

## A GEOSTATISTICAL REVIEW OF THE BITUMEN RESERVES OF THE UPPER CRETACEOUS AFOWO FORMATION AGBABU AREA, ONDO STATE, EASTERN DAHOMEY BASIN, NIGERIA

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### Abstract

This study was an attempt at a geostatistical estimation and quantification of two Upper Cretaceous tar-bearing horizons X and Y from forty boreholes as against the conventional, non-spatial estimation methods that were used to estimate the reserves by previous authors. This is with a view to possibly obtaining a reliable, unbiased assessment of the bitumen reserves in the study area.

The geologic continuity in the depth, thickness and dry tar concentration from the horizons were quantified using exponential variogram models and gridded using the ordinary kriging algorithm. The gridding allowed for estimation of the modelled properties at 2800 points making up 2673 squares (sub-areas) of approximately 150 x 150 m<sup>2</sup> each. The estimated parameters were used to obtain the total mineable tar sand (TMT) in metric tonnes, bitumen-in-place (BIP) and probable recoverable reserves (pRRE) in barrels at 10%, 25%, 50%, 75%, 85% and 90% recovery factors (RF).

The TMT for the X and Y horizons is about 3.99 billion metric tons while the BIP is about 2.76 billion barrels. The RREs are 275 million barrels, 689 million barrels, 1.38 billion barrels; 2.07 billion barrels; 2.34 billion barrels and 2.48 billion barrels at 10%, 25%, 50%, 75%, 85% and 90% respectively. These values are different from the estimates by previous workers by a factor of 2.17. This difference was attributed to the fact that (1) previous estimate was limited to within 50 m overburden, and that (2) kriging provides best linear unbiased estimates. The reserves estimates obtained in this study are therefore considered to be more representative of the bitumen reserves from the two horizons within the project area.

**Keywords:** Geostatistical; Bitumen; Reserves; Review; Dahomey Basin; Nigeria.

### 1. Introduction

The Cretaceous tar sand formations in Ondo State occur on the eastern margin of the Dahomey (Benin) Basin (Fig.1). This is a coastal sedimentary basin extending from the Ghana-Ivory Coast boundary, through Togo and Benin Republics to Southwestern Nigeria [1]. The basin ends at the western margin of the Niger Delta Basin from which it is separated by the Okitipupa structural high and a major regional fault, the Benin Hinge Line [2-3]. Several works have been in this study area [4-15] but the currently quoted estimate of the bitumen reserves in the area is based on the use of non-geostatistical estimation methods [4].

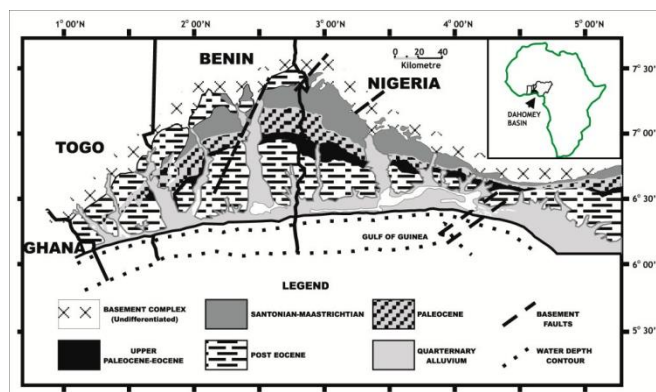


Figure 1 Regional Geologic Map of the Dahomey Basin [1] [26]

The non-geostatistical methods have been shown to make the description and quantification of spread and standard deviation of data distribution difficult because they do not incorporate spatial locations of data in their defining computations compared to geostatistical estimation methods [16]. Geostatistical estimation methods on the other hand, thrive on the fact that they provide a set of statistical tools for incorporating the spatial and temporal coordinates of observations in earth data processing [17]. The methods clearly identify the basis of the models used [18] unlike many other estimation methods (such as linear regression, inverse distance, or least squares) that do not state the nature of their model. The geostatistical methods assume the source data points are a specific statistical sample or realization from some true underlying surface function, and this sample is first analyzed in order to create a suitable model that will provide the best possible estimate of this underlying surface [19]. Moreover, geostatistical methods have been shown to provide reliable estimate and improved answers to problems of exploration and exploitation of mineral deposits [20-24].

Adegoke *et al.* [4] conducted detailed studies of the Agbabu area portion of the tar sand belt that showed that the tar sands occur as two distinct stratigraphic bands (X and Y horizons) separated by a uniformly thick oil shale within the Upper Cretaceous Afowo Formation. The petrophysical properties obtained for each horizon included depth, thickness and dry tar concentration from the analysis of cores and logs in forty boreholes [15, 25]. They obtained the currently quoted reserves by limiting their estimation of the bitumen reserves to within overburden of less than or equal to 50 m for possible surface mining at that time.

The current article seeks to re-appraise the bitumen reserves using the ordinary kriging geostatistical method with a view to modeling the spatial structure of the initial borehole data and possibly obtaining a much more reliable and unbiased estimate of the bitumen reserves.

## 2. Review of the Geologic Setting of the Study Area

The project area (Fig. 2) is a portion of the Dahomey Basin in southwestern Nigeria [4]. The inception and development of the Dahomey Basin was triggered by the tectonic activities which accompanied the opening of the Atlantic Ocean and separation of West African from Brazil during the Cretaceous [25]. Basement subsidence during lower Cretaceous resulted in the deposition of a thick sequence of continental sediments. During the early Late Cretaceous (probably Santonian), there was another episode of major tectonic activities associated with closure and folding of the Benue trough. The granites, gneisses and associated pegmatites in the Dahomey Basin were tilted and block-faulted forming a series of horsts and grabens [25].

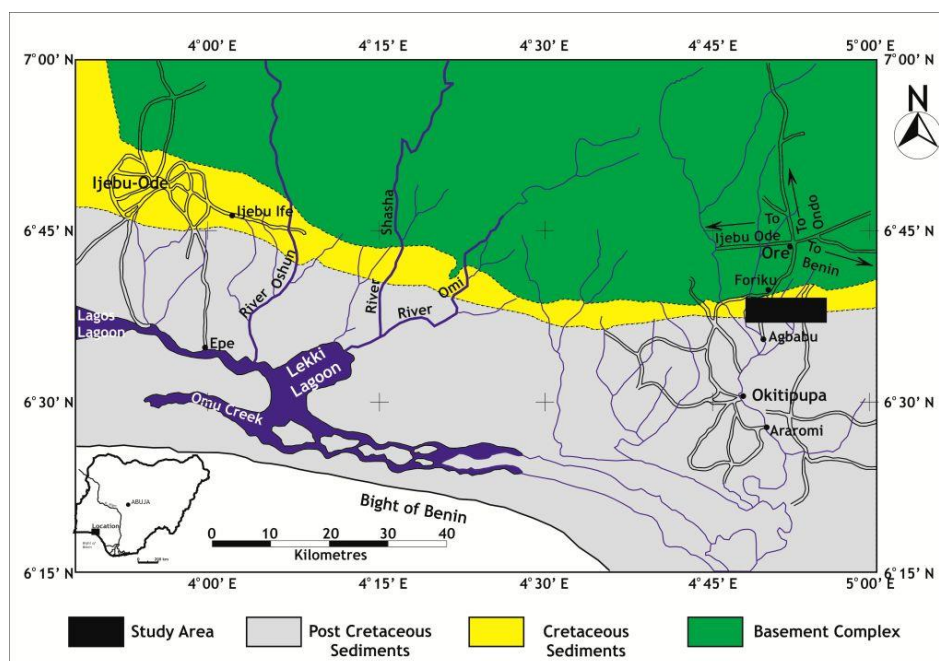


Figure 2 Geological Map of Southwestern Nigeria Showing the Study Area [4, 6,13].

During the Maastrichtian, the basin became quiescent and has experienced only gentle subsidence since then. Relatively thick sequences of sands with interbedded organic shales

were deposited in an environment that changed rapidly from continental and estuarine initially through brackish to open marine. These sands, are moderately to very heavily impregnated with bituminous heavy oils [4]. By Upper Maastrichtian to Palaeocene times, normal marine conditions were fully established in much of the basin as adjudged by the abundant record of marine molluscs, benthonic and planktonic foraminifera, ostracodes and spores. The transitional to the fully marine lower Tertiary sequence is mostly shales, rich in organic matter with subordinate sandstone and occasional thin limestone bands [4].

The stratigraphy of the Dahomey Basin was studied by [26] but was reviewed by [25] on the basis of fresh subsurface data. The Dahomey basin is a coastal sedimentary basin filled with over 2500 m of Cretaceous and younger sediments unconformably overlying the block faulted Basement Complex rocks [15]. The basin's sedimentary fill was subdivided into three intervals by [27] namely, (a) Sand and sandstones at the base, (b) alternating sands and shales and (c) upper shales. These divisions correspond to the three formations of Ise, Afowo and Araromi respectively [25]. The generalized stratigraphic column of the Basin is shown in Figure 3.

Period	Age	Stratigraphic Units
Neogene	Recent	Alluvium
	Oligocene to Pleistocene	Benin Formation
Paleogene	Eocene	Ilaro Formation Oshosun Member
	Paleocene	Imo Akinbo Formation Ewekoro Formation
Late Cretaceous	Neocomian to Maastrichtian	Abeokuta Group Araromi Formation Afowo Formation Ise Formation
Precambrian to Lower Paleozoic		Basement Complex

Figure 3: Stratigraphic Successions in Eastern Dahomey Basin [25] [28][29].

## 2.1 Ise Formation

This Formation is the oldest, and overlies the weathered Basement Complex [25-26]. It is comprised of conglomeratic sands showing upward fining variation into finer grained sands. Kaolinitic clays are quite obvious as interbeds and at the sediment/basement contact. Quartz is the major constituent of the sands, though some other minerals (mica, heavy minerals) have been reported in minor amounts. Ise sediments are water-bearing [1] and are hardly encountered in the stratigraphic record as most of it had been eroded following the Santonian tectonics that affected the basement complex rocks. A Niccomian age is assigned to this Formation [25].

## 2.2 Afowo Formation

The Afowo sediments indicate the commencement of deposition in a transitional environment after the entirely basal and continental Ise Formation [25-26]. The sediments are composed of interbedded sands, shales and clays. The sands are tar-bearing whilst the shales are organic rich [1]. Outcrops of this formation are commonly encountered within the tar sand belt and are easily recognizable because of the presence of sticky and viscous tar seeping out of the sandy portions of the Afowo Formation. The age is Maastrichtian [25].

## 2.3 Araromi Formation

Sediments of the Araromi Formation represent the youngest and topmost sedimentary sequence in the sub-basin. They are comprised of shales, fine grained sands, thin interbeds of limestone, clay and lignitic bands. It is attributed to an age range of Maastrichtian to Palaeocene [25-26]. This formation acts as the top seal preventing upward loss of the oils [1].

## 3. The Kriging Technique

Kriging is a geostatistical algorithm that has its origin in mining exploration for the prediction of ore trends [30]. It is a collection of techniques that create surfaces that incorporate the statistical properties [31]. It is synonymous with optimal prediction [32]. It is a method of interpolation which predicts estimated values from observed data at known locations. This method uses variogram to express the spatial variation, and it minimizes the error of predicted values which are estimated by spatial distribution of the predicted values. It is also defined as optimal interpolation based on regression against observed  $Z$  values of surrounding data points, weighted according to spatial covariance values [17]. It has the characteristics of being able to minimize estimation error (the difference between measured value - the re-estimated value) and honor "hard" data. Moreover, in comparing estimation methods, [33] showed that kriging was the best in that it overestimates the least. According to [30], kriging process can be divided into two tasks, namely (1) quantifying the spatial structure of the data by the use of variogram and (2) producing a prediction (a matrix solution) surface

There are a number of kriging algorithms [30,34-42] and each is distinguished by how the mean value is determined and used during the estimation process. The four most commonly used methods are: simple kriging (SK), ordinary kriging (OK), kriging with an external drift (KED), and indicator kriging (IK). For the purpose of this study, the ordinary kriging algorithm was adopted. It is considered to be the most straight-forward since it is the only algorithm that can compute from semi-variogram (or co-variogram) relationship without having to provide additional qualifying data or pre- or post-manipulation of the sample data or kriging results [43-44].

According to [17], all kriging estimators are variants of the basic linear regression estimator  $Z^*(u)$  defined as

$$Z^*(u) - m(u) = \sum_{\alpha=1}^{n(u)} \lambda_{\alpha} [Z(u_{\alpha}) - m(u_{\alpha})] \quad 1$$

where  $(u, u_{\alpha})$  is the location vectors for estimation point and one of the neighbouring data points, indexed by  $\alpha$ ;  $n(u)$  is the number of data points in local neighbourhood used for estimation of  $Z^*(u)$ ;  $m(u)$ ,  $m(u_{\alpha})$  are the expected values (means) of  $Z(u)$  and  $Z(u_{\alpha})$ ; and  $\lambda_{\alpha}(u)$  is the kriging weight assigned to datum  $Z(u_{\alpha})$  for estimation location  $u$ . The same datum will receive different weight for different estimation location.

The goal is to determine weights,  $\lambda_{\alpha}$ , that minimize the variance of the estimator,  $\sigma_E^2(u) = \text{Var}\{Z^*(u) - Z(u)\}$  under the unbiasedness constraint  $E\{Z^*(u) - Z(u)\} = 0$ . The random variable (RV)  $Z(u)$  is decomposed into residual and trend components with the residual component treated as a random function (RF) with a stationary mean of 0 and a stationary covariance,  $C(h)$  which is a function of lag,  $h$ , but not of position,  $u$ . The residual covariance function is generally derived from the input semivariogram  $\gamma(h)$  model defined as

$$C(h) = C(0) - \gamma(h) = \text{Sill} - \gamma(h) \quad 2$$

The OK estimates the value of a point from a set of nearby random variables  $Z(u_{\alpha})$  [18]. The system includes  $(n(u)+1)$  linear equations with  $(n(u)+1)$  unknowns. In this case, the system of equations for the kriging weights turns out to be:

$$\begin{cases} \sum_{\beta=1}^{n(u)} \lambda_{\beta}^{OK}(u) C(u_{\alpha} - u_{\beta}) + \mu_{OK}(u) = C(u_{\alpha} - u) & \alpha = 1, \dots, n(u) \\ \sum_{\beta=1}^{n(u)} \lambda_{\beta}^{OK}(u) = 1 \end{cases} \quad 3$$

This can be written in matrix form as  $K\lambda_{OK}(u) = k$ . Such that  $\lambda_{OK}(u) = K^{-1}k$ . Where  $K$  is the matrix of covariances between data points, with elements  $K_{\alpha, \beta} = C(u_{\alpha} - u_{\beta})$ ,  $k$  is the vector of covariances between the data points and the estimation point, with elements given by  $k_{\alpha} = C(u_{\alpha} - u)$ , and  $\lambda_{OK}(u)$  is the vector of ordinary kriging weights for the surrounding data points [45]. Multiplying  $k$  by  $K^{-1}$  will downweight points falling in clusters relative to isolated points at the same distance [45].

#### 4. Methodology

This paper used the ordinary kriging algorithm to provide a geostatistical reserves estimate of the bitumen within the study area. The inputs into the kriging algorithm were the depth, thickness and dry tar concentration obtained from forty boreholes drilled in the area. The methodology was achieved in three main steps: (1) quantification of geologic continuity, (2) estimation of data using ordinary kriging algorithm, and (3) determination of bitumen-in-place (BIP) and probable recoverable reserves estimates (pRRE) of bitumen.

##### 4.1 Quantification of Geologic Continuity

The geologic continuity in the depth, thickness and dry tar concentration was quantified through variogram analysis. After trying out several models, the exponential model was selected as the most appropriate to model the geologic continuity of the various data with different sill and range values for the X and Y horizons. The exponential variogram model is defined mathematically as,

$$\gamma(h) = c \left[ 1 - \exp\left(-\frac{3h}{a}\right) \right] \quad 4$$

where  $c$  = contribution (a measure of variance),  $a$  = practical range,  $h$  = lag distance. The experimental variogram was compared to the mathematical model until a best fit was achieved. Figure 4 summarizes the variogram characteristics of the petrophysical parameters obtained from the modelling.

##### 4.2 Estimation of Bitumen Properties

The point kriging algorithm with no drift (Ordinary Kriging) in Surfer 8, a surface mapping software from Golden Software™ was used to interpolate the depth, thickness and dry tar content constrained by the variogram model for each horizon. The gridding allowed for the estimation of these properties at 2800 points making up 2673 cells. Each cell is a square whose length is 153.6098 m and width is 152.4055 m, approximately 0.15 km in both directions and having an area of 0.023 km<sup>2</sup>.

##### 4.3 Determination of Bitumen-in-Place and Probable Recoverable Bitumen Reserves

The reserves estimate for bitumen in the study area was achieved in four steps. First, the volume of tar sand per cell was estimated by multiplying the average thickness with the area of the cell. Second, the mineable reserves of tar sand which is also the bulk weight was obtained by multiplying the volume with a tonnage factor (density) of 2.24 g/cm<sup>3</sup> [4]. Third, the bitumen-in-place (BIP) in metric tons was calculated by multiplying the mineable tar sand with average tar concentration. Finally, the BIP in barrel was obtained by multiplying the BIP in metric tons by an estimated barrel factor of 6.4977. The barrel factor was derived from the average specific gravity for bitumen in the study area.

The probable recoverable reserves estimates at 10%, 25%, 50%, 75%, 85% and 90% recovery factors for the X and Y horizons respectively were determined for the project area and presented in Table I. The reserves estimate obtained at 85% recovery factor in this study was compared to that obtained by [4] at the same recovery rate being the rate at which the Athabasca tars were recovered at the time based on the similarities in the properties with the bitumen of Nigeria.



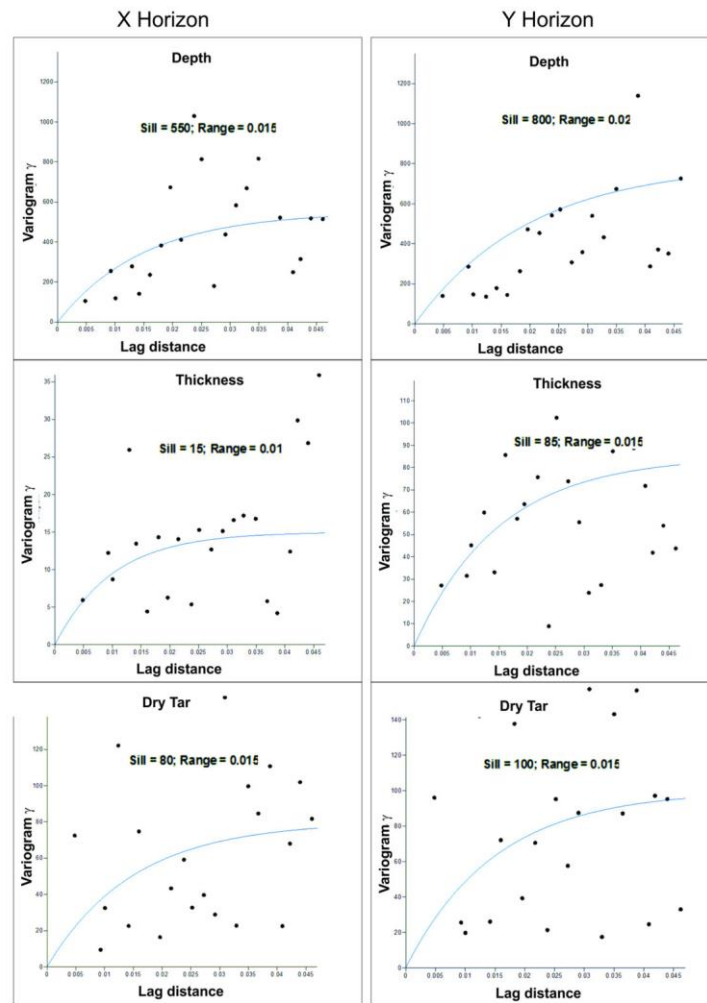


Figure 4 Variogram Characteristics of the Petrophysical Parameters for Horizons X and Y

Table 1 Reserves Estimates for the Project Area

	X-Horizon	Y-Horizon	Project Area (X+Y) horizons
Total Mineable Tar sand (metric tonnes)	2,020,137,993.19	1,975,639,879.94	3,995,777,873.13
Bitumen-in-Place (metric tonnes)	228,556,540.11	196,009,961.57	424,566,501.68
Bitumen-in-Place (barrels)	1,485,091,830.67	1,273,613,927.31	2,758,705,757.98
Recovery Rate			
10% (barrels)	148,509,183.07	127,361,392.73	275,870,575.80
25% (barrels)	371,272,957.67	318,403,481.83	689,676,439.50
50% (barrels)	742,545,915.33	636,806,963.66	1,379,352,878.99
75% (barrels)	1,113,818,873.00	955,210,445.48	2,069,029,318.49
85% (barrels)	1,262,328,056.07	1,082,571,838.21	2,344,899,894.28
90% (barrels)	1,336,582,647.60	1,146,252,534.58	2,482,835,182.18

## 5. Discussion of Results

Figure 5 shows the depth maps for X horizon (Fig. 5a) and the Y horizon (Fig. 5b). The depth of X horizon varies between 2.73 m and over 62.08 m while that of the Y horizon varies from about 17 m to over 84 m. Depth to the tops of the bituminous layers relatively increases southward and represents the variation of the overburden thickness over the two horizons.

The thicknesses of the X and Y horizons are shown in Figures 6a and 6b respectively. For the X horizon, the thickness varies from about 5 m to over 21 m and the thickest portions, greater than 15 m occur in the southwestern and eastern parts of the study area. BH20, BH29, BH36 and BH39 are among the boreholes that sampled the thickest interval of the X horizon. A central low thickness zone with values less than 11 m and sampled by BH17, BH30, and others is sandwiched between these thickest portions. In the Y horizon, the thickness varies from about 2 m to over 29 m. The thickest portions

are in the northwest corner and in the eastern part of the study area with values above 15 m. These portions are sampled by boreholes BH10, BH12, BH39 and BH57. While the areas with low thickness values (less than 15 m), sampled by BH11, BH20, BH30, and BH46 and others are common in the central area.

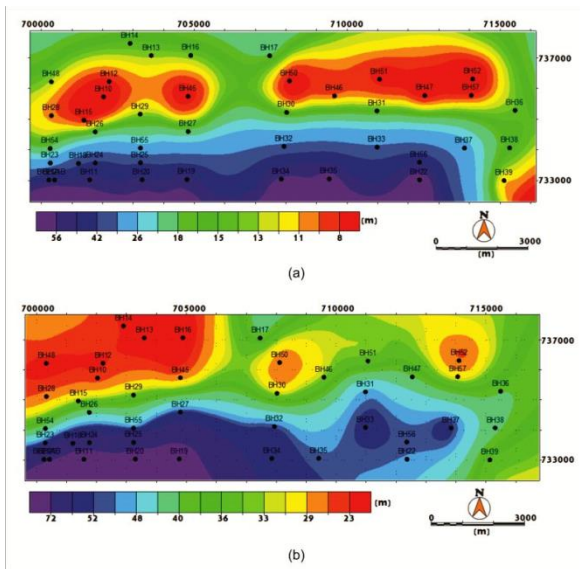


Fig. 5 Kriged Depth Map (m) for (a) X horizon and (b) Y horizon

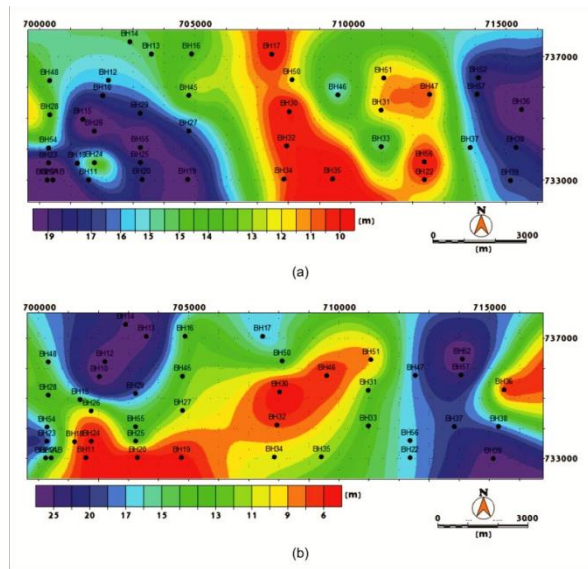


Fig.6 Kriged Thickness Map (m) for (a) X horizon and (b) Y horizon

The dry tar distribution varies for the X horizon from 3.90 to 36.33 wt% (Figure 7a). The highest dry tar contents with values between 11 wt% and greater than 23 wt % are in the northwest extreme corner and southwest end of the study area where BH 19, BH20, BH22 and BH51 are located. There are other smaller areas beneath BH32, BH36 and BH56 in the northeastern and southeastern corners with concentration between 11 and 13 wt% and central area with values less than 9 wt%. The dry tar distribution within the Y horizon (Figure 7b) varies between 5.02 wt% and 31.25 wt% and similar in most cases to that of the X horizon.

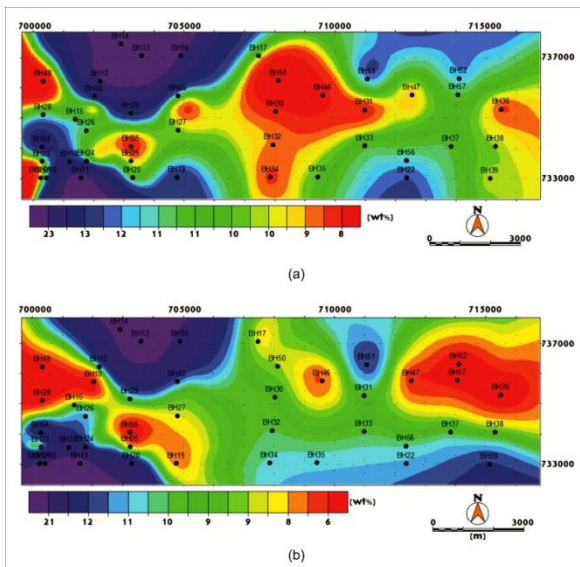


Fig. 7 Kriged Dry Tar Concentration Map (wt%) for (a) X horizon and (b) Y horizon

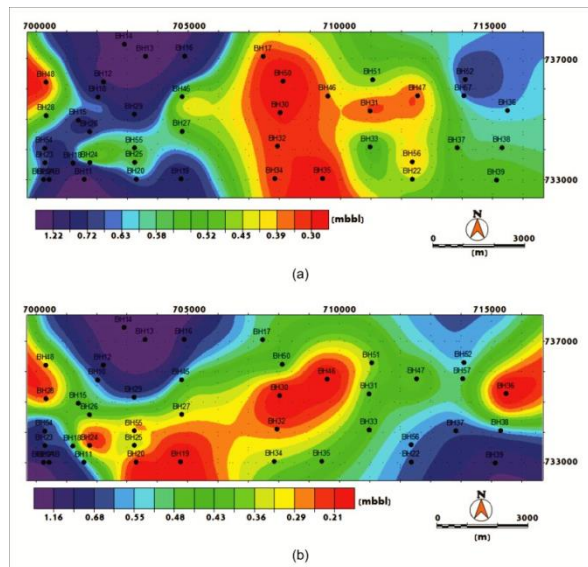


Fig. 8 Map of Bitumen-in-Place (mbbl) for (a) X horizon and (b) Y horizon

The BIP in barrels varies from a little over 166000 to over 1.81 million barrels for the X horizon (Figure 8a); and varies for the Y horizon between a little over 125000 to over 2.78 million barrels (Figure 8b). For the X horizon, possible BIP values greater than 500000 barrels might be encountered in the western and the northeastern portions of the study area. For the Y horizon, areas with possible BIP reserves greater than 500000 barrels might be found in the northwest, southwest, northeast and southeast corners of the study area. The broad area with reserves less than 300000 barrels occur in the central area for both horizons.

The total mineable tar sand (TMT) from the X and Y horizons (Table II) is about 3.99 billion metric tons and the BIP is about 424 million metric tons (equivalent to about 2.76 billion barrels). The RRE at 10%, 25%, 50%, 75%, 85% and 90% are 275 million barrels, 689 million barrels, 1.38 billion barrels; 2.07 billion barrels; 2.34 billion barrels and 2.48 billion barrels respectively. There is an increase factor of 2.17 when the 85% RRE value of 2.34 billion barrels obtained in this study was compared with the 85% RRE value of 1.08 billion barrels obtained by [4]. This increase was interpreted to be probably due to the unbiasedness and reliability of the kriging [33] method over non-spatial estimation methods adopted by previous authors and probably because the previous estimates were limited to overburden thickness not greater than 50 m for the two horizons.

## 6. Conclusions

This study has applied ordinary point kriging gridding algorithm to estimate the bitumen reserves using the depth, thickness and dry tar concentration data obtained from forty boreholes with a view to predicting bitumen-in-place (BIP) and recoverable reserves estimates (RRE) within the study area. The study quantified the spatial structure of the existing petrophysical parameters and used this to predict the values of reserves at unsampled locations. The results showed that at 85% recovery factor, the bitumen reserves in the study area is about 2.34 billion barrels. Compared to the 1.08 billion barrels obtained previously at the same rate, there is a difference factor of about 2.17. Since, the spatial variations of the input parameters (i.e. depth, thickness and dry tar) were quantified as against using a single average value, this study is therefore, proposing that the new estimate is much more reliable and reflects the bitumen reserves in the study area.

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