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Geo-electrical Prospecting for Ore Minerals in Kundu, Western Part of Zungeru Sheet163NW, Nigeria

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Abstract
Analysis of Global Digital Elevation Model (GDEM) and surface geological mapping were combined with vertical electrical resistivity sounding (VES), spontaneous potential (SP) and induced polarisation (IP) sounding to identify locations with possible subsurface ore mineral deposits within Kundu. The GDEM is a radar topographic imagery with 50m resolution .The GDEM's hillshade view revealed NNE-SSW lineaments that are laterally displaced by dextral faults. The geological mapping revealed that the lineaments are NNE-SSW striking outcrops of gneisses, schists and amphibolites. The gneisses and schists contain lenses of quarzites, and dip 30º to 70º SSE. Some of the rocks host fractures with veins of quartz mineralisation. The soundings were conducted at fifty one geo-electrical stations. Subsurface pegmatite bodies and quartz veins were inferred to constitute deduced subsurface fractures characterised by SP value between +20 and +40 mv. The subsurface pegmatite bodies and quartz veins at stations L1, L6, L23, L26 and L51 are associated with IP values higher than 10 ms, and consequently inferred to possibly host disseminated ore minerals. Massive ore minerals were inferred to be hosted within deduced subsurface fractures characterised by lower than 150 Ωm resistivity value and SP values in the neighbourhood of -100 mv. Such fractures were identified at sounding stations L9, L36, L45 and L50. The disseminated and massive ore minerals appear located in the central portion of Kundu, and aligned approximately N-S. The mineralising solutions were probably structurally controlled by N-S trending fractures. Coring combined with electrical logging can now be conducted in the town within the region defined by latitude N9.822º, N9.834º and longitude E6.145, E6.149. Geochemical analysis of the cores is recommended to ascertain the types of ore minerals present. Further work such as assaying and reserves estimation is suggested after coring to warrant taking investment decision.

Introduction
The Federal Government of Nigeria has emphasised that resurgence of the mining industry is a key to reviving Nigerian economy (Faruk, 2016). This notwithstanding, adequate mineral exploration is yet to be conducted within much of the Nigerian basement (Olade, 1976). The poor exploration status of the Nigerian basement complex informed the first article in the communiqué of the Nigerian Society of Mining Engineers' 15th Annual General Meeting. The article urged upon adequately financing relevant government agencies to conduct detailed exploration, as well as releasing available information on mineral deposits to prospective investors. Mining activity is sustainable only when mineral exploration replaces mined ore minerals. An ore mineral in this context is a mineral deposit from which a metal can be mined and delivered to the market place profitably (Bateman, 1981; Guilbert and Park, 1986).
Ore minerals are commonly found in hydrothermal veins hosted by fractures and pegmatites in places where igneous rocks intrude into schists, quarzites, and amphibolites. This type of geological setting characterises Kundu and its immediate environs. Artisans are sometimes seen panning for gold along the banks and floodplains of River Kaduna as it traverses the amphibolite-schist-quarzite complex on the east of Kundu. In spite of the ore indicative geological setting and occasional fortuitous success in gold panning, detailed systematic ore prospection is yet to be conducted in the town. This work was thus carried out to identify areas possibly underlain with subsurface ore minerals in Kundu.

Geographical Location and Regional Geological Setting
Kundu is a small sized town in western portion of Zungeru Sheet 163 topographic map of Nigeria. It is located within latitude N9°49' to N9°50' and longitude E6°08' to E6° 9' 30'' in northwest of Zungeru, in north-central Nigeria. The town is bounded on its east and southeast by mylonitic amphibolite-schist-quarzite complex that bears shear and crenulation cleavages. Granitic and

charnokitic rocks outcrop within other parts of its neighbourhood (Fig.1). This geological setting of the town and its immediate neighbourhood constitute a potential setting for deposition of ore minerals.

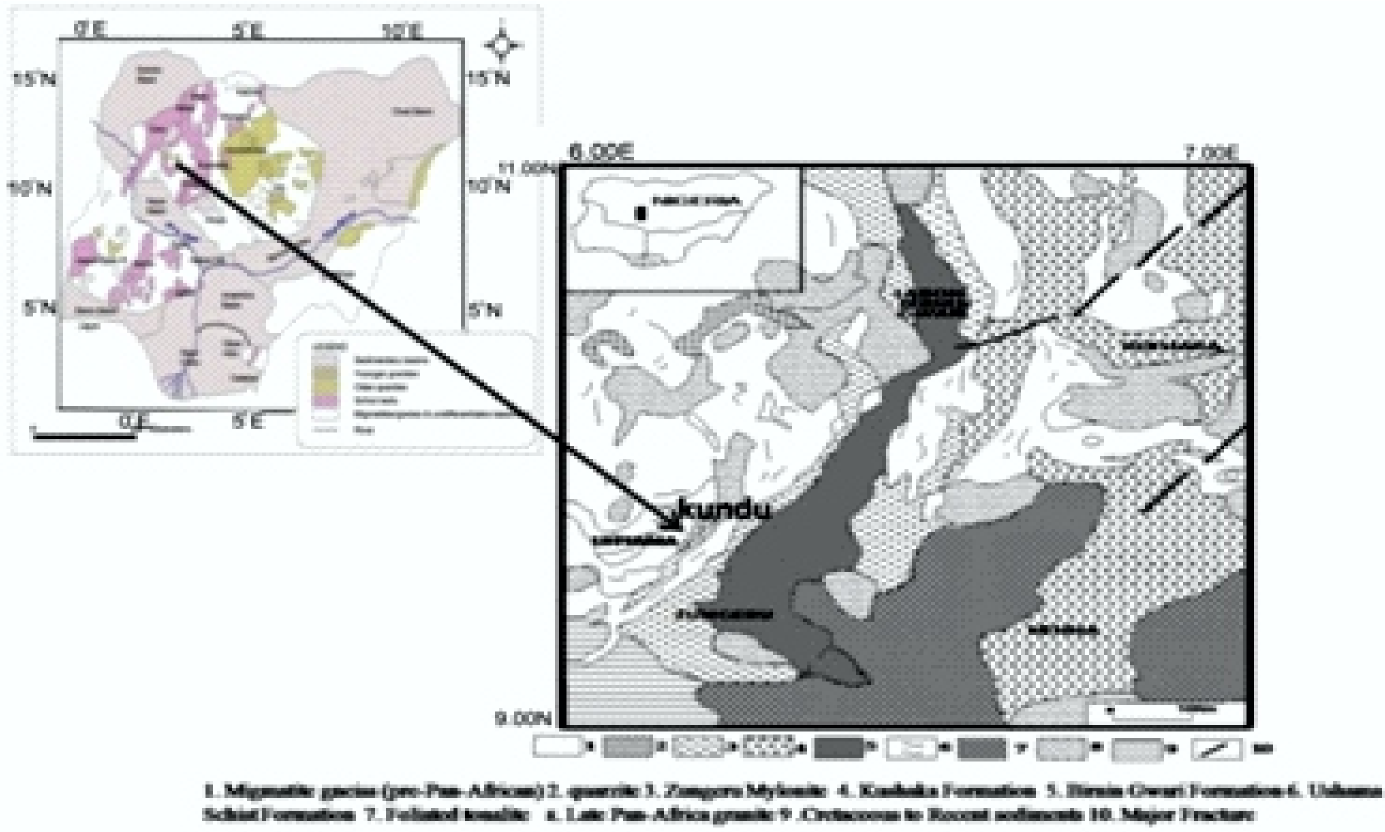

Figure 1: Geological map of Minna-Zungeru region (Ajibade and Woakes,1989)

The rocks within and around Zungeru are Precambrian to Lower Paleozoic in age, and they can be grouped into three main lithostratigraphic units: 1) gneiss-migmatite complex in high-grade (amphibolite) metamorphic facies; 2) supracrustal Younger metasediments and metaigneous rocks in low-grade (greenschist to lower amphibolites) metamorphic facies; 3) granitic through granodoiritic to dioritic and gabbroic intrusives and their extrusive equivalents.

These rocks are an integral part of the Nigerian cratonic basement called northern Nigerian Massif. The gneiss-migmatite complex are mostly pink to grey coloured, quartzo-feldsphatic in composition, and older than Late Proterozoic. The gneisses comprise paragneisses and orthogneisses. There are also quarzites (which could be magnetite or haematite bearing, or micaceous), paraschists, orthoschists, and amphibolites. The quarzites, schists, and amphibolites occur as supracrustal relic rafts and xenoliths within the gneisses and migmatites. They are remnants of ancient metasediments and metaigneous rocks that resisted granitisation and migmatisation during successive crustal reactivations.

The supracrustal Younger metasediments and metaigneous rocks are distinguished into Kushaka Schist, Birnin Gwari and Ushama Schist Formations. They constitute elongated ridges aligned with NNE-SSW trending synformal troughs they infill. Their lithologies comprise phyllites, mica schists, quartz schists, ferruginous quarzites, banded quarzites, massive and banded amphibolites. Isoclinal folding, steeply dipping and NNE-SSW striking foliation characterise the schists and amphibolites. They are more spatially extensive, but less deformed than the relics of Ancient metasediments and metaigneous rocks scattered within the migmatites-gneiss complex. The contact of the low-grade schist formations with the migmatites-gneiss complex is commonly gradational. Intricate intercalations of dark grey amphibolites with light coloured fine grained rocks, which are exposed within the channel of River Kaduna at Zungeru, constitute a set of mylonites. The mylonites constitute a structural disconformity that stratigraphically separates the migmatites-gneiss basement complex from the body of overlying low grade supracrustal schist formation. Various bodies of granitic, granodioritic, dioritic and gabbroic rocks intruded into the migmatites- gneiss complex and overlying supracrustal schist formations during the Pan African orogeny. These bodies are called Older Granites. The Older Granites were in turn intruded into by a suite of volcanic rocks during a Lower Paleozoic epeirogenic uplift that succeded the Pan African orogeny.

Review of Relevant Literature

Wright *et al.* (1985) reported that Cu, Pb and Zn ores occur within Lower Proterozoic to Upper Proterozoic rocks in the West African basement, where the mineralisation is associated with igneous intrusives within Younger supracrustal schist formations. Garba (2002) remarked that gold mineralisation and rare metals (Ta, Nb) bearing pegmatites around Zungeru region are aligned along regional lineaments created during the Pan African orogeny. Ajibade *et al.* (2008) reported that some gold mineralisation is hosted within the Ushama Schist Formation.

Kearey and Brooks (1988) grouped ore minerals into massive and disseminated deposits. They described a massive ore deposit as a single mass with over 50% of the mineral constituent and a minimum cross-sectional area of $100m^2$. The disseminated deposit contains less than 20% of the mineral constituent, and the mineral occurs as scattered specks and veinlets within the deposit (Pardo *et al.*, 2012). Many of the ore minerals are electrically conductive, unlike their commonly highly resistive host rocks. This electrical conductivity contrast (or resistivity contrast) forms the basis of their prospection with geoelectrical resistivity, spontaneous potential (SP) and induced polarisation (IP) methods (Parasnis, 1986; Keller and Frischknecht, 1966; Ako *et al,*1978; Lowrie,1997; Kearey *et al.,*2002; Salmirine and Turunen, 2007; Musset and Khan, 2009; Pardo *et al.,*2012). Schlumberger brothers successfully prospected for ore minerals with apparent resistivity and spontaneous potential methods in the 1900's. Since then, the methods have detected numerous ore bodies such as Kimheden ore body at Skellefte in northern Sweeden, copper ore at Chalkidili in northern Greece and sulphide orebody at Sariyer in Turkey (Reynolds, 2011). Disseminated ore minerals are localised as simple crystals separated from each other by resistive gangue minerals (Keller and Frischknecht, 1966). Resistivity anomalies require continuous conductors such as massive orebodies, and cannot be generated by disseminated orebodies (Lowrie, 1997). The IP method has since the late 1940s been deployed to prospect for disseminated orebodies (Dobrin and Savit,1988). Notable success in IP prospecting include Kalgoorlie ore field in western Australia (Telford *et al.,* 2001), Gortdrum copper-silver deposit in Ireland (Seigel, 1962), copper-gold orebody within Malmfalten ore district in Sweden in (Malmquist and Parasnis,1972; Rezvani, 2015) and copper mountain deposit in Quebec in Canada (Hallof,1966). Moreira *et al,*(2016) employed DC resistivity and IP to ascertain continuity of gold lodes in Rio Grande, southern Brazil.

Methodology

Methodology deployed is anchored on Arbenz, 1976's concept that exploration is a venture in the unknown, which employs techniques of interpolation, extrapolation, and comparison to predict subsurface rock content ahead of drilling.

Pattern of lineaments and faulting in the area was examined on ASTER (Advanced Space Borne Thermal Emission and Reflection Radiometer)'s GDEM, which is a radar topographic image with 50m resolution. The GDEM was obtained from https://reverb.echo.nasa.gov., georefrenced and processed into hillshade view using *ArcMap GIS* software.

Surface geological mapping of Kundu and its immediate neighbourhood was carried out to ascertain the rock types present, the strike as well as dip direction and dip magnitude of foliated rock outcrops. Vertical electrical resistivity sounding, SP and IP soundings were conducted along ten traverses at an average of five stations per traverse. The traverses were taken along foliation dip direction (SSE) while measurement electrodes were planted along foliation strike, using Schlumberger field array.

Geographic coordinates of the sounding locations were determined using the geographic positioning system (GPS, the *etrex Garmin- legend* type)). The sounding equipment employed is resistivity meter SAS 3000.

Results and Discussion

Figure 2 is the hillshade radar topographic image of Kundu and its environs.

The NNE trending lineaments represent outcropping ridges of gneiss, schist and amphibolites in the area. The lineaments are displaced laterally by faulting in which net lateral movement is eastward. These are dextral faults. Such lineaments and faults are commonly zones of mineralisation (Billings, 2000; Chernoff and Whitney, 2007). Figure 3 is the geological map for Kundu and its environs.

The map reveals extensive bodies of gneiss, schist and some amphibolites. These rock bodies trend NNE-SSW as revealed in the hillshade topographic image for the area. They dip steeply SSE, with dip magnitude as high as 70°. Lenses of quartzite bodies dot the gneisses and the schists. Closely spaced fractures in form of shears are found in the outcropping quarzites (Fig.4)

Quartz veins are found within the outcropping schists (Fig.5) and amphibolites (Fig.6). Sheared zones within quartzite bodies and such quartz veins do host gold and base metal ores (Woakes *et al.* 1987).

The gneiss belongs to the gneiss-migmatite complex. The schists, quarzites and amphibolites constitute Younger metasediments and metaigneous rocks in the area. All the rock bodies extend far beyond the town, and are thus in regional metamorphism.

Geo-Electrical Sounding Data and Their Interpretation

Table 1 presents the geolectric sounding stations and their geographical coordinates. Table 2 is VES and SP data for geoelectric stations L9, L30, L43, L45, and L50. The graphical plot of these data is given as figures 7, 6,9,10 and 11. The SP values (close to -100mv) are similar to SP anomaly associated with a massive ore body at Sariyer in Turkey and in Chalkidiki in northern Greece (Reynolds, 2011). SP anomalies in the neighbourhood of -100mv (or higher values) are usually due to presence of ores (Parasnis, 1986; Telford *et al*., 2001; Reynolds, 2011). The deduced

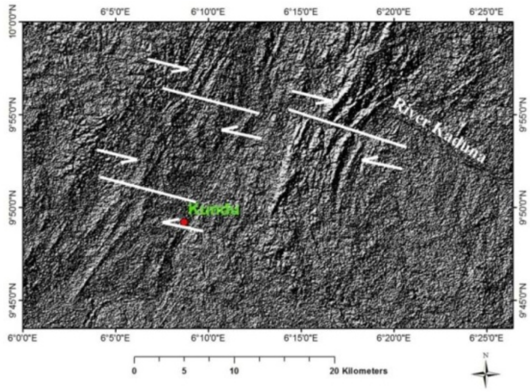

Fig.2: Hillshade topographic image for Kundu and environs

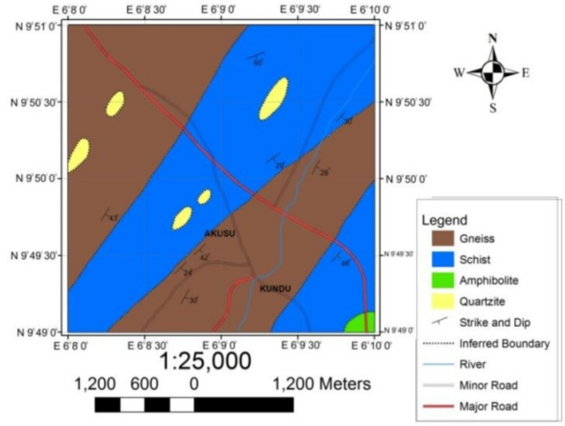

Fig.3: Geological map of Kundu and its environs

Fig.4: Closely spaced fractures on outcropping quartzite at N9^{0}49'417", E6^{0}8' 428"E, west of R. Kaduna

Fig.5: Quartz vein on outcropping schist at N9^{0}49'30.3"; E6^{0}8'52.1" N9^{0}49'417", NW potion of Kundu

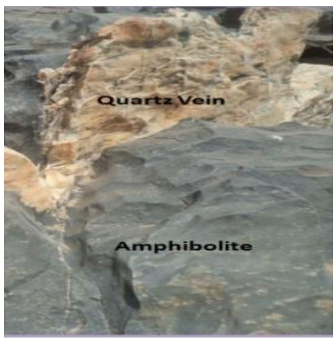

Fig.6: Quartz vein on outcropping amphibolite at N9^{0}49'18.6"; E6^{0}8'31.2" (around railway bridge on R. Kaduna, at Zungeru)

possible subsurface locations of massive ore deposits within Kundu are indicated in the figures

Table 1: Geoelectric stations and their geographic coordinates

long.	Lat	VES location	long.	Lat	VES location	long.	Lat	VES location
6.15**00**	9.8219	L1	6.1461	9.8266	L15	6.1457	9.8311	L30
6.1522	9.822	L2	6.145	9.8276	L16	6.1445	9.8313	L31
6.1497	9.822	L3	6.1438	9.8274	L17	6.1435	9.8315	L32
6.1348	9.8223	L4	6.1428	9.8286	L18	6.1432	9.8317	L33
6.1348	9.8223	L5	6.1487	9.8238	L19	6.142	9.832	L34
6.1476	9.8232	L6	6.1459	9.8288	L20	6.1456	9.8327	L35
6.1415	9.8242	L7	6.1487	9.8238	L21	6.145	9.326	L41
6.146	9.8239	L8	6.1445	9.8207	L22	6.1481	9.8278	L43
6.1459	9.8215	L9	6.1471	9.829	L23	6.149	9.8275	L44
6.1443	9.8216	L10	6.1479	9.8289	L24	6.1498	9.8268	L45
6.1477	9.8224	L11	6.1489	9.8289	L25	6.1502	9.8265	L46
6.1479	9.825	L12	6.143	9.8238	L26	6.1502	9.8257	L47
6.147	9.8252	L13	6.1483	9.8296	L27	6.1476	9.8267	L48
6.1461	9.8285	L14	6.1475	9.8301	L28	6.1492	9.8256	L50
						6.1485	9.8253	L51

Table 2: VES and SP data for geoelectric stations L9, L30, L43, L45, and L50

AB/2	VES 9	SP 9	**VES 36**	**SP 36**	**VES 43**	**SP 43**	**VES 45**	**SP 45**	**VES 50**	**SP 50**
1	25.85	75.46	889.91	33.19	43.109	63.12	77.795	16.8	42.022	76.57
2	36.07	75.1	536.59	-12.28	56.707	59.78	30.96	-16.8	21.635	77.43
3	51.65	72.53	635.06	35.24	55.644	47.98	28.739	-16.72	29.642	80.89
5	59.67	65.97	869.2	35.38	66.854	59.19	40.285	16.47	36.747	90.54
6	63.3	81.995	924.585	66.93	60.8105	29.03	34.333	39.41	38.4775	2.53
8	70.93	-70.17	875.91	-98.48	49.201	-90.39	103.62	63.14	42.96	-6.68
10	77.18	-29.365	796.715	-82.3	31.781	-46.17	30.344	37.5	52.3005	11.95
15	102.17	-98.06	636.9	-61.65	87.381	-0.341	51.929	11.72	72.589	17.13
20	97.26	-69.86	675.29	-56.22	108.355	-0.34	67.551	12.19	97.353	17.29
30	135.44	-53.42	627.84	-77.4	744.74	-0.339	106.13	-5.033	147.98	-0.717
40	212.92	19.9965	953.61	10.585	257.115	-11.539	144.27	-47.52	318.49	10.969
50	287.88	0.113	1085.2	0.128	247.72	-29.4	219.47	-80.58	2591.1	-10.57
60	332.97	93.05	1390.5	0.128	310.48	-2.514	80.716	-81.15	251.95	0.773
70	390.51	77.85	1212.1	0.126	394.86	-0.634	410.47	-81.5	275.51	-5.868
80	458.785	33.435	956.2	4.04	510.105	4.047	441.59	-41.7	627.07	38.139
90	504.2	78.51	3731..3	-5.644	373.52	-7.865	441.16	-0.3	76.045	-68.81
100	513.44	27.339	21.524	6.151	7945.595	-6.412	3357.444	-3.85	1303	70.865

Table 3 is data for VES, SP and IP for locations L1, L6 and L23. Table 4 is corresponding data for locations L30, L40 and L51.

Table 3: VES, SP and IP data for geoelectric stations L1, L6 and L23

AB/2	VES1	SP 1	IP 1	VES 6	SP 6	IP6	VES 23	SP 23	IP 23
1	349.4	8.282	1.94	22.84	0.233	1.29	67.232	-0.108	2.45
2	345.87	4.082	2.95	24.55	0.264	1.69	36.092	-0.11	-1.24
3	129.81	0.643	2.92	21.69	0.279	1.76	37.084	-0.111	1.92
5	248.69	-0.98	3.27	22.71	0.278	-11.1	45.267	-0.114	-4.68
6	243	18.865	2.875	25.01	0.192	10.445	24.383	-1.643	83.145
8	273.09	49.33	2.73	30.37	0.12	12	74	-3.198	30.7
10	333.42	28.825	3.09	35.89	0.114	20.97	14301.9	-2.242	73.05
15	439.06	15.8	2.54	46.55	0.112	17.1	1417.5	0.536	0.78
20	650.4	18.99	2.84	54.64	0.107	-6.52	2416.9	2.937	0.75
30	697.2	19.17	2.7	75.51	0.101	-16	119.38	8.97	10.3
40	666.96	41.265	10.26	138.43	49.26	-24.93	636.175	65.16	-609
50	749.7	-57.18	7.36	154.07	9.417	-19.9	214.8	39.28	-4.67
60	938.74	-53.09	1.82	230.51	-2.801	-21.7	254.73	40.57	13.7
70	1173.5	-47.43	2.94	192.31	-14.67	-6.69	615.27	43.83	-275
80	1254	-34.76	7.22	125.73	39.38	-22.25	377.345	22.95	-422.5
90	-	-	-	252.25	252.25	-4.04	302.19	0.155	-7.58
100	-	-	-	-	-	-	321.43	27.264	2.84

Table 4: VES, SP and IP data for geoelectric stations L30, L40 and L51

AB/2	VES 30	SP 30	IP 30	VES 40	SP 40	IP 40	VES 51	SP 51	IP 51
1	82.877	0.824	0.02	104.06	46.55	0.77	51.075	-6.947	0.59
2	25.099	0.509	-2.14	22.17	46.58	1.81	32.038	-3.294	-2.58
3	26.05	1.88	-1.12	16.91	46.61	118	41.546	-3.393	1
5	32.791	0.631	0.6	23.137	46.68	132	58.465	9.94	-8.89
6	35.4075	23.0045	3.895	19.47	23.455	282.65	57.154	22.91	7.34
8	36.67	-46.21	8.45	35.142	0.113	10.7	73.465	23.7	-32
10	37.5233	32.203	56.9	43.259	0.117	-12.6	71.1695	12.28	16.215
15	8.6525	-13.11	2018	67.07	0.123	-51.1	95.544	-0.104	-25.4
20	191.03	-21.98	-701	117.8	0.122	-157	107.46	-0.104	8.74
30	6.257	-28.34	-4428	167	0.113	-140	175.6	-0.103	-24.6
40	111.223	34.77	651.5	44.985	70.095	582.5	121.36	-0.117	302.15
50	196.36	27.29	15.2	424.19	98.86	-196	235.44	-0.132	17.2
60	125.47	27.26	269	1141	97.77	-214	252.23	-0.131	7.63
70	296.42	27.29	17.8	19929	96.67	-439	303.84	-74.91	-9.03
80	346.885	3.725	11.455	290.75	50.6115	-84.2	360.35	21.22	-9.16
90	423.51	0.163	-4.67	2349.3	-3.27	-271	409.3	40.01	3.51
100	444.685	0.231	2.905	83839.05	-5.5745	-304	267.31	19.542	1390

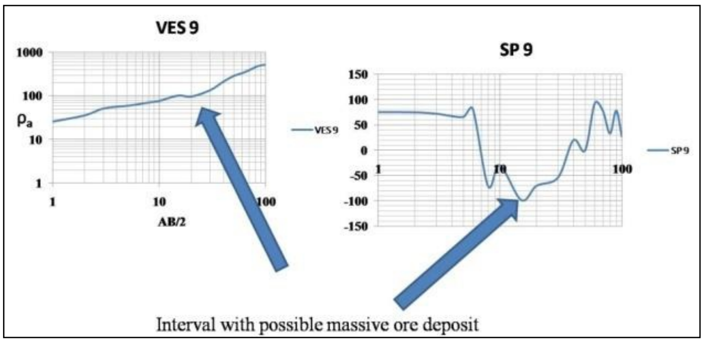

Fig.7: Possible massive ore deposit at geoelectrical station 9

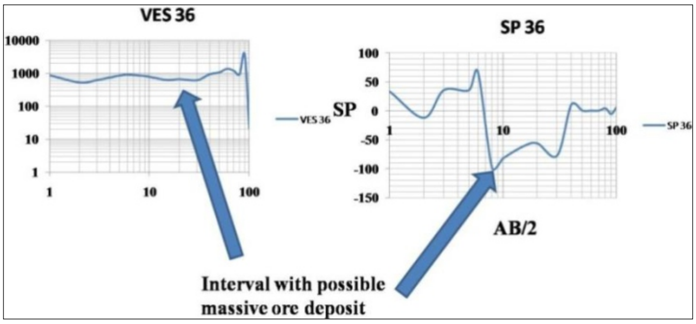

Fig.8: Possible massive ore deposit at geoelectrical station 36

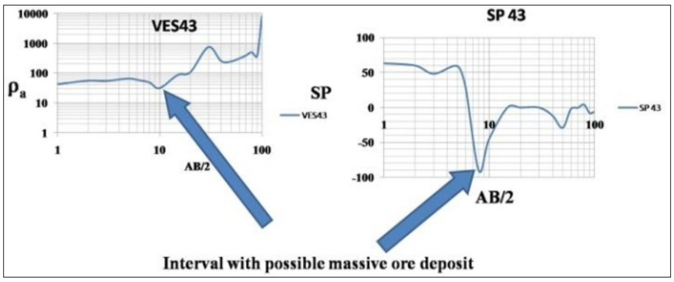

Fig.9: Possible massive ore deposit at geoelectrical station 43

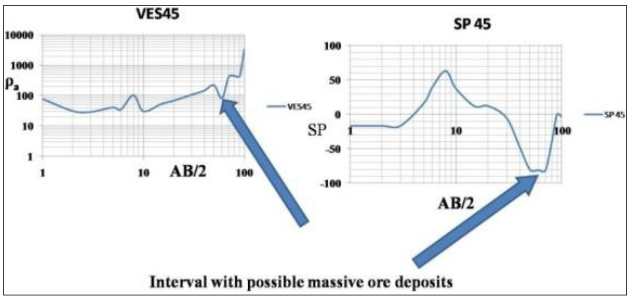

Fig.10: Possible massive ore deposit at geoelectrical station 45

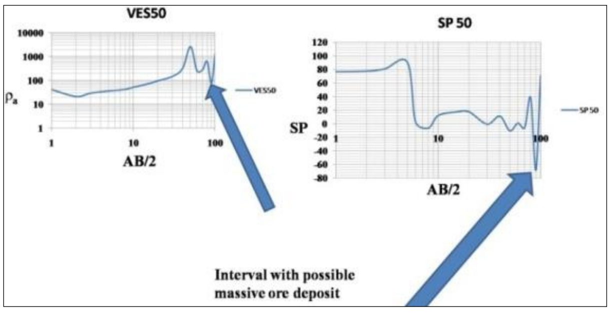

Fig.11: Possible massive ore deposit at geoelectrical station 50

Figures 12 and 13 are deduced possible subsurface locations of pegmatites or quartz veins at geoelectric stations L1 and L6, and L23 and L26 respectively. They have subsurface intervals with SP values that range between +20 and +40 mv. Such SP values characterised pegmatites bearing ore minerals at Nedra in Leningrad (Semenov, 1980). Similar bodies of pegmatite and quartz veins at geoelectric stations L30 and L51 are shown in figure14.

Disseminated minerals are possibly present where the inferred quartz veins and pegmatites are characterised by IP values higher than 10 ms and a local drop in resistivity value. The subsurface locations of these probable disseminated minerals are shown in figures 15, 16, 17 and 18. They share similar ρ_a and IP values with disseminated copper ore in Quebec reported by Hallof(1966), and disseminated copper-gold orebody in Malmfalten ,Sweden, reported by Rezvani (2015).

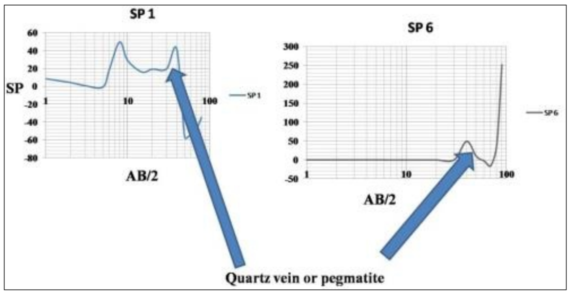

Fig.12: Possible locations of subsurface pegmatite or quartz veins at geoelectric stations L1and L6

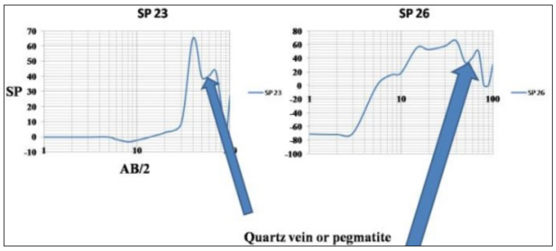

Fig.13: Possible locations of subsurface pegmatite or quartz veins at geoelectric stations L23and L26

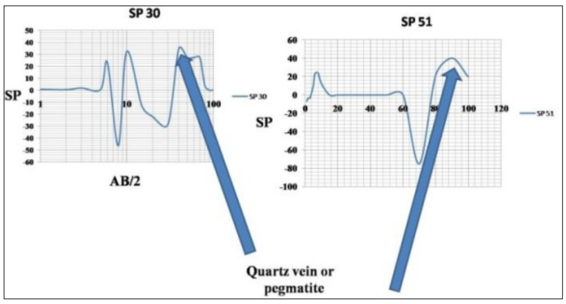

Fig.14: Possible locations of subsurface pegmatite or quartz veins at geoelectric stations L30and L51

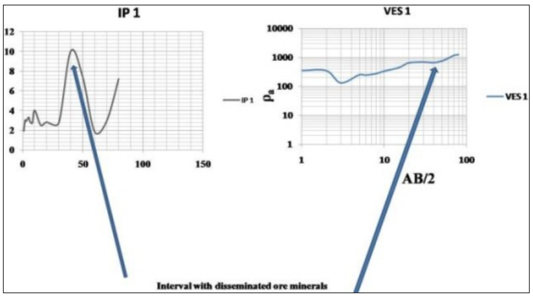

Fig.15: Possible locations of subsurface pegmatite or quartz veins with disseminated minerals at geoelectric stations L1

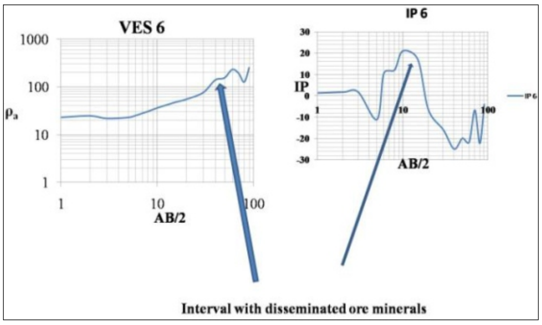

Fig.16: Possible locations of subsurface pegmatite or quartz veins with disseminated minerals at geoelectric stations L6

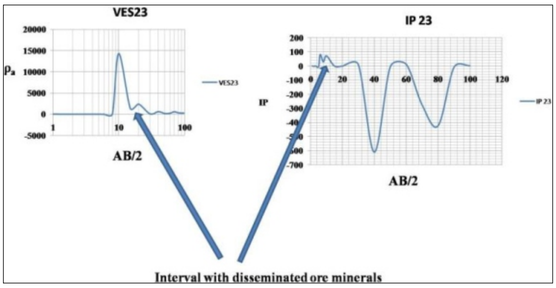

Fig.17: Possible locations of subsurface pegmatite or quartz veins with disseminated minerals at geoelectric stations L23

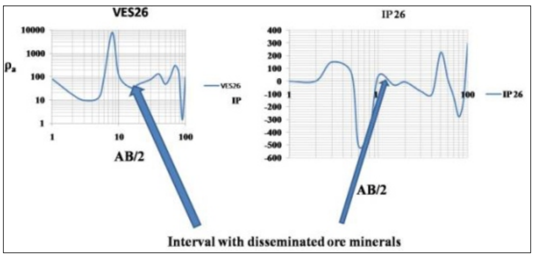

Fig.18: Possible locations of subsurface pegmatite or quartz veins with disseminated minerals at geoelectric stations L26

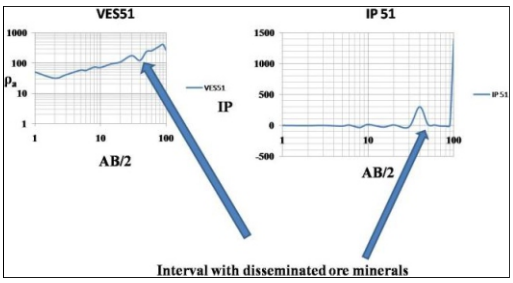

Fig.19: Possible locations of subsurface pegmatite or quartz veins at geoelectric stations L51

Maps of inferred probable spatial locations of massive and disseminated ore minerals are figures 20 and 21.

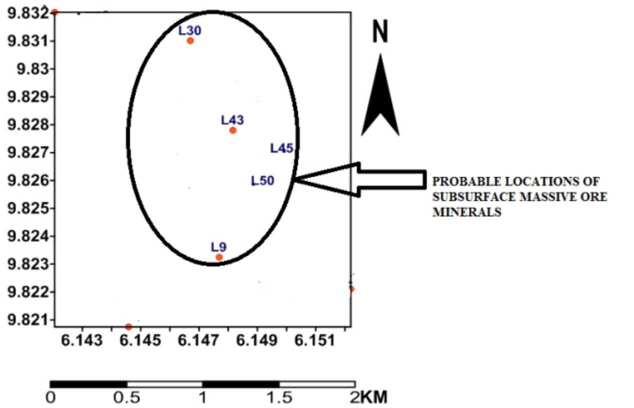

Fig.20: Map showing inferred locations of probable subsurface massive ore minerals

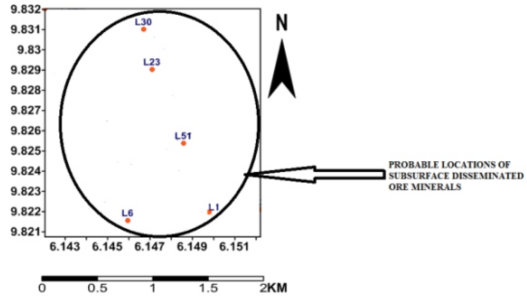

Fig.21: Map showing inferred locations of probable subsurface disseminated ore minerals

Both types of ore minerals seem located in the central portion of the study area, roughly along N-S direction. This suggests that the possible mineralising solutions were directed by fractures trending in the strike direction.

Conclusion

The hillshade view of radar imagery for the surface topography revealed NNE-SSW trending lineament that are dextrally faulted. These lineaments represent NNE-SSW striking gneisses, schists and amphibolites. These faults may be part of possible subsurface mineralised fractures.

Some schist and amphibolites outcrops within Kundu bear fractures that have become emplaced with quartz veins. The probable existence of these veins within the subsurface was revealed by measured SP values between +20 and +40 mv. Inferred quartz veins marked with IP values equal to or greater than 10 ms possibly host disseminated ore minerals in the area. Massive ore minerals are possibly hosted in inferred subsurface fractures characterised by low resistivity and SP values equal to or higher than -100 mv. Both inferred disseminated and ore minerals appear to occur the central portion of Kundu, and are roughly aligned along N-S. The mineralising solutions were probably structurally influenced by N-S fractures.

Core drilling accompanied with resistivity, SP, and IP logging can now be conducted in the town within the portion defined by latitude N9.822º, N9.834º and longitude E6.145, E6.149. Geochemical analysis of the cores is recommended to ascertain the types of ore minerals present.

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