Delta (defined by Benin W. Gilli-Gill and Benin Flank) on east-west generalised geological section from Volta delta through Dahomey miogeocline to Oban hills.

After Whiteman, 1982.

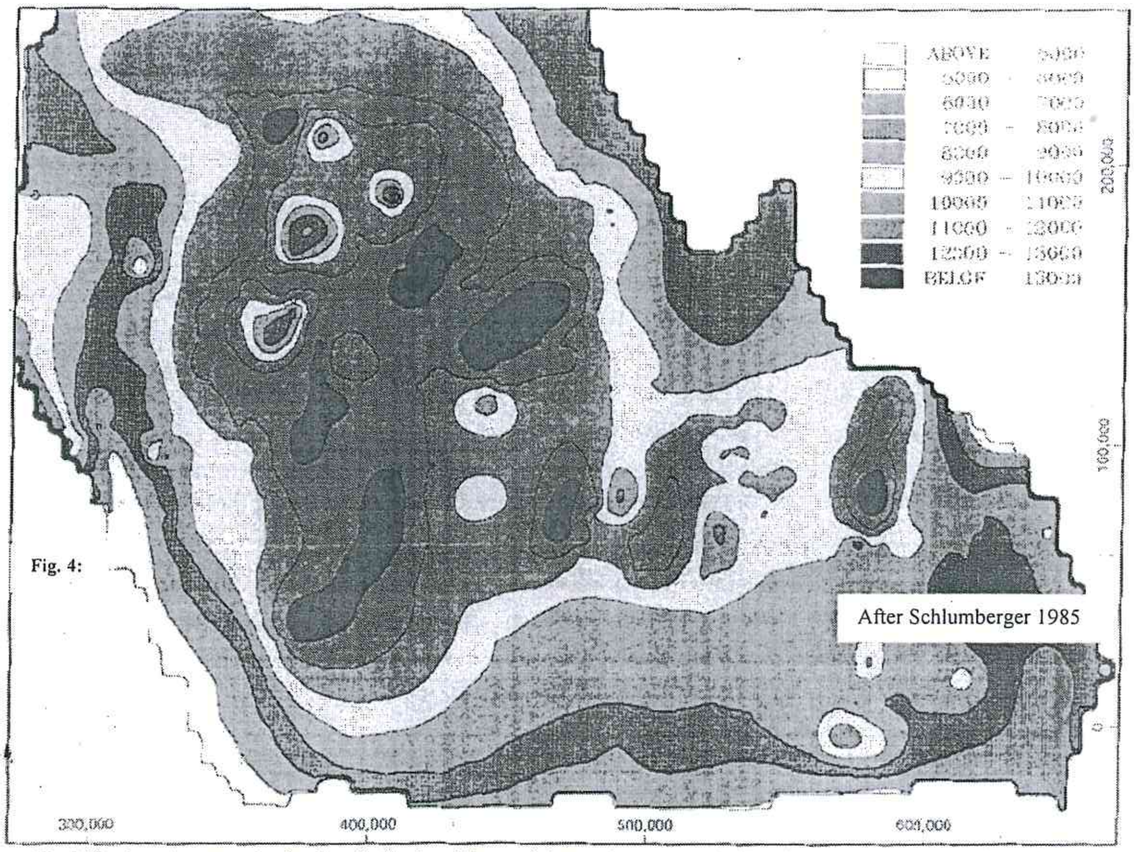


Fig. 4:

Fig. 3-12a. A contour map showing the distribution of the top of abnormal pressure in the Niger Delta area, based on data from 225 wells

Overview of Overpressure Concept and Related Drilling Problems

The subsurface pressure at any depth arises from the overburden weight above it. It is called the overburden pressure at the depth. Overburden pressure is the algebraic sum of matrix pressure (also known as lithostatic pressure) and pore pressure (also known as fluid pressure).

Overburden Pressure = Matrix Pressure + Pore Pressure

This algebraic relationship implies that the overburden weight above any depth is borne partly by the pore fluids and partly by the rock matrix. The overburden pressure, matrix pressure and pore pressure are routinely expressed as pressure gradients in psi/ft in well drilling and completion operations.

Overburden pressure in most sedimentary basins increases linearly with depth, resulting in a pressure gradient of about 1psi/ft. Thus pore pressure increases with depth. If the pore fluid is in continuous communication with the surface, the pore pressure is hydrostatic i.e. equal to that of a vertical column of water at the depth being considered. Thus hydrostatic pressure zones are regarded as open systems. Pore fluids under hydrostatic pressure have pressure gradient that lies between 0.43 and 0.47 psi/ft, depending on the pore water salinity.

The absolute value of pore pressure for fluids at any depth in hydrostatic pressure zone is given as follows:

$$Pp = ((dP/dD))_{water} \times D + 14.7 \text{ Psi}.$$

Pp = pore pressure.

dP/dD = prevalent hydrostatic pressure gradient.

D= depth at which Pp is determined

14.7 = value of atmospheric pressure in Psi

Constant salinity and continuity of water pressure gradient from the surface is assumed.

Pore fluids under hydrostatic pressure imply their host rock unit has been normally compacted. Compaction results from free escape of pore fluid accompanied by pore volume reduction, under the action of overburden weight that accumulated during subsidence. The result is a maximum matrix pressure. The extent of compaction is governed by the amount and rate of overburden loading and the hydraulic conductivity (rate of pore fluid dispersal) of the rock units.

During rapid sedimentation and subsidence, pore water is unable to escape from thick units of impermeable matrix and these results in undercompaction. The pressure on the rock matrix is reduced and the pore content bears a larger proportion of the overburden pressure, thereby acquiring pressure higher than hydrostatic. The pore pressure approaches the overburden pressure while the matrix pressure is abnormally low. The subsurface portion where pore pressure approximates overburden pressure is overpressure zone. An overpressure zone is a closed system since its pore fluids are cut off from communication with their neighbourhood pore fluids. Fig 5 is a schematic representation of a model structural configuration that can produce the pre – requisite closed system for overpressure generation in NW Niger Delta.

The absolute pore pressure (Pa) value at any depth (D) in an overpressure zone

can be conceptualised algebraically as follows:

$$Pa = ((dP/dD))_{water} \times D + 14.7 + C \text{ Psi}.$$

Where C is a positive constant and dP/dD is the overlying hydrostatic prevalent pressure gradient.

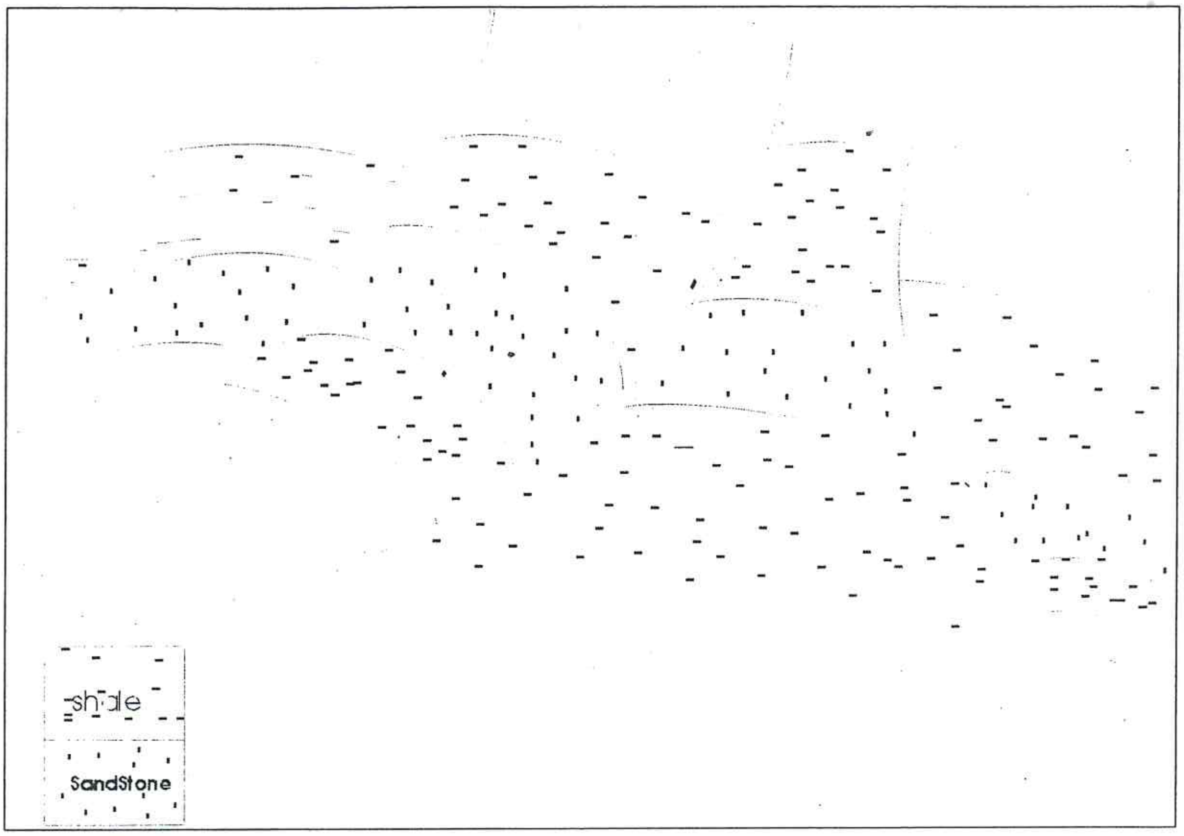


Fig. 5: Schematic Model of structural Configuration for abnormal pore pressure generation

Desirable effects of overpressure include:

1. Affecting hydrodynamic gradient by their higher potential and thereby encouraging hydrocarbon migration, and
2. Reinforcing seal efficiency, thereby protecting hydrocarbon accumulations.

Many major finds in young basins form around areas of anomalous geopressure (LeRoy *et al*, 2001). Waters (1987) remarked that prolific producing sands do not exist within overpressure zones.

It is common during drilling operation for the drilling mud's hydrostatic pressure to be lower than pore pressure in overpressure zone. This is under-balance drilling. The pressure differential is directed towards the hole, and tends to induce hole instability. One manifestation of hole instability is caving or bridging and fill on the hole bottom when going in hole. Kick (unwanted flow into the hole) or worse still blow – out (violent unwanted flow into the hole) may occur in the permeable portions of the hole during under- balance drilling. The bit has penetrated overpressure zones in many parts of the Niger Delta. Between 1950 and 1978 there were 13 blow – out incidents, four resulting in the loss of well or drilling rig or both (Ikeagwuani, 1979). At least one blow – out with fire out-break occurred in Northern Depobelt in 1993.

When deep wells are drilled with high density mud, the drilling mud's hydrostatic pressure becomes excessively higher than pore pressure in the normally compacted portion of the hole. If this portion is uncased, the drilling string can get stuck there. It will become impossible to raise, rotate or lower it. In the hydrostatic pressure zones, the excessive mud pressure can also induce formation wall fracturing – which will cause loss of circulation (mud volume returning from hole lesser than that going in). Added rig time is spent on solving hole instability and fishing stuck pipe. These are heavy additions to overall well cost (Bratton *et al*, 2001).

Methodology

An overpressure well chosen from NW Niger Delta was renamed OH to preserve its data confidentiality and technical value.

Resistivity, penetration rate, and gas chromatographic logs of OH (recorded in the conventional spectral form) were digitized and tabulated. The top of Agbada Formation was established. The lower portion of the Agbada Formation was also established. Resistivity and rate of penetration values of shales in the Agbada Formation were plotted on a semi-log (log-linear) graph. Lines of best fit were drawn through the plotted values to establish two trends: the trend in which the values increase with depth, and the trend in which the values decrease with depth. Trend patterns were compared with the pattern of occurrence of methane, ethane, propane and butane contents of formation gas liberated in shales. These were also compared with thickness variation and mineral composition variation in the shales.

Data analysis and discussion

Agbada Formation begins at 8550ft in well – OH. This depth is marked by the first appearance of glauconitic shales. Beneath it, ditch cuttings become generally glauconitic, calcareous and shelly. Shale resistivity is generally higher than 12 ohm – metre above this depth. But the resistivity dropped markedly to generally ≤ 7 ohm – metre from the depth downwards, and log motif is generally upward coarsening (Fig 6 and table 1)

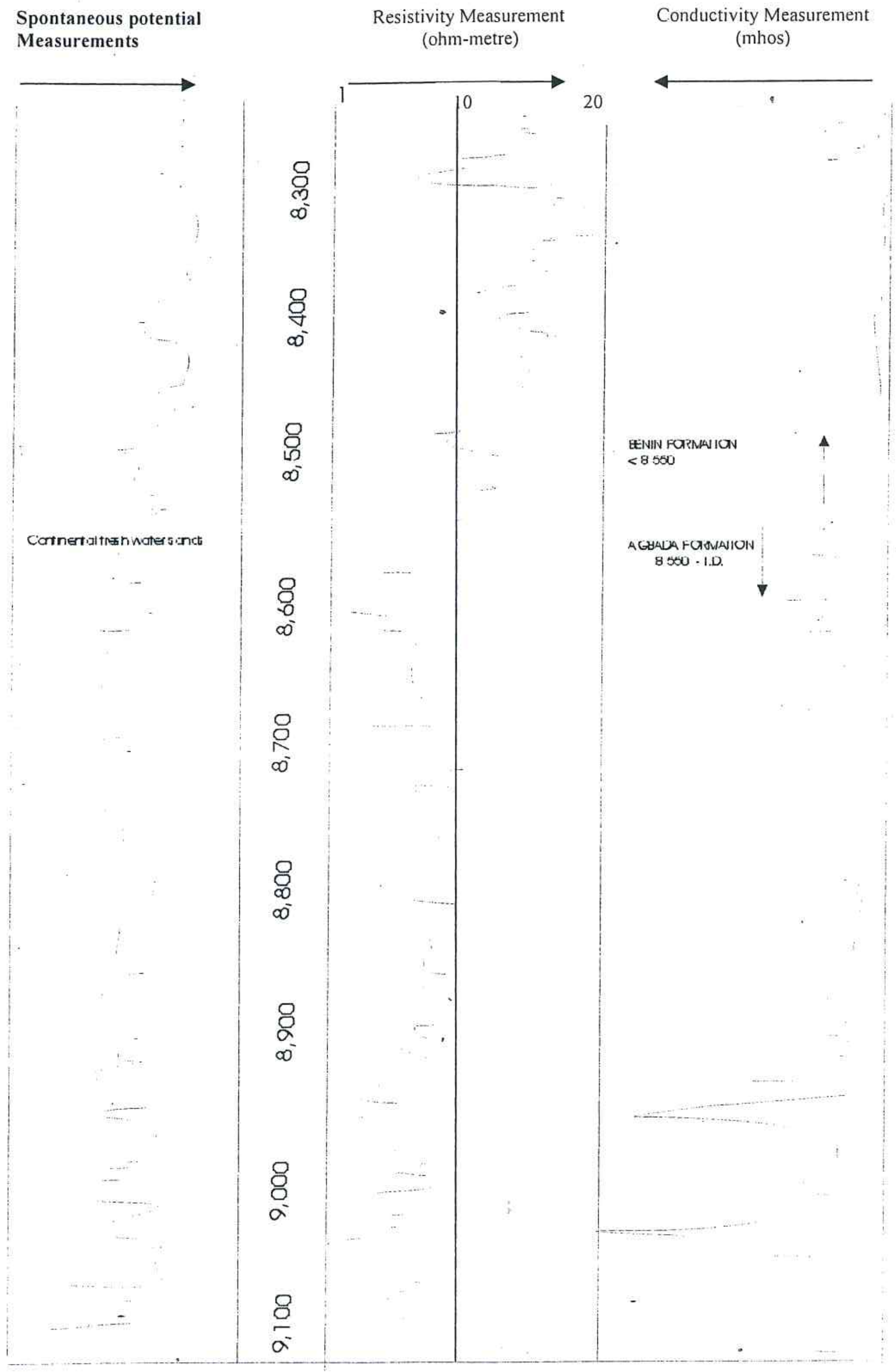


Fig. 6: Part of composite log of Well OH

Table 1

Values of Resistivity, Rate of Penetration and Gas Chromatogram in Drilled Agbada Shales in Well OH, NW Niger Delta.

Top of Agbada Formation: 8550ft.

Shale Depth (ft)	Shale Resistivity (Ohm-metre)	ROP in Shale (ft / 5 min)	C_1 (Methane)	C_2 (Ethane)	C_3 (Propane)	C_4 (Butane)	Mud weig (Ibs / gal)
85.70	6	25	7	-	-	-	9.7
8670	3	27	7	-	-	-	//
8685	3.5	28	7	7	-	-	//
8970	1.5	20	10	-	-	-	//
9050	1	28	7	-	-	-	//
9080	3.5	30	7	-	-	-	//
9205	3	22	7	-	-	-	//
9235	3	30	7	-	-	-	//
9355	3.5	40	7	-	-	-	//
9390	5	37	7	-	-	-	//
9425	5	30	7	-	-	-	//
9460	6	31	-	-	-	-	//
9575	4	40	7	-	-	-	9.9
9675	3	40	7	-	--	-	//
9715	6	22	-	-		-	//
Shale Depth (ft)	Shale Resistivity (Ohm-metre)	ROP in Shale (ft / 5 min)	C_1 (Methane)	C_2 (Ethane)	C_3 (Propane)	C_4 (Butane)	Mud weig (Ibs / gal

9830	5	22	7	-	-	-	9.9
9945	1.8	40	5	-	-	-	//
10,035	4.5	25	3	-	-	-	//
10,110	2	37	5	3	-	-	10.3
10,230	1.8	50	3	-	-	-	//
10,285	4	-	3	3	-	-	//
10,430	3	40	5	-	-	-	//
10,610	3	70	5	3	4	-	//
10,650	3.5	40	35	20	7	-	//
10,700	3	55	75	35	20	15	//
10,770	2	55	15	10	7	-	//
10,800	4	60	40	25	15	20	//
10,850	4	40	-	-	-	-	//
10,950	3.5	55	50	30	10	7	//
11,035	3	55	50	30	10	7	//
11,165	3	50	-	-	-	-	//
11,220	2.5	60	10	5	5	-	//
11,250	3	50	5	5	5	-	//
11,320	2	20	250	60	20	20	//
11,500	3	30	130	60	45	20	//
11,520	2.8	35	35	35	30	7	//
11,630	2	50	35	35	30	7	//

Shale Depth (ft)	Shale Resistivity (Ohm-metre)	ROP in Shale (ft / 5 min)	C_1 (Methane)	C_2 (Ethane)	C_3 (Propane)	C_4 (Butane)	Mud weight (Ibs/gal)
11,670	2.4	50	35	35	30	7	10.3
11,740	2	25	35	20	20	10	//
11,800	1.5	30	20	15	7	10	//
11,830	1.7	40	200	150	150	-	//
11,910	2.8	50	25	130	60	70	11.4
12,210	3	50	-	-	-	-	//
12,260	4.7	40	-	-	-	-	//
12,350	3	50	10	15	15	15	//
12,400	3	48	180	130	70	45	//
12,445	3	48	-	-	-	-	//
12,660	2.50	128	-	-	-	-	13.7
12,880	3	96	10	20	20	20	//
12,980	4	40	-	-	-	-	14.3
13,035	3	60	-	-	-	-	//
13,010	2.8	55	-	-	-	-	//
13,120	3	80	-	-	-	-	14.9

Thus the freshwater continental Benin Formation bottoms at 8550ft.

The lower portion of the Agbada Formation begins at 9550ft in OH. Sand percentage per 100ft is > 40% above this depth and ≤ 40 % below it (table 2).

TABLE 2: Sand Percentages Per 100ft Increment in Depth in Well OH (Agbada Formation Top: 8550ft)

Depth Interval (ft)	Sand Percentage	Stratigraphic Interpretation
8550 – 8650	60	Upper Agbada
8650 – 8750	60	//
8750 – 8850	70	//
8850 – 8950	40	//
8950 – 9050	50	//
9050 – 9150	55	//
9150 – 9250	65	//
9250 – 9350	50	//
9350 – 9450	60	//
9450 – 9550	80	Lower Agbada
9550 – 9650	40	//
9650 – 9750	30	//
9750 – 9850	40	//
9850 – 9950	55	//
9950 – 10050	40	//
10050 – 10150	40	//
10150 – 10250	40	//
10250 – 10350	60	//
10350 – 10450	20	//
10450 - 10550	60	//
Depth Interval (ft)	Sand Percentage	Stratigraphic Interpretation
10550 – 10650	30	Lower Agbada
10650 – 10750	0	//
10750 – 10850	0	//
10850 – 10950	60	//
10950 – 11050	30	//
11050 – 11150	50	//
11150 – 11250	15	//
11250 – 11350	10	//
11350 – 11450	40	//
11450 – 11550	45	//
11550 – 11650	35	//
11650 – 11750	30	//
11750 – 11850	5	//
11850 – 11950	30	//
11950 – 12050	35	//
12050 – 12150	35	//
12150 – 12250	40	//
12250 – 12350	40	//
12359 – 12450	20	//
12450 – 12550	50	//
12550 – 12650	30	//

12650 – 12750 12750 – 12850 12850 – 12850 12950 - 13050	30 30 30 35	//

Short and Stauble (1967), Schlumberger (1985), Udo and Ekweozor (1988), Doust and Omatsola (1990), and Braide (1993), distinguished the lower and upper portions of the Agbada Formation. They recognized higher sand content in the upper portion and higher shale content (lower sand content) in the lower portion.

Fig 7 is a linear – log plot of resistivity and ROP values against depth, for shales of Agbada Formation. Values of both physical quantities increase with depth until 10650 ft depth, where they change trend and begin to decrease with depth. The shales above 10650ft depth are interpreted to be normally compacted.

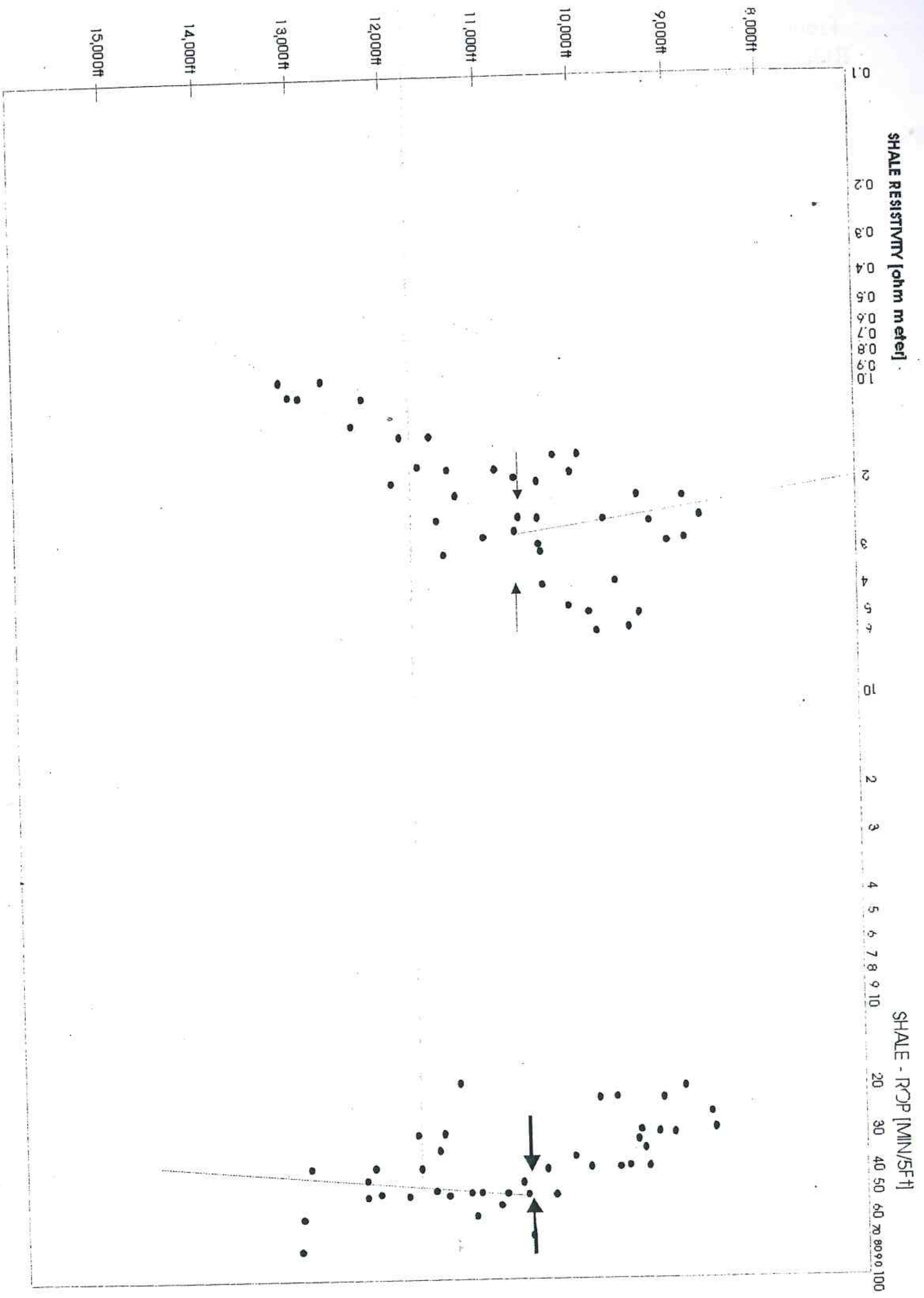


Fig. 7: SHALE RESISTIVITY AND ROP VERSUS DEPTH

Trend of increasing shale resistivity and ROP with depth is routinely associated with zone of normal compaction (Onuoha 1983, Mouchet and Mitchell 1985, Schlumberger 1985 and 1987, Vern *et al* 1998). Fluid resistivity is assumed constant for shales in the upper portion of the Agbada Formation. When fluid resistivity remains constant, a unit increase in shale resistivity comes from a reduction in porosity by overburden effect. In the upper portions of the Agbada Formation, shales are saturated only with marine water and thus expected to have a constant or near constant pore fluid resistivity. Shales in the upper portions of the formation, lack the necessary thermal maturation for petroleum generation (Evamy *et al* 1978, Ejedawe *et al* 1984, Udo and Ekweozor 1988, Ekweozor and Daukoru 1992). Therefore there is no residual petroleum to affect their pore resistivity.

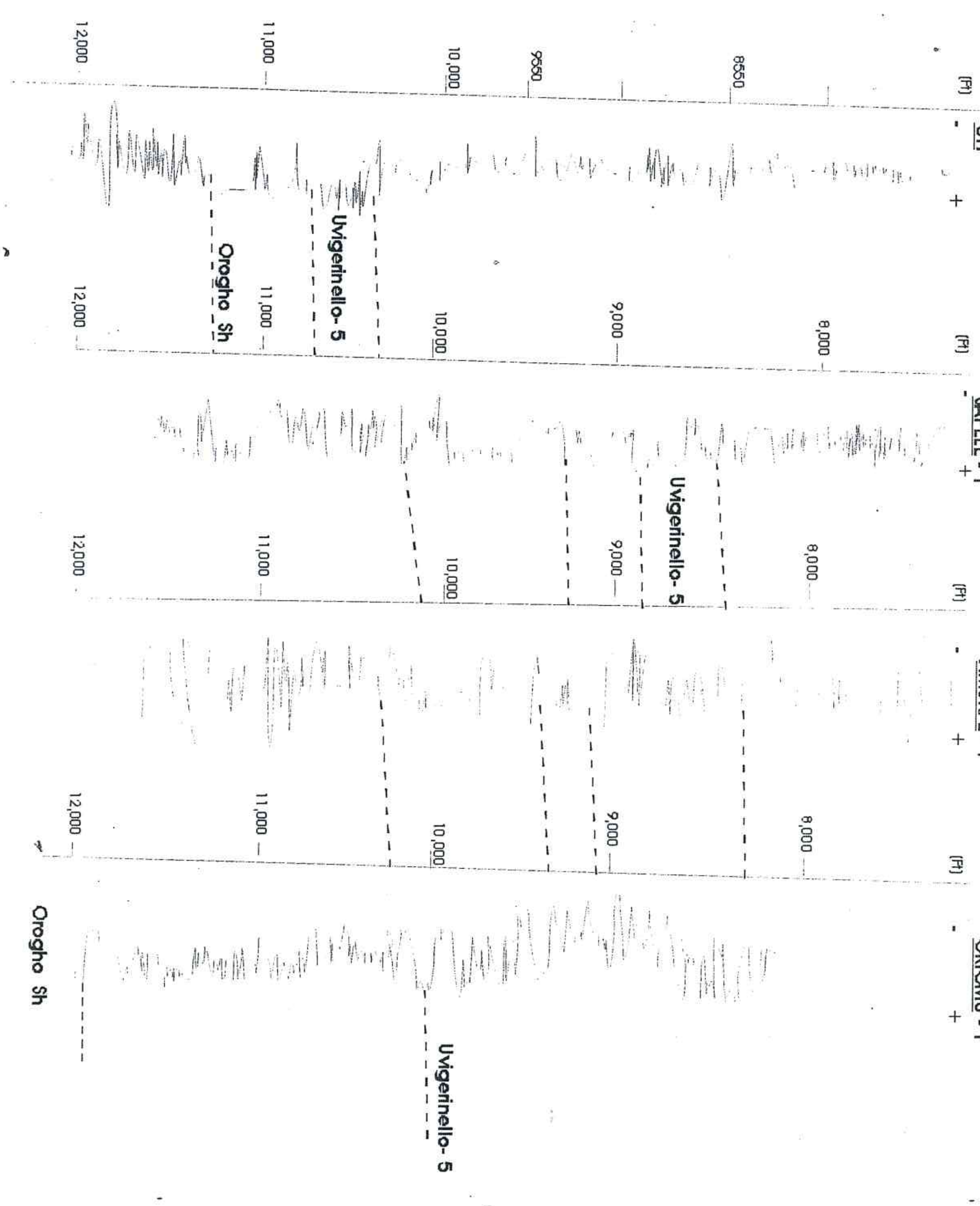
The shales below 10,650 ft depth are interpreted to be undercompacted. Trend of decreasing shale resistivity and ROP with depth is commonly associated with undercompaction (Onuoha 1983, Schlumberger 1985 and 1987, Mouchet and Mitchell 1989, Vern *et al* 1998). The decreasing values of resistivity and ROP in the shales come essentially from the relative increase in porosity. Increasing relative porosity under increasing overburden load implies increasing volume of pore fluid under increasing overburden load. The bulk density of shales becomes abnormally low. The shale matrix stress consequently gets abnormally low. The pore fluids bear the bulk of the overburden stress. It is this that makes the shale matrix mechanically weaker (i.e. gives them low tensile strength) and increases ROP in them.

Thus depth from 10650 ft downwards forms the overpressure zone, whose top is the 10650 ft depth horizon. Depth above 10650 ft forms the hydrostatic pressure zone.

Gas chromatogram content (methane, ethane, propane and butane proportion of the liberated formation gas) from the sands in the overpressure zone increased enormously.

Table 1 shows that ethane, propane and butane are generally absent between 8570 and 10650 ft – zone interpreted to be under hydrostatic pressure. Ethane begins to show up from 10, 110ft depth, as the top of the overpressure is approached. The top of the overpressure zone downwards is marked by abundant shows of methane, ethane, propane, and butane, and or sharp increase in background gas. The increase in gas shows is due to the generally higher gas content in under-compacted shales, increased ROP and a drop in differential pressure. Mouchet and Mitchell (1989) remarked that under-compacted clay zone often have high gas content, and that the occurrence or increased incidence of heavier gas components is commonly observed when drilling into overpressure transition zone. The 10,650 ft depth – level is the top of 250 ft thick shale with abundant calcite crystals. The carbonated shale is interpreted to be a seal, capping the overpressure zone. The shale is the first regional transgressive marine shale in well OH, and is interpreted as being lithostratigraphically equivalent to Uvigerinella – 5 (Fig 8) of Ladipo (1992).

Fig. 8: Stratigraphic position of Uvigerinella - 5 in well Oh and some other wells in NW Niger Delta (Addapted from Ladipo 1992)



Hottman and Johnson (1965) noted that during the mid – 60's, various workers in the Gulf Coast of the United States observed that resistivity and density decreased markedly in thick shales prior to significant pressure kicks.

At well – sites in NW Niger Delta, early warning of overpressure risks will come from a reversal in resistivity and ROP trend in the Agbada Formation shale, the appearance of increased content of background gas, propane and butane in shales and the recognition of Uvigerinella – 5 by lithostratigraphic correlation. The engagement of LWD tools will provide resistivity measurements, and facilitate lithostartigraphic correlation with mud – log data in real - time. In the Niger Delta, the LWD resistivity tools have proved that it can give a comparable resistivity measurement to the corresponding induction wire – line devices (Adeyemo, 1993).

The top of the overpressure zone is blurred when examined with only resistivity measurements or ROP measurements. But it becomes clearly identifiable when the two measurements are combined and backed up with analysis of chromatogram composition of gas shows, and the composition and thickness of shales. Successful overpressure modelling requires an integration of ;data from diverse sources (Bridges, 2003).

The recognized top of overpressure zone in well OH falls within the generalized depth range forecast for NW Niger Delta by Schlumberger, 1985 (fig. 4). Pockets of high shale resistivity in the overpressure zone are associated with residual petroleum in source rocks (constituted by the host shales).

Conclusions

Overpressure zones in NW Niger Delta exist in the lower portion of Agbada Formation, where shale percentage per 100ft is ≥ 60%. At the top of the zone, ROP and resistivity values in shales show a reversed trend from downward increasing to downward decreasing. The reversal is supported by marked increase in ethane, propane and butane content of the formation gas liberated from the shales. The overpressured top is the shallowest regional marine transgressive shale, and is marked with calcitization. Lithostratigraphically, it is the Uvigerinella – 5 shale. Early warning at the well – site will be obtained from combination of LWD resistivity and mud log data.

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