Journal of Environment and Earth Science
ISSN 2224-3216 (Paper) ISSN 2225-0948 (Online)
Vol.12, No.11, 2022

Mapping Sandy Titano-Uraniferous Deposits in Tabou Region, South-West Cote d'Ivoire: Contribution of Magnetometry and Gamma-Ray Spectrometry

Simon Pierre Djroh[1,3]* Fossou Jean-Luc Hervé Kouadio[1] Gnamba Franck Emmanuel Gouedji[2]
Esaïe Parfait Guigui[1,3] Loukou Nicolas Kouamé[1]
1. Applied Geophysics Research Team Laboratory, Mineral and Energy Resources (LGRME), Faculty of Earth Science and Mineral Resources, Félix Houphouët Boigny University, 22 BP 582 Abidjan, Côte d'Ivoire
2. Geology and Mining Sciences, University of Man, BP: 20 Man, Côte d'Ivoire
3. Geophysical Research Office of Côte d'Ivoire, Cocody M'Badon, 01BP: 4765 Abidjan, Côte d'Ivoire
* E-mail of the corresponding author: djrohsp@gmail.com; ORCI ID:0000-0002-1984-782X

Abstract
The work of the *Geological and Mining Research Office* (BRGM) in Côte d'Ivoire, with Tagini and Papon, has revealed, in addition to substances such as gold and manganese, indications of nuclear substances in some areas of the country. Côte d'Ivoire's mining policy is to develop the riches of its subsoil. The lack of information on the reserves of nuclear substances does not currently allow the Ivorian state to exploit these nuclear resources. This work is part of the framework to deepen our knowledge on these substances.Carried out in the south-west of Côte d'Ivoire, along the coast, this study confirmed the reported uraniferous indications and helped to identify their origin. Uranium accumulations were found in beach sediments in significant quantities between Bliéron and Soublaké.
Keywords: Uranium, Magnetometry, Gamma-ray spectrometry, Tabou, Côte d'Ivoire.
DOI: 10.7176/JEES/12-11-02
Publication date: November 30th 2022

1. Introduction

The Ivorian coastline has a fluvial and marine sands deposit that extend from west to east. They are composed of white, milky-white and brown sands for most of the beaches, but also blackish sands which are located exclusively on the South-West beaches in the Tabou region (Figure 1). This colouring is evidence of the presence of titano-uranic oxide of silica, an occurrence that has been highlighted by geological studies (Tagini, 1971; Papon, 1973). Similar deposits have been mapped by Bouhaouli (1976) and Mhammdi et al. (2005**)** on the Moroccan Atlantic coast. The bedrock of the south-western beaches, on the other hand, presents a series of intensely metamorphosed quartzo-feldspathic and basic rocks whose geochemical contents contrast with the subjacent deposit of titano-uraniferous sand. The present study aims to provide a precise mapping of these sands based on their magnetic and gamma ray spectra. It locates the origin of the black sands and provides perspectives on further studies to evaluate their exploitable potential.

(a) *(b)* (c) *(d)*

Figure 1: Black sand from beaches; *(a)* Soublaké beach, *(b)* Boubré beach, *(c)* Beach between Soublaké and Boubré, *(d)* Biléron beach.

2. Study area and geological context

The study area is located in the south-western part of Tabou department between 665,000 and 68,000 Westing and 478,000 and 495,000 Northing (WGS84/UTM 29N). It has a strong hydrographic network, which is provided by the Cavally river and its tributaries composed of *Nouble*, *Ouepo*, *Degne, Soublake* and *Tabou* coastal rivers (Figure 2). The geology of the study area is composed of grey tonalitic gneisses, magnetite quartzites and migmatites with biotite, on which recent sediments lie unconformably (Papon, 1973; Camil, 1984; Thieblemont, 2004; Kouadio et al., 2016; Kouadio, 2017; Kouassi et al. 2018). These rocks, oriented NE-SW, are Liberian in age and are affected by granulite metamorphism facies (Kouadio, 2017). Unconformably, this ensemble is underlain by Quaternary sandies deposits in which titano-uraniferous occurrences are concentrated (Figure 3).

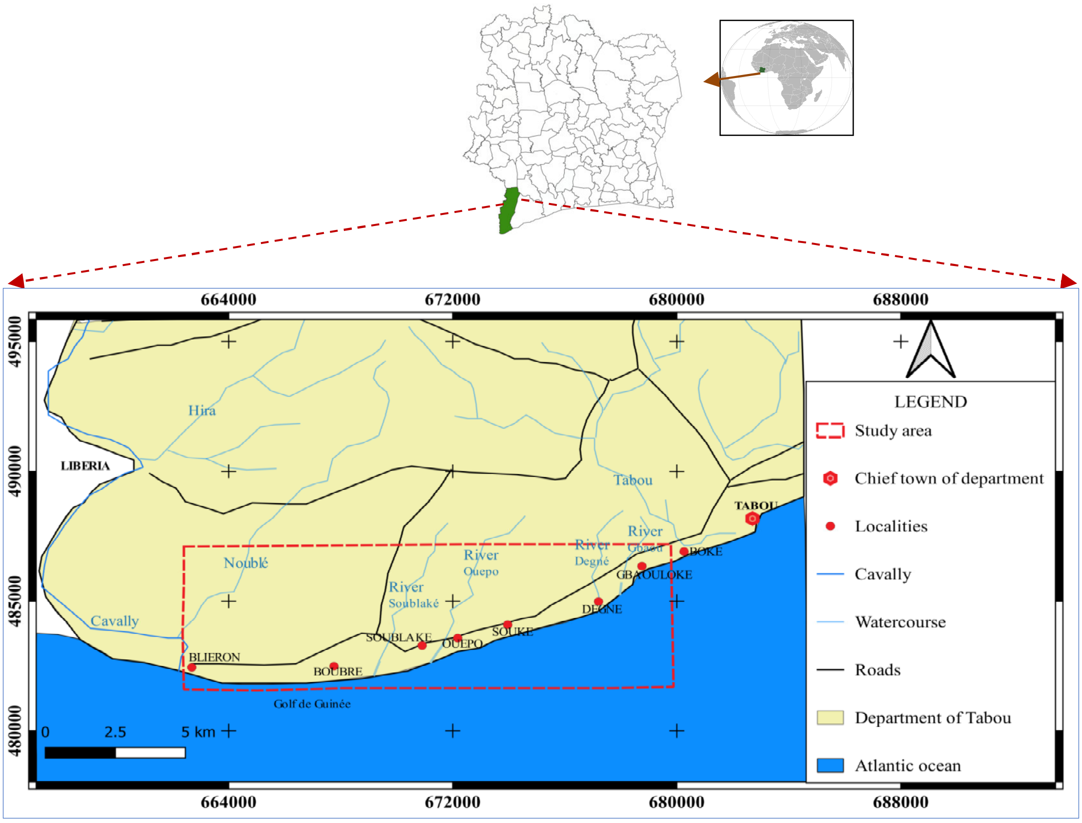

Figure 2: Location of the study

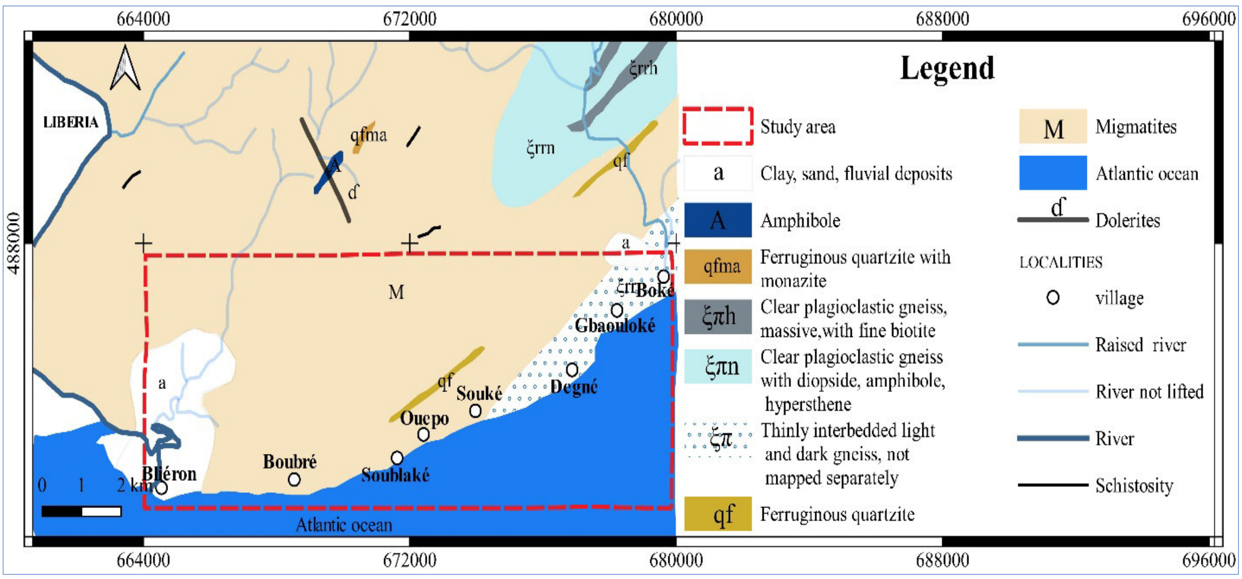

Figure 3: Geological map of the study area (Papon, 1973).

3. Methodology

The crystalline rocks that outcrop on the south-western coastline of Côte d'Ivoire are mainly composed of migmatites and gneisses. Alteration of these rocks releases particles, sands and colloids, which in places concentrate titanium and uranium oxides. The mapping of these titanium-uranium sands is based on magnetic and gamma(γ) spectrometry methods.

- The former is based on the measurement of the magnetic susceptibility of crystalline rocks and sediments of the coastline, which in places contain titano-ferric oxides (magnetite (Fe_3O_4), titanomagnetite ($Fe_{x-y}Ti_yO_4$) and ilmenite ($FeTiO_3$)). These minerals have their own magnetic remanence, which locally amplifies the magnetic spectrum within sandy rocks and sediments. Applying the high frequency filter to the magnetic signal eliminates the spectrum of the crystalline rocks while enhancing the response of the oxides present in the sediments. Magnetic data acquisition was carried out with two G 858 SX Caesium magnetometers for the total field measurement; one at the base station and the other in walk-around mode. Two Fast Fourier Transform (FFT) filters were applied to the data to estimate the apparent magnetic susceptibility values of the crystalline rocks and the magnetic spectrum values of the sediments. These are the magnetic susceptibility (L (r, θ)) and downward continuation (H(r)) filters defined by equations (1) and (2) respectively:

$$L(r,\theta) = \left(\frac{1}{2\pi F \cdot H(r) \cdot \Gamma(\theta) \cdot \mathrm{K} \cdot (r,\theta)}\right) \quad (1)$$

and

$$H(r) = e^{-hr} \quad (2)$$

With $H(r) = e^{-hr}$; $\Gamma(\theta) = [\mathrm{Sin}\, Ia + i\,\mathrm{Cos}\, I \cdot \mathrm{Cos}\,(D-\theta)]^2$ et $\mathrm{K}(r,\theta) = \left[\frac{\mathrm{Sin}\,(ar\,\mathrm{Cos}\,\theta)\ \cdot\ \mathrm{Sin}\,(ar\,\mathrm{Sin}\,\theta)}{ar\,\mathrm{Cos}\,\theta \cdot ar\,\mathrm{Sin}\,\theta}\right]$

H(r): downward continuation; $\Gamma(\theta)$: correction for the geometric effect; $\mathrm{K}(r,\theta)$: Reduction to the pole;
F: Total geomagnetic field; *h*: depth in ground units; *I* geomagnetic inclination; *Ia*: pole reduction amplitude inclination; *D*: geomagnetic declination; θ: latitude; *r*: wavenumber.

The first filter (L (r, θ)) provides information on the distribution of the acid, basic and ultrabasic units. It facilitates the reading of the geological map and highlights the discontinuities linked to the distribution of titanium-iron oxides in the matrix of crystalline rocks. Thus, this filter discriminates between basic and ultrabasic rocks, potential sources of titanium-iron oxides, within the coastal basement. As for the Downward Continuation (H(r)) filter, it enhances the magnetic spectrum of the titanium-iron oxides contained in the sediments while attenuating the magnetic response of the ferromagnesian minerals of the basement, and thus facilitates their mapping.

- The second approach is based on the detection, with a GBO 32 spectrometer, of the gamma decay spectrum from uranium oxides (UO_2) contained in the sediments. This device converts the detected spectral energy into an equivalent value (eU) expressed in parts per million (ppm), which reflects their relative abundance in the coastal sediments. The application of the high frequency filter on this spectrum allows the delimitation of uranium concentration zones within these sediments.

Crystalline rocks samples, taken from some coastal outcrops, were used to carry out geochemical measurements of major elements (Table I). The obtained grades reflect the concentrations of oxides present in these rocks, and may provide information on the origin of titanium and uranium oxides observed on the coastline.

Table I: List and coordinates of the collected samples.

N°	Localities	Sample CIxx	Easting-UTM	Northing-UTM
1	Boké	CI06	678792	486096
2	Boké	CI08	678837	486122
3	Dégné	CI10	677101	484830
4	Dégné	CI11	677035	484748
5	Yonaké	CI14	676154	484520
6	Yonaké	CI15	676051	484438
7	Soublaké	CI16	671649	483214
8	Bliéron	CI18	663453	482554

CIxx= Sample Number, UTM= Universal Transverse Mercator (29N)

4. Results and discussion

4.1. Magnetometry

4.1.1. Magnetic susceptibility

It highlights three magnetic facies that reflect the distribution of titanium-magnetic minerals within the crystalline and metamorphic rocks of the coast (Figure 4). In the low latitude zone, magnetic anomalies are characterised by low values of magnetic susceptibility.

Thus, the first facies, which corresponds to low signatures, reflects the magnetic spectrum of rocks rich in ferromagnesian minerals. It is marked by a "red-indigo" hue and occurs in the villages of Boké, Gbaouléké, Yonaké and Souké. This facies is characterised by a magnetic susceptibility less than 0.157 (K) and reflects the signature of rocks with a high content of titano-ferric oxides. On the local geological map, this facies covers the orthogneiss of tonalitic composition which follows a NE-SW direction. At Souké village, this signature is more spread out and presents a heterogeneity that indicates the presence of a more moderate magnetic facies.

The second facies is characterised by a strong magnetic signature, which is related to the high values of magnetic susceptibility ($K \geq 0.160$) and is marked by a "bluish" colouration. This facies is mainly found in Boubré village and east of Bliéron village. It also appears westwards of Soublaké and Yonaké villages, and eastwards of Dégné and Gbaouléké villages. This signature reflects the magnetic response of migmatites and/or gneisses with a quartz monzonitic composition enriched in cardinal minerals.

The third and last facies is characterised by magnetic spectra that range from 0.157 to 0.160 (K). It is represented by a "yellow-orange" hue and is less extensive than the previous facies. It occurs at Bliéron, north and north-east of Soublaké village, at Ouépo, west of Yonaké and on the eastern edge of Dégné village. This facies also appears as a buttonhole between Gbaouléké and Boké villages. From a geological point of view, this signature reflects the magnetic reflection of orthogneisses with a granodioritic composition.

4.1.2. Downward continuation

The downward analytical continuation map reveals the residual signature of magnetic oxides in the sediments (Figure 5). It shows the spatial distribution of the high-frequency spectrum of magnetic oxides resulting from supergene alteration processes of the existing rocks. The titanium-iron sands are characterised by magnetic spectra with values ranging from 150 to 750 nanoTesla (nT). They are more or less continuously distributed along the coastline of the different villages, with exception with Bliéron where they present a more homogeneous and constant signature. These sandy deposits mostly form lenticular bands, which are mainly oriented E-W. Their average length and width are respectively around 600 and 80 m.

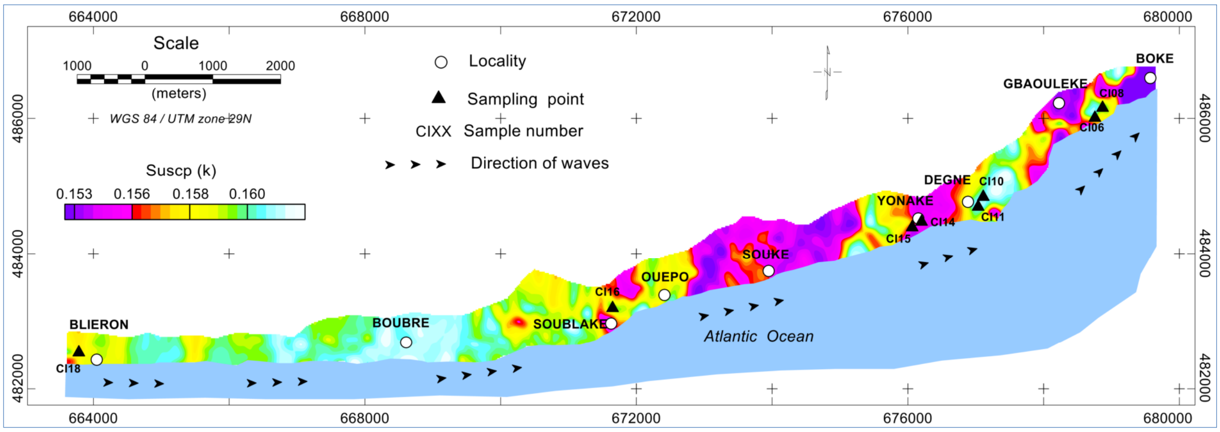

Figure 4 : Magnetic Susceptibily map.

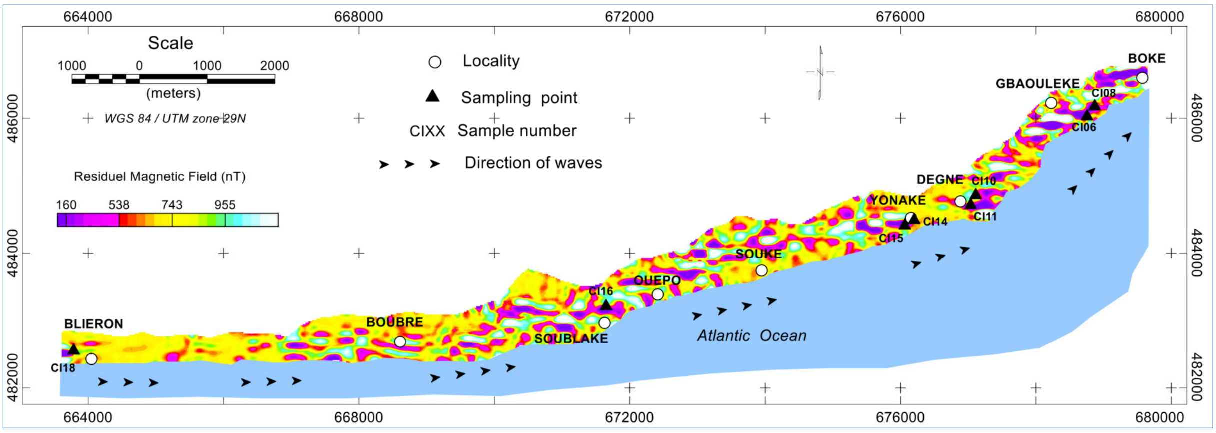

Figure 5: Downward Continuation of magnetic field.

4.2. Gamma spectrometry

Figure 6 shows the spatial distribution of the spectrum of uranium sands. It shows two main units, which are related to the uranium decay reported in ppm.

The first unit corresponds to the low values of the spectrum. It is represented by concentrations that oscillate between 0.07 and 10.5 ppm and is characterised by a "blue-green-orange" coloration. This unit covers most of the coastline. It extends from the Boké village to Soublaké and north of Boubré.

The second unit is characterised by relatively high spectral values ranging from 10.5 to 38 ppm. It is marked by a red hue and occurs continuously along the coastline from Bliéron to Boubré, but also in isolated pockets, north of Bliéron, Dégné and Ouépo villages.

4.3. Synthesis and discussion

The present work has mapped titano-uraniferous sands in the south-western Tabou coastline from geophysical data (Figures 5 & 6). This study shows a fairly continuous accumulation of titanium-uranium sands along the coast from Bliéron to Soublaké. On the mainland between Bliéron and Soublaké, the geophysical signature of the sands is quite weak, except for two areas. The first is located north of the Bliéron village at the confluence between the Noublé and Cavally rivers, where sediments have been transported to produce a strong spectral signature. The second area is located about 1.5 km west of Bouré village (Figures 5 & 6).

From Ouépo to Boké villages, the coast does not generally show titano-uranium deposits. These are found in the meanders of Ouépo, Dégné, Gbaouléké and Boké rivers. The results also show that, in this part of the coastline, titaniferous sands are not generally associated with uranium sands. In addition, the beaches are poor in titaniferous sands, whereas uranium-bearing sands are more abundant northwards of Ouépo, Souké and Gbaouléké villages, at the bends formed by the coastal rivers (Figure 7).

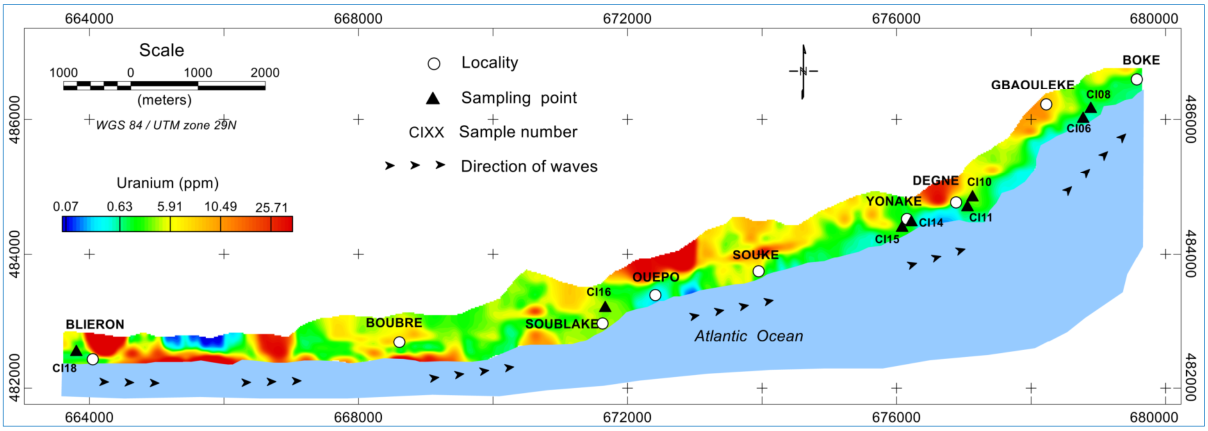

Figure 6 : Uranium spectrum map.

These results also show a contrast between these sandy deposits and the underlying lithologies. Indeed, most of the coastline metamorphosed crystalline rocks do not contain a significant proportion of iron and uranium oxide (Table II & III). The example of samples CI16 and CI18, collected respectively at Soublaké and Bliéron beaches, support this statement. Sample CI16 is an orthogneiss with a trondhjemitic composition with low geochemical contents of magnetic oxides [Fe_2O_3 (3.03%) & FeO (2.73%), MgO (0.62%) & TiO2 (0.31%)] against a high proportion of cardinal oxides [SiO2 (72.28%) & Al_2O_3 (13.87%)] (Kouadio, 2017). Similarly, sample CI18 is a gneiss with a quartz monzonitic composition whose geochemical contents also reveal a low level of magnetic oxides [Fe_2O_3 (2.77%) & FeO (4.49%), MgO (1.54%) & TiO (0.16%)] against a high level of non-magnetic oxides [SiO_2 (72.35%) & Al_2O_3 (13.36%)] (Kouadio, 2017). This lack in ferromagnesian oxides corroborates the relatively low magnetic signature observed between Bliéron and Soublaké villages (see Figure 4). Furthermore, the geochemical uranium content of these samples is around 0.3 ppm.

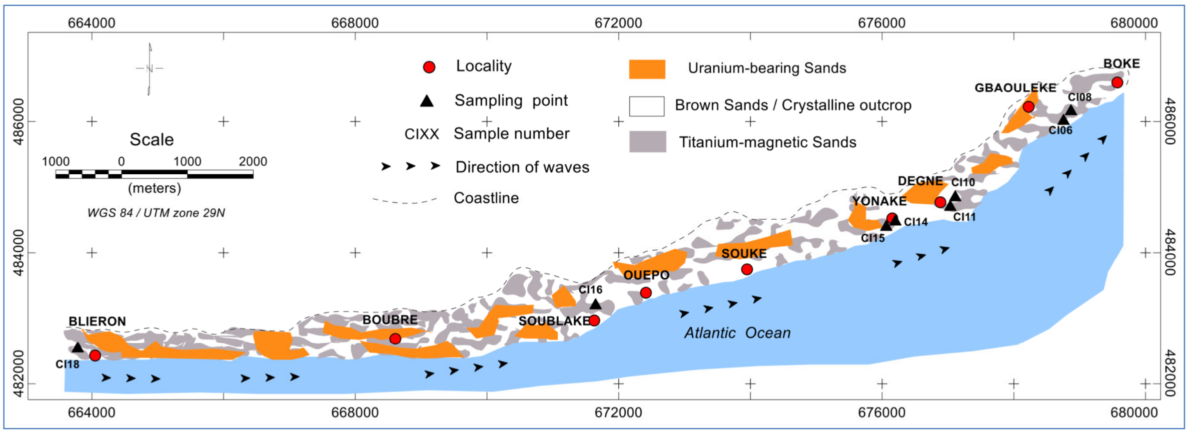

Figure 7 : Synthesis map.

Table II: Major (%) and trace (ppm) elements composition of paragneiss (Kouadio, 2017).

	CI15	CI22	CI23
SiO_2	63,99	64,71	64,05
Al_2O_3	15,4	15,72	15,32
Fe_2O_3	7,68	7,93	7,74
FeO	6,91	7,14	6,96
CaO	2,56	1,87	2,73
MgO	3,75	2,52	2,35
Na_2O	3,04	3,21	3,55
K_2O	1,89	2,34	1,73
MnO	0,1	0,1	0,07
TiO_2	0,75	0,86	0,83
P_2O_5	0,18	0,06	0,12
Cr_2O_3	0,033	0,033	0,025
LOI	0,23	0,25	0,96
SUM	99,66	99,66	99,53
Ba	377	484	600
Co	22,3	20,9	20,1
Cs	2,2	1,1	1,7
Nb	10,5	7,6	6,9
Rb	108,2	86,7	85,9
Sn	<LD	<LD	<LD
Sr	240,5	320,5	431,4
Ta	0,8	0,5	0,6
Th	13,8	5,4	5,1
U	2,8	0,7	1,2
V	84	114	112
Zr	203,8	279,4	178,9

LD: Detection limit. LOI: Loss on fire

However, this portion of the coastline concentrates most of the titano-uraniferous sand deposits, thus highlighting the contrast between these sandy deposits and the lithologies that constitute the underlying basement. From Ouépo to Boké villages, the situation is practically the same, with magnetic oxide contents ranging from 2 to 8% compared to 80 to 87% for non-magnetic oxides. As for the uranium content, it does not exceed 3 ppm on this part of the coastline.

From these findings, the titano-uraniferous sands of the Tabou coastline would come from a supergene alteration process of continental basic and ultrabasic rocks. Indeed, previous studies carried out by Papon (1973) in the northern part of western Tabou, revealed several lithologies that concentrate ferromagnesian minerals (see Figure 3). Indeed, this author highlighted ferruginous quartzics with monazites and itabirites, amphibolites and gneisses through a migmatitic basement. In the Man region, authors such as Camil (1984), Kouamelan (1996), Pitra et al. (2010) and Koffi et al. (2020) have also identified in the Archean and Proterozoic domains, several basic and ultrabasic formations. Kouadio (2017**)** also identified quartz monzonites with traces of uranium at Bliéron. In addition to these formations, there are iron deposits in Monts Nimba and Klahoyo, and in Monts Trou and Tia, which concentrate titaniferous ores. Under the effect of supergene alteration, the particles pulled out from the continental rocks would be drained by the Cavally River and coastal rivers such as the *Nouble* river, the *Ouepo* river, *Degne* river, *Gbaouleke* river and the *Tabou river;* thus, ensuring their N-S displacement at the south-western coast of Tabou (Figure 2).

Table III: Major (%) and trace (ppm) elements composition of orthogneisses of tonalitic and trondhjemitic composition (Kouadio, 2017).

	Tonalite				**Trondhjemite**				
%	CI01	CI11	CI14	CI25	CI03	CI06	CI08	CI10	CI16
SiO_2	66,55	66,73	71	68,35	74,77	70,92	74,9	72,01	72,28
Al_2O_3	15,74	15,02	14,18	14,48	10,83	16,62	11,95	13,55	13,87
Fe_2O_3	4,5	5,43	4,1	4,89	6,69	0,94	3,97	3,9	3,03
FeO	4,05	4,89	3,69	4,4	6,02	0,85	3,57	3,51	2,73
CaO	4,53	3,92	3,19	3,93	2	1,53	1,67	3,09	2,9
MgO	1,92	1,56	0,8	1,24	0,23	0,15	0,5	0,75	0,62
Na_2O	4,15	4,35	4,06	4,01	4,35	6,9	4,4	3,42	3,8
K_2O	1,24	0,8	1,19	1,18	0,7	1,74	1,48	2,01	2,01
MnO	0,07	0,09	0,04	0,06	0,07	0,01	0,11	0,04	0,03
TiO_2	0,43	0,65	0,37	0,46	0,26	0,05	0,34	0,41	0,31
P_2O_5	0,13	0,13	0,13	0,17	0,05	0,03	0,07	0,1	0,07
Cr_2O_3	0,008	<0,001	0,004	0,005	<LD	0,008	<LD	<LD	0,002
LOI	0,25	0,84	0,36	0,39	0,09	0,36	0,35	0,21	0,32
Oxides	99,57	99,56	99,46	99,22	100,09	99,31	99,8	99,6	99,3
Ba	474	348	424	259	362	545	620	865	436
Be	<LD	2	2	<LD	2	2	<LD	2	2
Co	14	10,5	6,7	9,9	2,6	0,8	2,6	6,4	4,1
Cs	0,5	<LD	0,2	0,2	<LD	<LD	<LD	0,5	0,4
Nb	4,6	11,8	6,4	11,9	7,2	0,5	10,2	6,2	5,6
Rb	34,5	13,9	30,5	46,9	3	10,8	10,9	71,7	47,2
Sn	<LD	2	1	3	4	<LD	2	<LD	<LD
Sr	383,6	219,9	298	245,9	255,2	449,6	128,4	220,7	224,4
Ta	0,6	1	0,1	2	0,5	<0,1	0,7	0,5	<LD
Th	0,7	13,2	1,1	4,7	2,1	0,3	<LD	15,2	6,1
U	<LD	1,5	0,2	2,4	0,4	0,1	0,2	1,7	0,2
V	69	59	32	36	<LD	<LD	<LD	30	11
W	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD	<LD
Zr	134,7	316	245,9	271,8	556,2	61,8	277,3	291,2	216,2

LD : Limite de détection. LOI : Perte

The sedimentation of the titano-uraniferous sands along the coast, between Bliéron and Soublaké, would be ensured by the West to East oriented marine current; which favours their deposition in unconformity on the Proterozoic basement (see Figure 7). Some authors such as Berger (1956) and Mhammdi et al (2005) have also highlighted titaniferous sands on the Moroccan Atlantic coast. The granulometric study and mineralogical analysis carried out by Mhammdi et al. (2005**)** on these titaniferous sands allowed the characterisation of the sedimentary dynamics and the determination of their ilmenite and magnetite content. Although the scientific approach of this author is different from the methodology developed during this study, his results clearly link the black sands of the Moroccan coast to the ferromagnesian minerals, ilmenite and magnetite, which were mapped using a magnetometer at the Tabou coastline.

5. Conclusion

The present study mapped the titano-uraniferous sands of the Tabou coastline using magnetometry and gamma spectrometry (uranium). The results show a uniform accumulation of black sands on the Bliéron and Soublaké coastline.

The titano-uraniferous sands probably originate from supergene alteration, products of basic and ultrabasic complexes, itabirites and iron deposits that are localized upstream of the coastline in the Cavally river watershed. The rivers of this basin ensure a N-S flow of detritus towards the Atlantic Ocean and thus concentrate the black sands in the estuaries. The marine currents, oriented E-W, favour their deposition in unconformity on the Proterozoic formations of the coast between Bliéron and Soublaké. For future work, it would be desirable to carry out granulometric, morphoscopic and mineralogical studies of the titano-uraniferous sands mapped in the estuaries and on the coast between Bliéron and Soublaké in order to assess their exploitation potential.

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