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Efficiency Comparison of Reverse Circulation and Diamond Drilling for Phosphate Exploration in Nigeria's Sokoto Basin

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Abstract

This study compares reverse circulation (RC) and diamond core (CD) drilling for exploring phosphate nodules in Nigeria's Sokoto Basin. A programme of 15 RC wells (1000 m) and 2 CD wells (151 m) assessed performance metrics. RC drilling was significantly faster, progressing three times quicker than CD, and successfully identified phosphate layers 93% of the time. However, its bulk samples caused nodule breakage, reducing grade accuracy. Conversely, CD provided intact cores for precise stratigraphy with 78% recovery but was slower and 40% more expensive. Mineralisation was found primarily in the Dange formation's gypsiferous shales, with optimal depths varying regionally from under 15 to over 100 metres. The analysis concludes RC is best for rapid lateral resource scoping, while CD is essential for detailed vertical delineation. A cost-time trade-off exists, favouring a hybrid strategy: initial RC mapping followed by targeted CD for reserve classification. The findings offer an optimisation framework for sedimentary phosphate exploration, though future work should integrate advanced coring and 3D modelling to better account for the basin's geological trends.

Keywords

Drilling Efficiency, Phosphate Exploration, Sokoto Basin, Reverse Circulation, Diamond Core Drilling, Resource Estimation

1. Introduction

Exploring Nigeria's phosphate deposits in the Sokoto Basin is vital for economic diversification and agricultural development, but faces unique geological challenges requiring optimal appraisal methods [1]-[3]. Phosphate mineralisation there, found in Paleocene formations, shows variable geometry and grade distribution [4]-[6].

Effective exploration requires accurate, cost-effective drilling methods, as methodology selection is a primary determinant of data quality, cost, and viability [7]-[11]. Methods must provide representative samples and precise geological logging [12]-[18]. The choice between reverse circulation (RC) and diamond core (CD) drilling is critical; RC offers speed and lower cost for reconnaissance [19] [20], while CD provides intact core for detailed geology and metallurgy despite higher cost [21].

Evaluating techniques for phosphate involves balancing key factors: penetration rates, cost per metre, sample quality and representativeness (critical for nodular deposits), data fidelity, depth capabilities, logistics, and environmental impact [22]-[26]. While speed and cost are important [27]-[31], sample quality is paramount to avoid distorting resource estimates in variable deposits [32]-[38]. Sample outcomes directly link to geological data fidelity [26] [39]-[41], and practical considerations like terrain and climate are also key [42] [43]. The study synthesises field data to establish guidelines for selecting the optimal drilling method for different Sokoto Basin exploration stages, aiming for effective exploration with mitigated financial risk.

2. Materials and Methods

2.1. Location and Description of the Study Area

The Sokoto Basin in north-western Nigeria, covering approximately 64,000 km^2 [44]-[49], contains a prospective phosphate area of about 9000 km^2 [2] [50] [51]. Phosphate mineralisation is hosted in the west-dipping shale horizons of the Dange Formation [1]-[3] [6] [52]. Due to the basin's gentle westward dip, the mineralisation depth increases from east (15 m) to west (>100 m), extending into Kebbi State [52]-[54]. **Figure 1** shows the location map of Sokoto Basin with its drainage pattern.

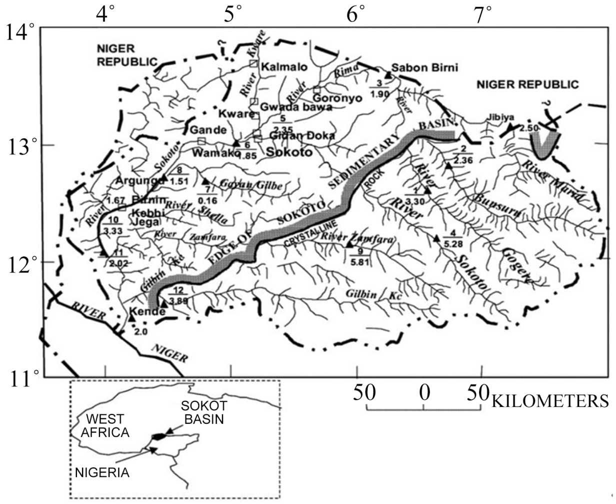


Figure 1. Location map of the Sokoto Basin with drainage pattern (Inset: Map of West Africa showing the location of Nigeria with reference to the position of Sokoto Basin, [44]).

2.2. Field Studies

A drilling programme was planned in the Sokoto Basin to determine the continuity and estimate the size of phosphate resources. Since the phosphate is not in a continuous layer, the plan combined two drilling methods: Reverse Circulation (RC) drilling to collect bulk samples for analysis, and Diamond Core (CD) drilling for detailed geological logging and future research.

The basin was divided into three zones (eastern, central, western), with wells spaced progressively farther apart (10 km, 20 km, and 40 km, respectively) based on the known characteristics of the mineralisation in each area.

Three rigs were used: a Comacchio Geo 602 Explorer with a riffle splitter (**Figure 2**) for all RC drilling, and two HYDX-5A rigs (**Figure 3**) for all CD drilling. The RC programme used a pneumatic hammer, drilling 15 wells to 1000 m total. The CD programme used HQ/NQ cores with water-based drilling, completing 2 wells to 151 m total.

Figure 2. Multipurpose Comacchio Geo 602 Explorer complete with riffle splitter.

Figure 3. HYDX-5A Multipurpose core drilling rig.

The disparity in well count—RC (15) versus CD (2)—was deliberate. The RC programme provided rapid, cost-effective reconnaissance across the vast 9000 km^2 basin, while the two CD wells delivered high-fidelity calibration and grade data at key locations. Drilling followed a chronological sequence across the Gwadabawa and Binji areas, with all three rigs deployed to accelerate the work. Vertical drilling was used throughout for CD due to the mineralisation's nature.

2.3. Sample Collection, Labeling and Logging

The study employed a random sampling technique across all locations. Two methods were used: RC (Reverse Circulation) drilling, which collected cyclone-separated cuttings logged via "Sailform" software, and CD (Core Drilling) for continuous cores. For RC drilling, samples were collected from the cyclone base for every meter of drilling depth, as illustrated in **Figure 4**.

Figure 4. Sample collection at the base of cyclone.

These samples were placed in systematically labelled bags, which were marked with key identifiers including the study name, drilling type, well ID, and sample depth, an example of which is shown in **Figure 5**. Sample logging was conducted in two phases, with initial real-time logging of weight and lithological data into "Sailform" using a comprehensive template that captured well ID, depth, location, and other meta data.

Figure 5. Sample packaging and labelling.

Samples were collected per meter and placed in labelled trays for initial review. Suspected phosphate horizons were then re-examined after being split with a ripple splitter (**Figure 6**) to ensure representative sampling and avoid bias. For these horizons, 2 - 3 kg samples were systematically collected, tagged, and sent to the lab, with duplicate samples stored and their tag numbers recorded in the "Sailform" software.

Figure 6. Ripple splitter, splitting and tagging of suspected phosphate horizons.

2.4. Sample Movement and Storage

After drilling, samples were moved to a secure store, documented with check forms, and bagged separately for assaying with accompanying registers. Duplicates and non-tagged samples were systematically arranged in a well-ventilated, leak-proof store (**Figure 7**).

Figure 7. Sample storing in Sokoto town.

The drilling process involved a strict verification protocol before and after operations. Before drilling, a pre-sign-off form was completed by key personnel to confirm site safety, sample integrity, and capture technical details like the well ID and planned depth. After drilling, a post-sign-off form ensured the site was properly cleaned, rehabilitated, and the borehole was sealed with an engraved identification tag. Finally, the prepared and logged samples were dispatched to laboratory for phosphate analysis.

2.5. Laboratory Analyses and Sample Preparations

A total of 242 phosphate-bearing samples were collected and analyzed. To determine their elemental composition, the samples were prepared as homogeneous pellets and analyzed using X-Ray Fluorescence (XRF). To identify the specific phosphate minerals and their relative abundances, the samples were analyzed using X-Ray Diffraction (XRD). These analyses are essential for understanding the ore's properties and industrial potential.

2.6. Statistical Analysis

1) Description of phosphate's thickness, depth, and recovery rates

The wells in the western zone are the deepest, where phosphate is expected to be penetrated at over 100 m, such as in Sakwae, Matankari, and Kalgo areas. In the eastern zone around Chimola, Kagogo, Salame, and Kware, the wells are quite shallow, with phosphate forming in horizons below 15 m. Most of the wells in the eastern zone were bored using the RC method, with samples collected at every 1 m.

2) RC and CD metrics

Drilling reached depths of 40 - 93 m. The rock formation is varied, but shale from the Dange formation dominates and is the primary phosphate-bearing rock, often containing phosphatic nodules and gypsum, as confirmed by spot tests. Other rocks like limestone and marl are generally non-phosphatic. While phosphate mineralization is widespread from shallow depths down to 83 m, the optimal, richest horizon for mineralization typically begins below 15 m.

3. Results and Discussions

The discussions are premised on borehole data (**Table 1** and **Table 2**), results of laboratory analyses (**Figures 8-11**), summary of RC wells attributes (**Table 3**) and data from the lithologic logs of wells of the bedding units within the different formations of phosphate mineralisation in the Sokoto Basin (**Figures 12(a)-(n)**).

3.1. Drilling Efficiency

Drilling across 15 wells indicated widespread phosphate layers that thin southward, consistent with prior research [55] [56]. The local geology is complex, featuring a phosphate-bearing Dange Formation shale layer between sandy and limestone units. The Gamba Formation is often absent due to erosion. Phosphate layer variability is attributed more to local geological features like erosion and unconformities than to elevation, a conclusion supported by multiple studies [57]-[61].

Table 1. Chronological log of SPDD001 (Dange Formation, 71.8 m depth; Long. 5.28268, Lat. 13.42994, and elevation of 261 m).

S/No	Depth (m)	Unit/formation	Mineral	Grain size	Alteration	Texture	Colour	Over form	Lithology	Thickness	Solid core recovery (m)	Barrel core recovery (m)	Total core recovery (m)	Loss (-) Gain (+)	% Recovery
1	00 - 1.2	Gwandu	Quartz	Gravel	Siliceous	Coarse-grained	Brown	Coarse gravel	Sand and laterite	1.2	0	0.73	0.73	−0.47	60
2	1.2 - 3.77	Gwandu	Quartz	Pebble	Ferruginous sandstone	Coarse-grained to medium-grained	Reddish brown		Ferruginous sandstone, shale, and clay	2.57	0.37	0.33	0.7	−1.87	27
3	3.77 - 6.3	Gwandu	Quartz, feldspar, oolitic iron	Pebble	Carbonate	Fine-grained to medium-grained	Brown, yellowish-brown-white		Clay, ferruginous sandstone, and shale	2.53	1.34	1.19	2	−0.53	79
4	6.3 - 73	Gwandu	Quartz, mica		Siliceous	Medium-grained	Grey	-	Shale	1	0.9	-	0.9	−0.1	90
5	7.3 - 7.8	Gwandu	Calcite and quartz		Carbonate	Fine-grained	Reddish and grey		Clay and laminated limestone	0.5	0.38	0.72	1.1	0.6	220
6	7.8 - 12.69	Gwandu	Quartz and mica	Poorly sorted	Siliceous	Fine-grained and coarse	Brown and dark red		Clay and ferruginous sandstone	4.89	2.62	0.33	2.95	−1.94	60
7	12.69 - 20.52	Gamba	Quartz	Well sorted	Siliceous and carbonate	Fine-grained to coarse-grained	White and brown		Limestone and clay	7.83	0.7	0.5	1.2	−6.63	15
8	20.52 - 20.94	Gamba	Quartz		Siliceous	Medium-grained	Brown		Mudstone	0.42	0.33	-	0.3	−0.12	71
9	20.94 - 23.02	Gamba	Calcite		Carbonate	Fine-grained to medium-grained	White to brown		Limestone and clay	2.08	0.74	-	0.74	−1.34	36
10	23.02 - 24.64	Gamba	Quartz	Pebble	Siliceous	Coarse-grained	Reddish	Coarse gravel	Ferruginous sandstone	1.62	0.05	-	0.05	−1.57	3
11	24.64 - 25.24	Gamba	Calcite		Carbonate	Fine-grained to medium-grained	White		Limestone	0.6	0.23	0.26	0.49	−0.11	81
12	25.24 - 25.66	Gamba	Quartz		Carbonate	Fine-grained to medium-grained	Grey and yellow	-	Shale and mudstone	0.42	0.45	0.19	0.64	0.22	152
13	25.66 - 27.12	Kalambaina	Quartz		Siliceous	Medium-grained	White	-	Mudstone	1.46	0.07	-	0.07	−1.39	5
14	27.12 - 28.05	Kalambaina	Quartz, mica		Siliceous	Coarse-grained	White		Mudstone	0.93	0.15	0.05	0.2	−0.73	21

Continued

15	28.05 - 28.85	Kalambaina	Quartz, mica	Carbonate	Fine-grained	Grey		Limestone and shale	0.8	0.34	0.54	0.88	0.08	110
16	28.85 - 30.01	Kalambaina	Calcite and quartz	Carbonate	Fine-grained to medium-grained	White		Limestone	1.16	0.13	0.53	0.66	−0.5	56
17	30.01 - 30.74	Kalambaina	Calcite, quartz	Carbonate	Fine-grained to medium-grained	White		Limestone with traces of fossils	0.73	0.9	0.03	0.93	0.2	127
18	30.74 - 32.77	Kalambaina	Calcite and quartz	Carbonate	Fine-grained to medium-grained	Dull white		Limestone	2.03	0.10	-	0.10	−1.93	5
19	32.77 - 33.69	Kalambaina	Quartz and feldspar	Siliceous	Fine-grained	Brown	-	Clay	0.92	0.62	-	0.62	−0.3	67
20	33.69 - 34.71	Dange	Quartz, gypsum, mica, and glauconite	Siliceous	Fine-grained to medium-grained	Yellowish to greenish		Shale	1.02	0.80	0.20	1	0.02	98
21	34.71 - 35.51	Dange	Quartz, mica	Carbonate	Medium-grained	Greenish to yellow and grey		Shale	0.80	0.60	0.30	0.90	0.1	113
22	35.51 - 36.67	Dange	Quartz, mica	Siliceous	Fine-grained to medium-grained	Yellowish to green		Shale	1.16	0.86	-	0.86	−0.3	74
23	36.67 - 38.07	Dange	Quartz and olivine	Carbonate	Fine-grained	Greenish to yellow		Shale or clay	1.4	1.1	-	1.1	−0.3	78
24	38.07 - 39.51	Dange	Quartz, feldspar	Siliceous	Very fine-grained	Brown-pale green		Clay (bentonite)	1.44	0.23	-	0.23	−1.21	16
25	39.51 - 40.60	Dange	Quartz, gypsum	Carbonate	Fine-grained to medium-grained	Yellowish to green		Shale	1.09	2.02	0.2	2.22	1.13	203
26	40.60 - 42.04	Dange	Quartz and gypsum	Siliceous	Fine-grained to medium-grained	Dark		Shale	1.44	0.62	0.3	0.92	−0.52	156
27	42.04 - 43.25	Wurno	Quartz	Carbonate	Very fine-grained	Grey		Shale	1.21	0.24	-	0.24	−0.97	20
28	43.25 - 45.01	Wurno	Quartz and gypsum	Carbonate	Fine-grained to medium-grained	Dark		Shale and intercession of gypsum	1.79	0.22	0.72	0.96	−0.8	183
29	45.01 - 46.74	Wurno	Quartz	Carbonate	Fine-grained to medium-grained	Dark		Shale	1.73	1.9	-	1.9	0.17	109
30	46.74 - 48.11	Wurno	Quartz, mica	Carbonate	Fine-grained to medium-grained	Dark		Shale with traces of fossils	1.34	1.0	0.2	1.20	−0.14	90

Continued

31	48.11 - 49.91	Wurno	Quartz, mica		Carbonate	Fine-grained to medium-grained	Dark	Shale and intercalation of limestone nodules	1.8	1.06	0.44	1.50	−0.3	83
32	49.91 - 51.14	Wurno	Quartz, mica		Carbonate	Medium-grained	Dark	Shale	1.23	1.0	0.21	1.21	−0.02	98
33	51.14 - 53.66	Wurno	Quartz, mica		Siliceous	Fine-grained to medium-grained	Dark	Shale	2.46	1.58	0.28	1.86	−0.6	75
34	53.66 - 54.60	Wurno	Quartz, mica		Quartz, mica	Fine-grained to medium-grained	Grey to greenish	Limestone with traces of fossils and phosphate nodules	0.94	1.09	0.62	1.69	0.74	178
35	54.60 - 56.15	Wurno	Quartz, mica, pyrite		Siliceous	Fine-grained to medium-grained and coarse	Grey, yellowish, and green	Shale, pyrite, and limestone intercalation	1.55	1.10	0.20	1.30	−0.25	84
36	56.15 - 57.46	Wurno	Quartz, mica		Carbonate	Coarse-grained	Dark	Sandstone with voids	1.31	0.06	-	0.06	−1.25	5
37	57.46 - 58.62	Wurno	Quartz, mica		Siliceous	Fine-grained to medium-grained	Grey	Shale	1.16	0.16		0.16	−1	14
38	58.62 - 59.31	Wurno	Quartz, mica		Siliceous	Fine-grained	Grey	Shale	0.69	0.16	-	0.16	−0.53	23
39	59.31 - 60.51	Wurno	Quartz, mica		Siliceous	Fine-grained	Grey	Shale	1.2	1.0	0.1.	1.10	−0.1	92
40	60.51 - 61.57	Wurno	Quartz, mica		Siliceous	Fine-grained	Grey	Shale	1.06	0.36	-	0.36	−0.7	35
41	61.57 - 62.84	Wurno	Quartz, mica		Carbonate	Fine-grained to medium-grained	Dark-grey	Shale with intercalations of limestone nodules	1.27	0.71	0.36	0.89	−0.38	70
42	62.84 - 64.04	Wurno	Quartz, mica, and calcite	Fissile	Carbonate	Medium-grained	Dark, light to brown	Shale, limestone, and clay	1.20	0.6	0.52	1.12	0.08	93
43	64.04 - 65.46	Wurno	Quartz, calcite, and mica		Carbonate	Fine-grained to medium-grained	Grey	Shale	1.42	0.83	0.14	0.97	−0.45	68.3
44	65.46 - 66.86	Wurno	Quartz, mica		Carbonate	Medium-grained	Grey	Shale	1.40	0.98	0.12	1.1	−0.3	78
45	66.86 - 69.52	Wurno	Quartz, mica, calcite		Carbonate	Fine-grained	Grey	Shale with intercalations of limestone and gypsum	2.66	0.17	0.92	1.09	−1.57	40
46	69.52 - 71.83	Wurno	Quartz, mica		Carbonate	Medium-grained	Dark	Shale	2.31	1.5	0.3	1.8	−0.51	78

Table 2. Chronological sequence of SPDD00 w16 borehole (Long. 5.27935, Lat. 13.58550, and elevation of 259 m).

S/No	Depth (m)	Unit or formation	Mineral	Grain size	Alteration	Texture	Colour	Contact	Lithology	Thickness	Solid core recovery (m)	Barrel core recovery (m)	Total core recovery (m)	Loss (-) Gain (+)	% Recovery
1	00 - 1.16	Gamba	Quartz	Medium-grained	Siliceous	Semi, consolidated	Brown-whitish	Erosional	Sand and laterite	1.16	0.5		0.5	0.66	43.1
2	1.16 - 2.57	Gamba	Quartz	Medium-grained to coarse-grained	Siliceous	Consolidated	Yellow-reddish	Gradational	Sandstone and laterite	1.41	0.90		0.90	0.51	63.8
3	2.57 - 5.01	Gamba	Quartz	Coarse-grained	Siliceous	Consolidated	Dark reddish yellow		Ferruginous sandstone	2.44	0.84		0.84	1.6	34.4
4	5.01 - 6.73	Gamba	Quartz	Coarse-grained to medium-grained	Siliceous	Semi-consolidated	Dark red dish-yellow	Sharp	Iron, sandstone, and siltstone	1.72	0.96		0.96	0.76	55.8
5	6.73 - 7.03	Gamba	Quartz	Fine-grained	Siliceous	Semi-consolidated	Yellow	Gradational	Clay	0.3	0.28		0.28	0.02	93.3
6	7.03 - 7.83	Kalambaina	Quartz	Fine-grained	Fine-grained	Fine-grained	Yellow-light grey	Gradational	Clay and shale	0.8	0.79		0.79	0.01	98.6
7	7.83 - 10.13	Kalambaina	Quartz	Fine-grained	Fine-grained	Fissile	Light grey-reddish brown		Shale, laterite, and clay	2.30	1.67		1.67	0.63	72.6
8	10.13 - 12.35	Kalambaina	Quartz	Fine-grained to medium-grained	Siliceous	Consolidated	Dark reddish-brownish	Sharp	Ferruginous sandstone, clay, and intercalation of limestone	2.22	1.65		1.65	0.57	74.3
9	12.35 - 13.63	Kalambaina	Quartz	Fine-grained	Fissile	Carbonate	Dark grey	Sharp	Shale	1.28	1.26		1.26	0.02	98.4
10	13.63 - 14.17	Kalambaina	Quartz	Fine-grained	Fissile	Carbonate	Dark grey		Shale	0.54	0.48		0.48	0.06	88.8
11	14.17 - 16.13	Kalambaina	Quartz	Fine-grained	Fine-grained	Carbonate	Light grey	Gradational	Shale	1.96	1.85		1.85	0.11	94.4
12	16.13 - 16.84	Kalambaina	Quartz, pyrite, phosphate nodule	Fine-grained	Fissile	Carbonate	Light grey		Shale with phosphate nodules and pyrite	0.71	0.7		0.7	0.01	98.6
13	16.84 - 17.99	Kalambaina	Pyrite and quartz	Fine-grained	Fissile	Carbonaate	Dark grey		Shale with pyrite	1.15	1.14		1.14	0.01	99.1
14	17.99 - 20.02	Kalambaina	Quartz, pyrite	Fine-grained	Fissile	Carbonate	Light grey		Shale	2.03	2.0		2.0	0.03	98.5

Continued

15	20.02 - 21.52	Kalambaina	Quartz, gypsum	Fine-grained	Fissile	Carbonate	Light grey		Shale with lenses of gypsum	1.5	1.46	1.46	0.04	97.3
16	21.52 - 22.73	Kalambaina	Quartz, calcite	Fine-grained	Consolidated	Carbonate	White	Sharp	Limestone with traces of fossils	1.21	1.08	1.08	0.13	89.3
17	22.73 - 25.52	Kalambaina	Quartz, calcite	Fine-grained	Consolidated	Carbonate	Grey		Limestone	2.79	2.74	2.79	0.05	98.2
18	25.52 - 28.02	Kalambaina	Quartz, calcite	Fine-grained	Consolidated	Carbonate	White		Limestone	2.5	2.45	2.45	0.05	98.0
19	28.02 - 32.94	Kalambaina	Calcite	Fine-grained	Consolidated	Carbonate	White		Limestone	4.92	3.68	3.68	1.24	74.8
20	32.94 - 36.62	Kalambaina	Calcite, quartz	Fine-grained	Consolidated	Calcareous	Light grey	Gradational	Limestone with shell	3.68	2.10	2.10	1.58	57.1
21	36.62 - 42.12	Kalambaina	Quartz, calcite	Fine-grained	Consolidated	Calcareous	Light grey		Limestone	5.5	2.72	2.73	2.77	50
22	42.12 - 45.85	Kalambaina	Quartz, calcite	Fine-grained	Consolidated	Calcareous	Light grey		Limestone with shale	3.73	1.9	1.9	1.83	51
23	45.85 - 47.85	Dange	Quartz, pyrite, gypsum, and calcite	Fine-grained	Fissile	Carbonate	Light grey	Gradational	Shale	2.0	1.65	1.65	0.35	82.5
24	47.85 - 51.32	Dange	Quartz, pyrite, phosphate, and calcite	Fine-grained	Fissile	Carbonaceous	Dark		Shale with phosphate nodules, pyrite. Start	3.47	2.52	2.52	0.95	72.6
25	51.32 - 55.37	Dange	Quartz, phosphate	Fine-grained	Fissile	Carbonaceous	Dark		Shale with phosphate nodules	4.05	3.77	3.77	0.35	93.1
26	55.37 - 57.51	Dange	Quartz, gypsum, phosphate	Fine-grained	Fissile	Carbonaceous	Dark		Shale with phosphate nodules	2.14	1.8	1.8	0.34	84.1
27	57.51 - 60.79	Dange	Quartz, phosphate	Fine-grained	Fissile	Carbonaceous	Dark		Shale with phosphate nodules. End	3.28	1.83	1.83	1.45	55.8
28	60.79 - 63.01	Wurno	Quartz	Fine-grained	Fissile	Carbonaceous	Dark		Shale	2.22	1.21	1.12	1.19	54.5
29	63.01 - 64.35	Wurno	Quartz	Fine-grained	Fissile	Carbonaceous	Dark		Shale	1.34	1.33	1.33	0.01	99.3
30	64.35 - 68.72	Wurno	Quartz	Fine-grained	Fissile	Carbonaceous	Light grey and dark		Shale	4.37	2.73	2.73	1.66	62.5
31	68.72 - 72.32	Wurno	Quartz	Fine-grained	Fissile	Carbonaceous	Dark		Shale	3.6	2.41	2.41	1.19	67.0
32	72.32 - 75.72	Wurno	Quartz, pyrite	Fine-grained	Fissile	Carbonaceous	Dark		Shale	3.4	3.10	3.10	0.3	91.1
33	75.72 - 80.00	Wurno								4.28				

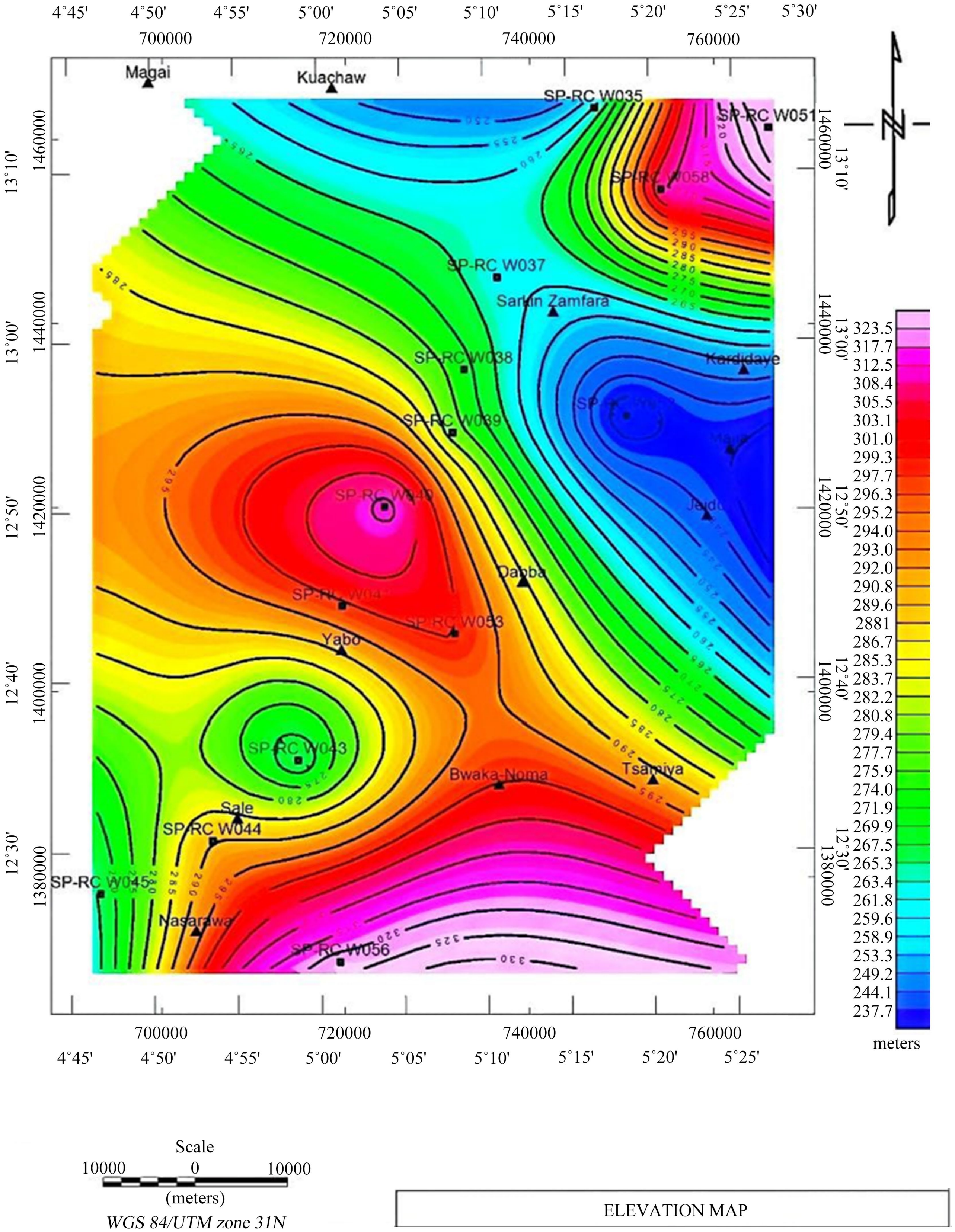


Figure 8. Elevation map of RC drilling boreholes showing wells distribution in relation to topography around Dange area of Sokoto Basin.

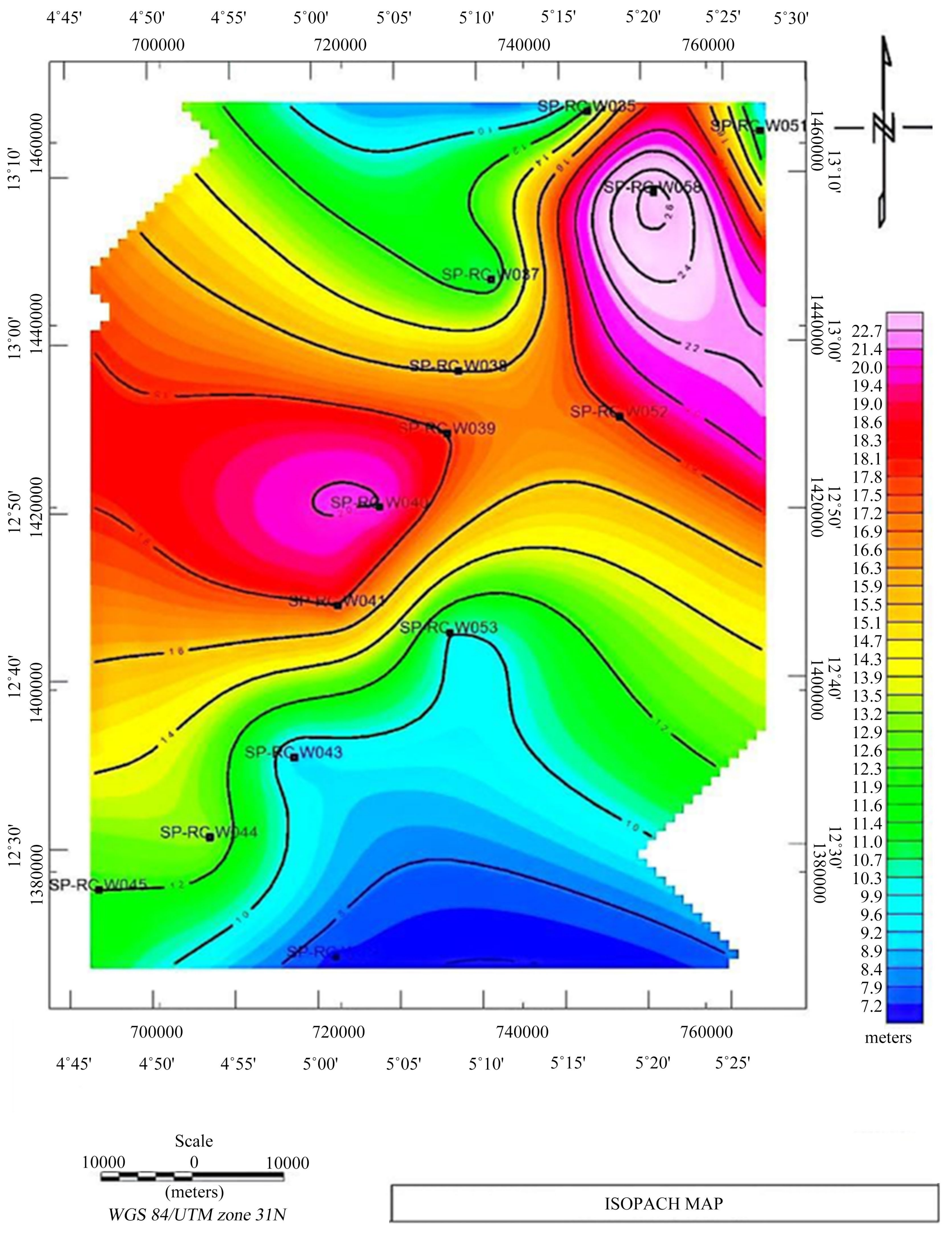


Figure 9. Isopach map showing thicknesses of phosphate bearing horizons recovered from 15 RC drilled wells within the Sokoto basin.

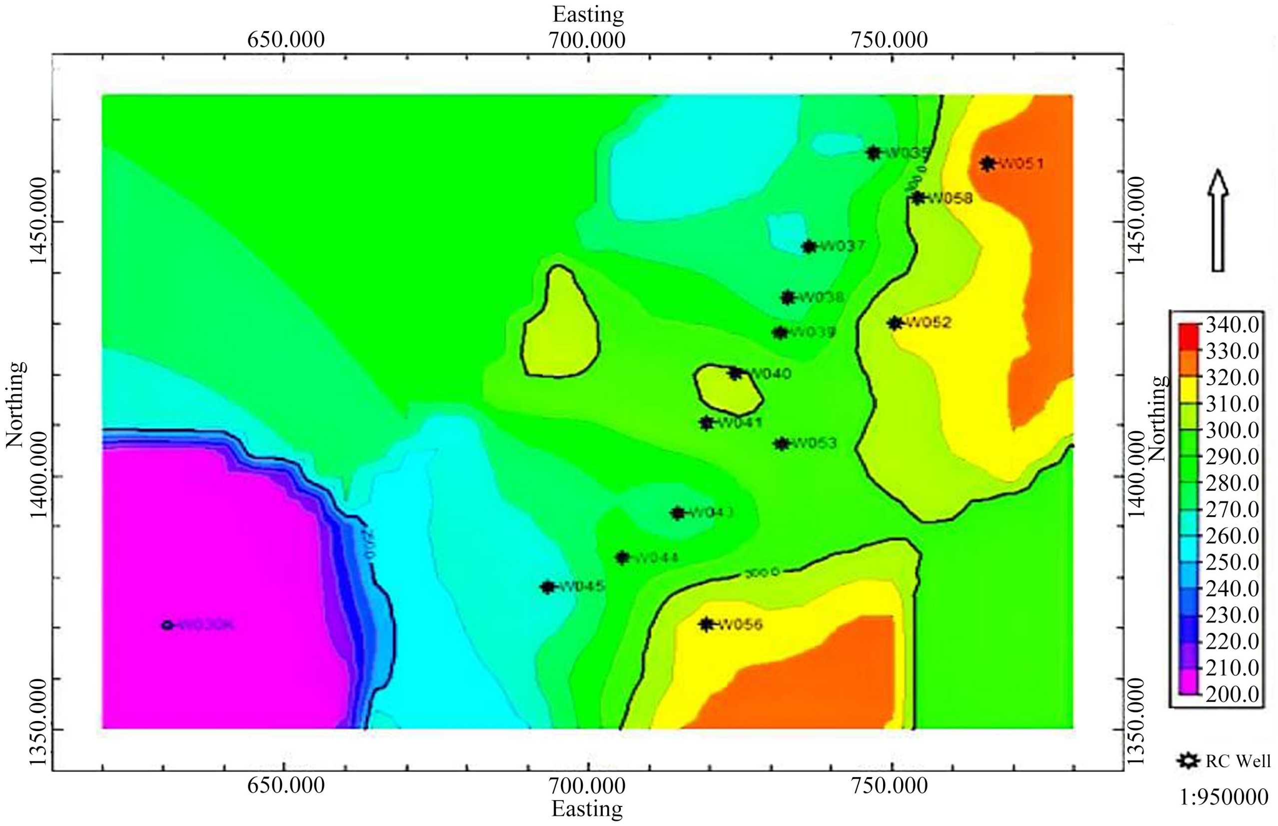


Figure 10. Elevation map showing drilled RC well locations.

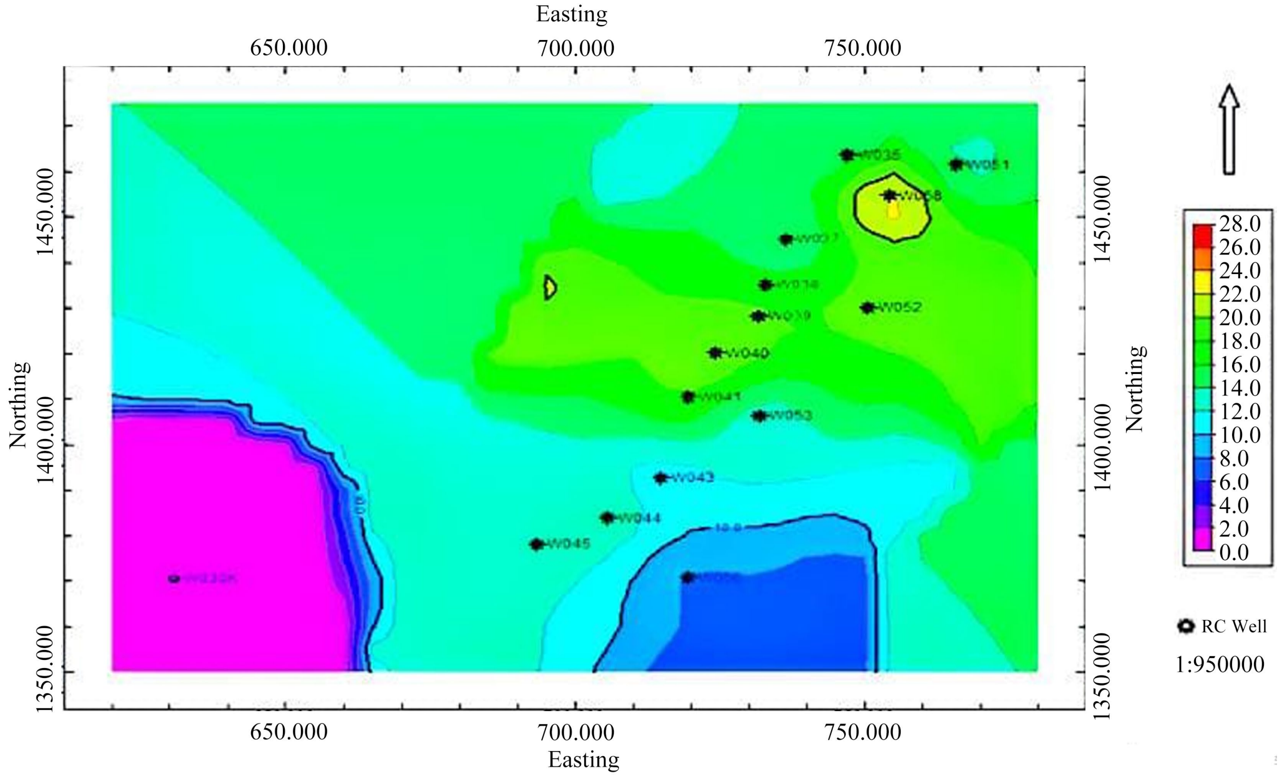
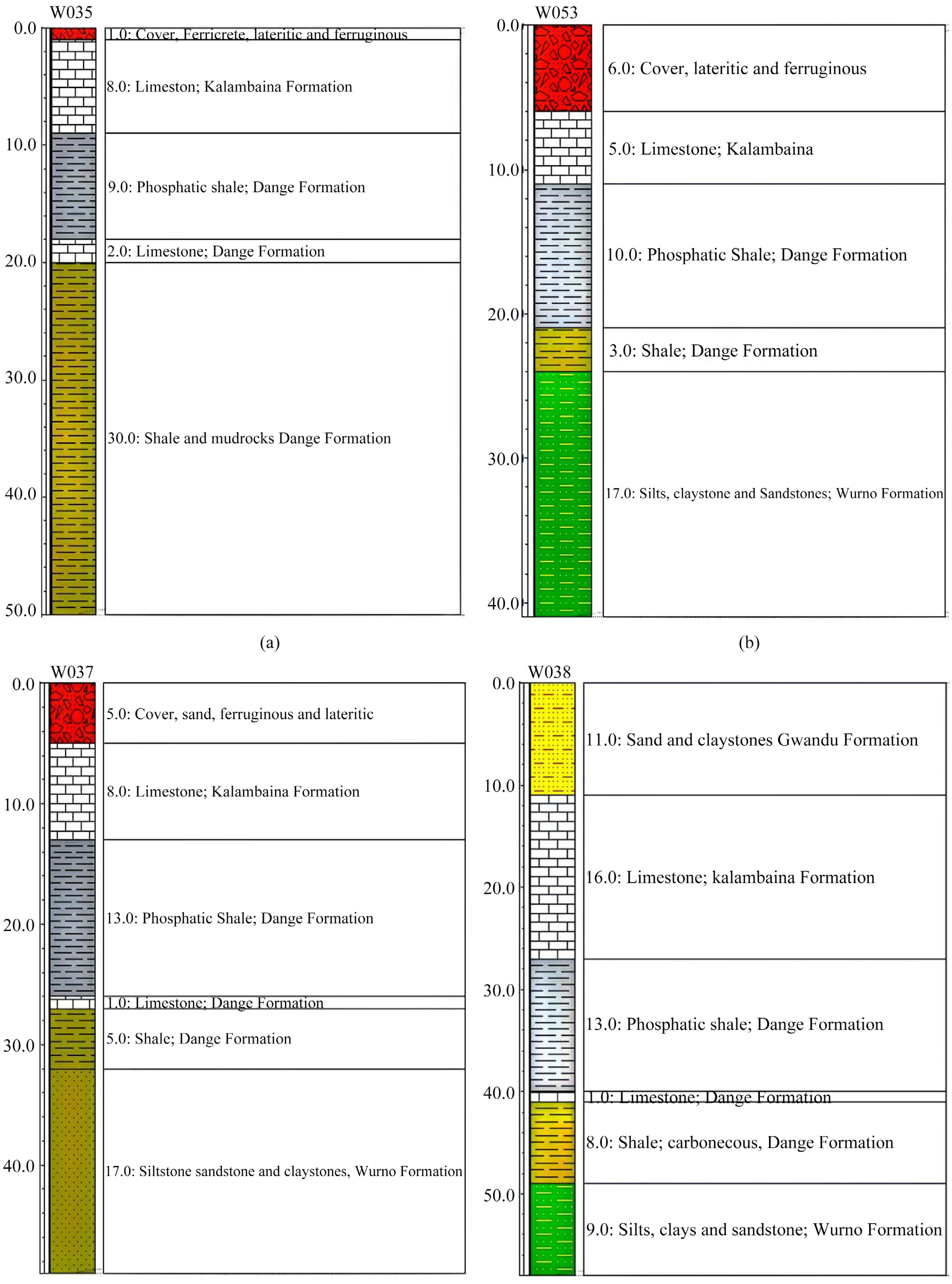
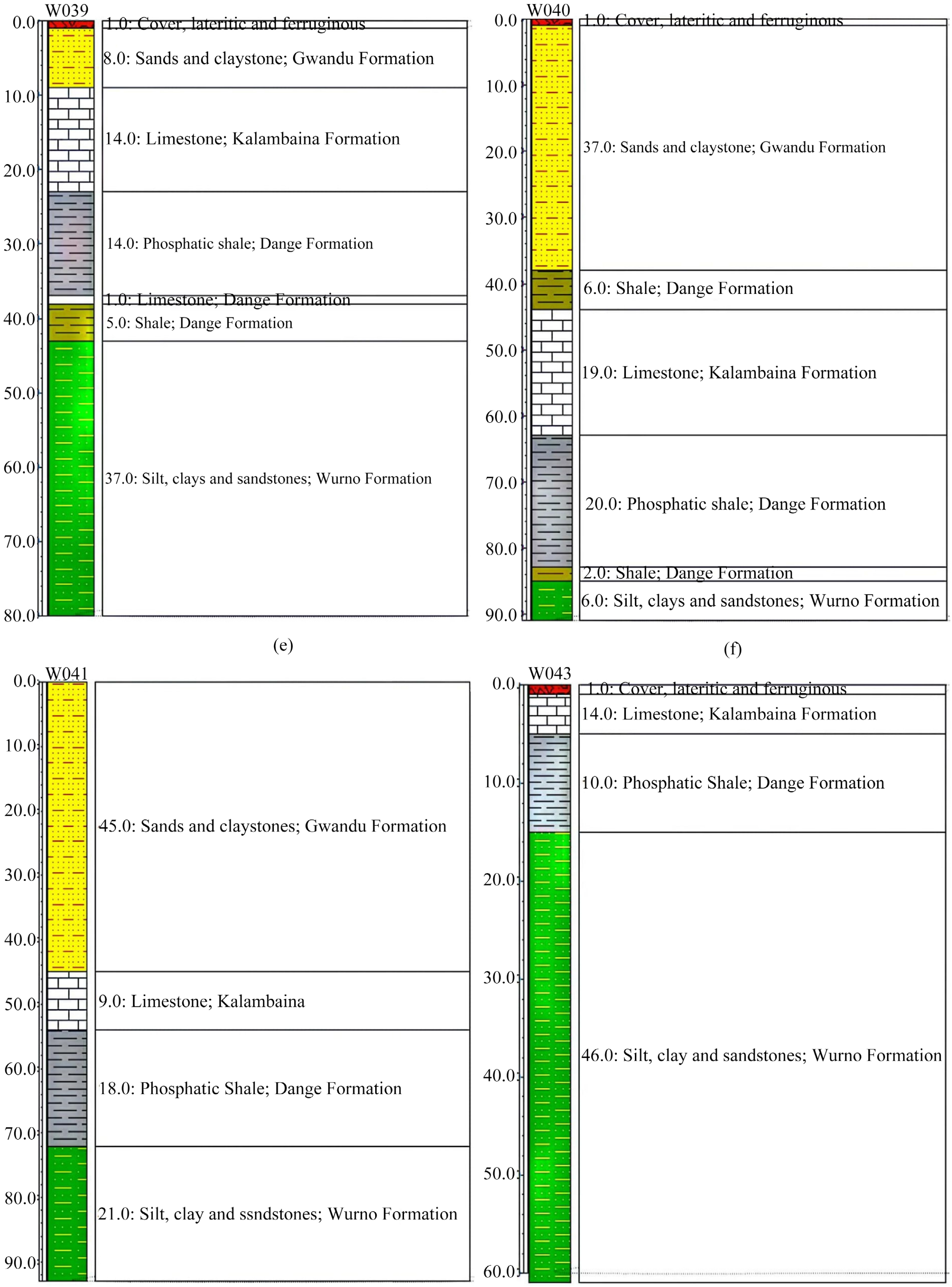


Figure 11. Inferred thicknesses of phosphate bearing horizons around Dange area where RC drilling was conducted.


W035
0.0
10.0
20.0
30.0
40.0
50.0
1.0: Cover, Ferricrete, lateritic and ferruginous
8.0: Limeston; Kalambaina Formation
9.0: Phosphatic shale; Dange Formation
2.0: Limestone; Dange Formation
30.0: Shale and mudrocks Dange Formation
W053
0.0
10.0
20.0
30.0
40.0
6.0: Cover, lateritic and ferruginous
5.0: Limestone; Kalambaina
10.0: Phosphatic Shale; Dange Formation
3.0: Shale; Dange Formation
17.0: Silts, claystone and Sandstones; Wurno Formation
W037
0.0
10.0
20.0
30.0
40.0
5.0: Cover, sand, ferruginous and lateritic
8.0: Limestone; Kalambaina Formation
13.0: Phosphatic Shale; Dange Formation
1.0: Limestone; Dange Formation
5.0: Shale; Dange Formation
17.0: Siltstone sandstone and claystones, Wurno Formation
W038
0.0
10.0
20.0
30.0
40.0
50.0
11.0: Sand and claystones Gwandu Formation
16.0: Limestone; kalambaina Formation
13.0: Phosphatic shale; Dange Formation
1.0: Limestone; Dange Formation
8.0: Shale; carbonecous, Dange Formation
9.0: Silts, clays and sandstone; Wurno Formation

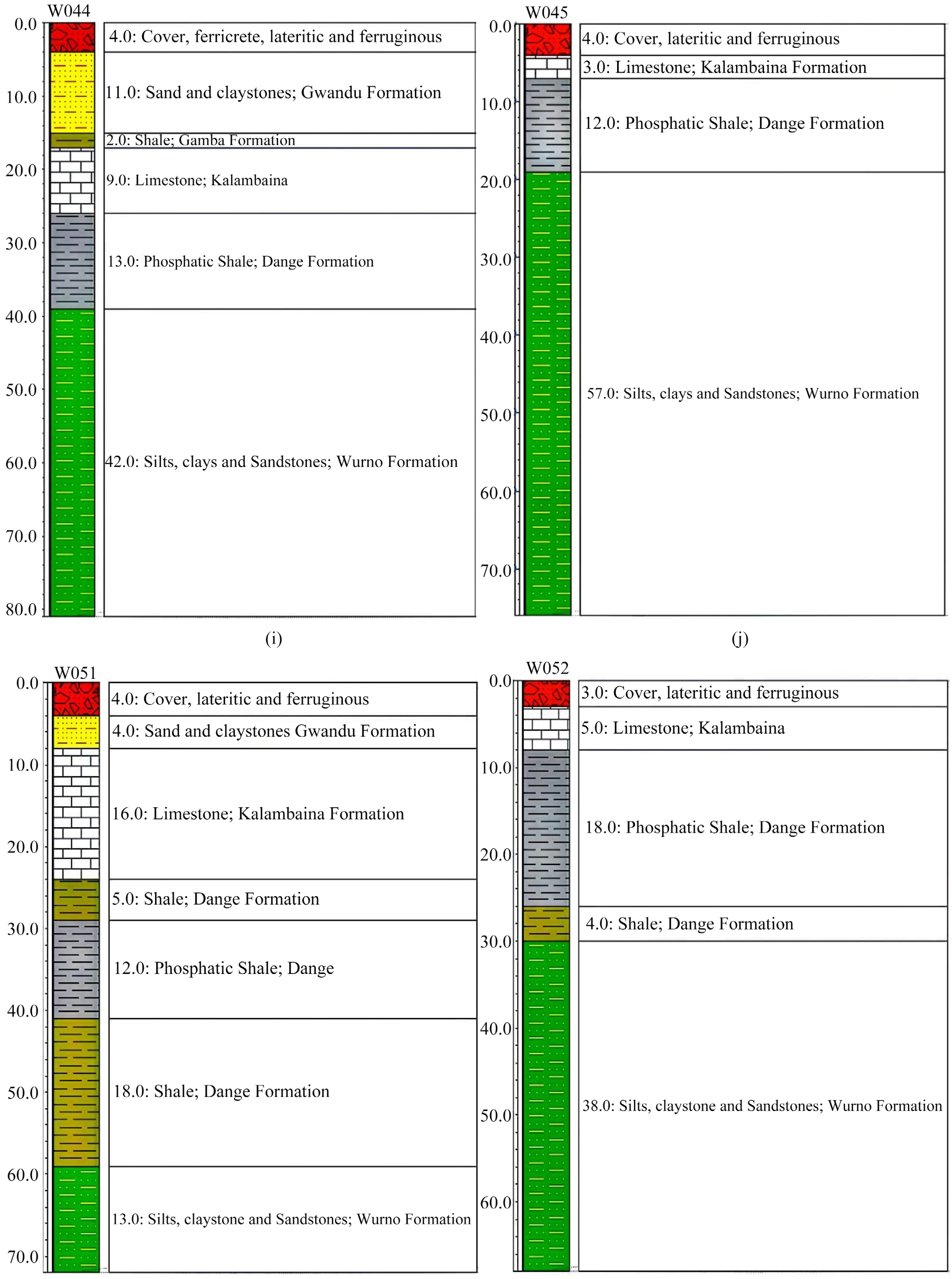
(a) (b)

(c) (d)


W039
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
1.0: Cover, lateritic and ferruginous
8.0: Sands and claystone; Gwandu Formation
14.0: Limestone; Kalambaina Formation
14.0: Phosphatic shale; Dange Formation
1.0: Limestone; Dange Formation
5.0: Shale; Dange Formation
37.0: Silt, clays and sandstones; Wurno Formation
W040
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
1.0: Cover, lateritic and ferruginous
37.0: Sands and claystone; Gwandu Formation
6.0: Shale; Dange Formation
19.0: Limestone; Kalambaina Formation
20.0: Phosphatic shale; Dange Formation
2.0: Shale; Dange Formation
6.0: Silt, clays and sandstones; Wurno Formation
W041
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
45.0: Sands and claystones; Gwandu Formation
9.0: Limestone; Kalambaina
18.0: Phosphatic Shale; Dange Formation
21.0: Silt, clay and ssndstones; Wurno Formation
W043
0.0
10.0
20.0
30.0
40.0
50.0
60.0
1.0: Cover, lateritic and ferruginous
14.0: Limestone; Kalambaina Formation
10.0: Phosphatic Shale; Dange Formation
46.0: Silt, clay and sandstones; Wurno Formation

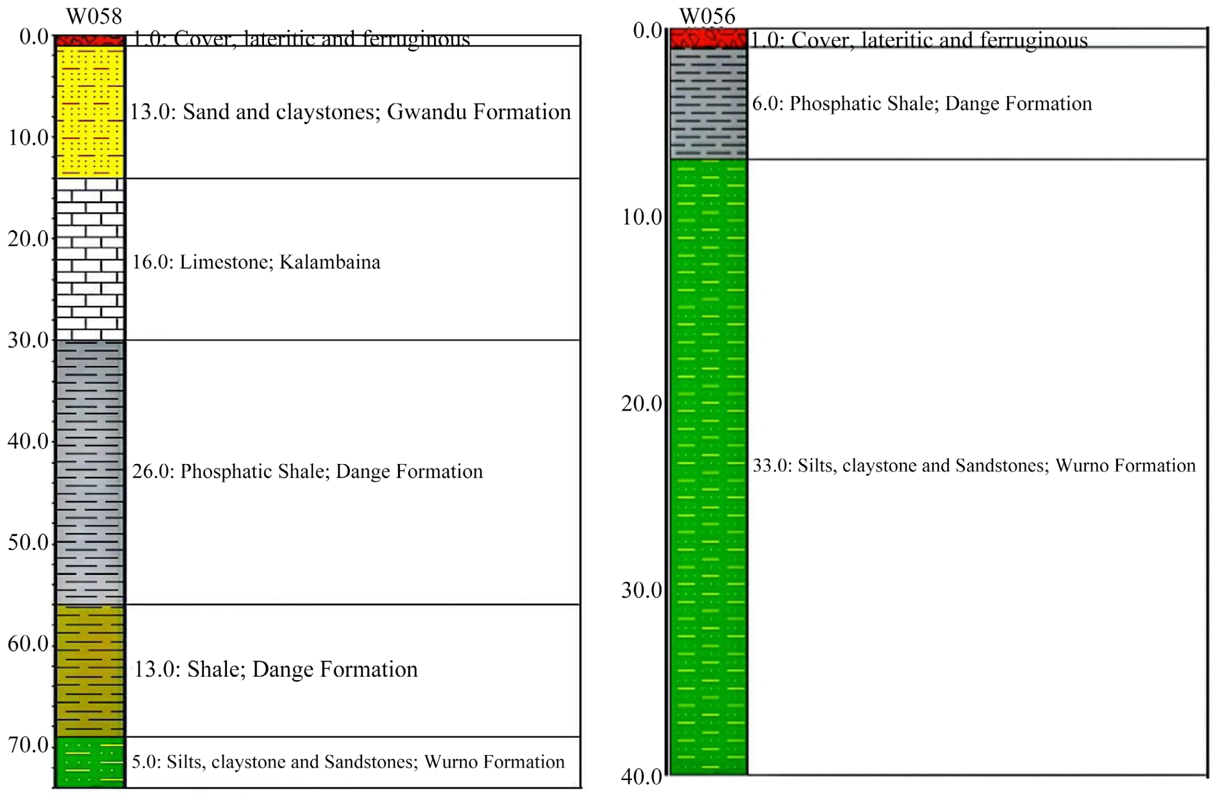
(e) (f)

(g) (h)


W044
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
4.0: Cover, ferricrete, lateritic and ferruginous
11.0: Sand and claystones; Gwandu Formation
2.0: Shale; Gamba Formation
9.0: Limestone; Kalambaina
13.0: Phosphatic Shale; Dange Formation
42.0: Silts, clays and Sandstones; Wurno Formation
W045
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
4.0: Cover, lateritic and ferruginous
3.0: Limestone; Kalambaina Formation
12.0: Phosphatic Shale; Dange Formation
57.0: Silts, clays and Sandstones; Wurno Formation
W051
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
4.0: Cover, lateritic and ferruginous
4.0: Sand and claystones Gwandu Formation
16.0: Limestone; Kalambaina Formation
5.0: Shale; Dange Formation
12.0: Phosphatic Shale; Dange
18.0: Shale; Dange Formation
13.0: Silts, claystone and Sandstones; Wurno Formation
W052
0.0
10.0
20.0
30.0
40.0
50.0
60.0
3.0: Cover, lateritic and ferruginous
5.0: Limestone; Kalambaina
18.0: Phosphatic Shale; Dange Formation
4.0: Shale; Dange Formation
38.0: Silts, claystone and Sandstones; Wurno Formation

(i) (j)

(k) (l)



(m) (n)

Figure 12. (a): Lithologic log of well 35 (N 13.22873, E 005.27907) kware, Kware LGA, Sokoto; (b): Lithologic log of well 53 (N 12.71278. E 005.13532) Gidan Dandala, Shagari LGA, Sokoto State; (c): Lithologic log of well 37 (N 13.06292, E 005.18015) Kalambaina, Wamako LGA, Sokoto State; (d): Lithologic log of well 38 (N 12.97233, E 005.14647), Bodinga LGA, Sokoto State; (e): Lithologic log of well 39 (N 12.91047, E 005.13461) Gadan Dadinkai, Bodinga LGA, Sokoto State; (f): Lithologic log of well 40 (N 12.83771, E 005.06572) Birnin Ruwa, Bodinga LGA, Sokoto State; (g): Lithologic log of well 41 (N 12.75044, E 005.02237) Dabagi, Yabo LGA, Sokoto State; (h): Lithologic log of well 43 (N 12.59028, E 004.97746) Jazomo, Shagari LGA, Sokoto State; (i): Lithologic log of well 44 (N 12.51159, E 004.89166); (j): Lithologic log of well 45 (N 12.45996, E 004.77916); (k): Lithologic log of well 51 (N 13.20801, E 005.45325) Wurno, Wurno LGA, Sokoto State; (l): Lithologic log of well 52 (N 12.92562, E 005.30902) Amana, Dange Shuni LGA, Sokoto State; (m): Lithologic log of well 58 (N 13.14804, E 005.34524) Wurno LGA, Sokoto State; (n): Lithologic log of well 56 (N 12.39171, E 005.01839) Murdowu, Tambuwal LGA, Sokoto State.

Table 3. Summary of RC wells attributes in the study area.

S/N	Well id	Easting	Northing	Elv (m)	EOH (m)	Suspected phosphate horizon	No. of samples for assay
1	SP-RC W030 (kebbi)	4.202632	12395300	205	66	No phosphate bearing formation	-
2	SP-RC W035	5.27907	13.22873	259	50	9 - 21 m	15
3	SP-RC W051	5.45325	13.20801	334	72	30 - 41 m	14
4	SP-RC W058	5.34524	13.14804	310	74	30 - 57 m	29
5	SP-RC W037	5.18015	13.06292	261	49	15 - 26 m	14

Continued

6	SP-RC W038	5.14647	12.97233	272	58	27 - 43 m	19
7	SP-RC W052	5.30902	12.92562	321	68	8 - 26 m	21
8	SP-RC W039	5.13461	12.91047	277	80	23 - 41 m	21
9	SP-RC W040	5.06572	12.83771	312	91	63 - 83 m	23
10	SP-RC W053	5.13532	12.71278	300	41	11 - 21 m	13
11	SP-RC W041	5.02237	12.74044	299	93	54 - 72 m	21
12	SP-RC W043	4.97746	12.59028	265	60	6 - 15 m	12
13	SP-RC W056	5.01839	12.39171	323	40	0 - 7 m	9
14	SP-RC W044	4.89166	12.51159	290	81	26 - 39 m	16
15	SP-RC W045	4.77916	12.45996	265	77	7 - 19 m	15
					Total = 1000		Total = 242

A comparison of drilling methods found RC faster and cheaper but with lower sample recovery, while DC was slower and more expensive but provided superior sample quality and recovery. The study acknowledges a potential limitation, as its DC dataset was much smaller than its RC dataset, possibly not capturing the basin's full complexity, a limitation also noted by few studies [62] [63].

3.2. Mineralisation Characteristics

The phosphate occurrences in the Dange Formation are found as nodules and pellets within shale layers 6.9 - 27 meters thick, associated with limestone, marl, black shale, and gypsum in the Chadawa area, consistent with prior Sokoto Basin studies [3] [64]. However, RC drilling is unsuitable for sampling these nodules as it fragments them, producing unreliable mineral content data and preventing accurate measurements, resulting in low-confidence data inadequate for detailed mine planning or financial analysis.

3.3. Challenges

RC drilling was primarily limited by sample contamination, where unconsolidated materials from overlying formations (e.g., the Gwandu Formation) infiltrated samples, obscuring the target phosphate shale and complicating the definition of mineralized zones. Conversely, CD was constrained by high costs and slow progress, exacerbated by a crew capacity gap, the inherently slow coring method, and difficult ground conditions that reduced progress to 2 - 2.7 meters per day and necessitated drilling mud for stability. These operational challenges find support in the literature [65] [66].

3.4. Spatial Distribution

The southward thinning of phosphate horizons shown by isopach mapping indicates that mineralization is not topographically controlled, particularly near the

Wurno and Bodinga wells. This supports the views of [53] [67]-[69] and is a critical pathfinder for phosphate exploration in the Sokoto Basin.

4. Conclusion

RC drilling is the fastest and most cost-effective method for a quick reconnaissance. However, to build a detailed resource model, CD is essential, though it requires more budget and planning. Because the phosphate mineralisation is discontinuous, the best strategy is to use a hybrid of both drilling approaches. This optimises costs and ensures the collection of data needed for a reliable and bankable resource. Further research in the study area is capable of adopting a two-phase drilling approach to locate targets with broad RC drilling and define the resource using focused CD. Improved efficiency and data quality can also be achieved with expanded drilling westward, enhanced CD training, and integration of new technologies like geophysical surveys.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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