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Mapping of Lithium-Bearing Pegmatites Using Aeromagnetic Data and Field Outcrop Descriptions in the Bougouni Area, Southern Mali

Séko Sanogo[1], Adama Youssouf Koné[1*], Ousmane Wane[1], Cyril Durand[2], Michel Dubois[2]

[1]Laboratoire de Géodynamique et Cartographie (LGC), Faculté des Sciences et Techniques (FST), Université des Sciences, des Techniques et des Technologies de Bamako (USTTB), Bamako, Mali
[2]LGCgE—Laboratoire de Génie Civil et géoEnvironnement, Institut Mines-Télécom, Université de Lille, Lille, France
Email: *koneadama2005@gmail.com

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Abstract

Within the West African Craton, the Baoulé-Mossi domain is known for its potential in mineral resource among which, lithium now occupies an important place. Tied to pegmatite facies, the lithium is beared by spodumene ($LiAlSi_2O_6$) mineral. In southern Mali, pegmatites are located in the Bougouni Pegmatite Province (BPP) and are generally hosted within magmatic (e.g., granodiorites, monzogranites etc.) or metamorphic formations. This province is classified as one of the most important Lithium-bearing in Africa. However, the poor knowledge on their repartition and the thickness of soil cover constitutes a handicap to their characterization. It is why available aeromagnetic data have been used to identify the probable areas for pegmatite intrusive which are followed on the ground. This study requires understanding pegmatites distribution and their spatial relationships with the host rocks in the Bougouni area. For this, aeromagnetic data interpretation has been integrated with field geological descriptions. This study has allowed to understand that pegmatites dykes of Bougouni are low or even non-existent magnetic signature. It was also established that these pegmatite dykes are contained in metasedimentary and granitoid rocks which have moderate to high magnetic response.

Keywords

Pegmatites, Spodumene, Lithium Mineral, Aeromagnetic Survey, Southern Mali, West African Craton (WAC)

1. Introduction

The West African Craton (WAC), particularly its southern part (**Figure 1A**) is known for its potential mineral resources (e.g., gold, copper, diamond, lithium) exploited as industrial [1] and artisanal mining sites [2]-[4]. These resources are located within the geological formation which mostly takes place during Eburnean orogeny (−2.2 - 2.0 Ga), [5]-[7]. The end of Eburnean orogeny is characterized by the stabilization of WAC.

In Mali, the Precambrian formations which shelter these mineral resources are mostly located in the west (Kedougou Kenieba Inlier and Kayes Inlier) and south (Baoulé-Mossi domain) part of the country. Within these formations, the mining activities are more focused on gold [1] [8] and often on diamond [9]. Also, many pegmatites facies are known in the Baoulé-Mossi domain: i) the pegmatite district of southeastern Ghana [10]; ii) the columbite-tantalite pegmatites of Issia in Côte d'Ivoire [11]; iii) the pegmatite district of the south-east of the Ivory Coast [12]; iv) the rare metal pegmatites of the Mangodara's district in Burkina Faso [13]; v) Dibilo lithic occurrences, Niger [14] (**Figure 1A**).

Recently, in southern Mali, a large number of research projects have been focusing on lithium resources, particularly in the Bougouni region, 160 km from Bamako (Mali's capital). This region is known for its potential lithium-bearing pegmatites that are associated geographically with granitoids namely Birimian (Paleoproterozoic). Previous studies [6] [15]-[17] have identified the presence of pegmatites in the Bougouni map sheet located between 7˚W - 8˚W and 11˚N - 12˚N. The Bougouni Pegmatite Province (BPP) is one of the most targeted regions in Africa for strategic metals due to its lithogenic potential. However, the BPP is poorly documented in the literature despite this potential. In Southern Mali, vegetation cover makes difficult the outcrop conditions of these rocks. For this reason, the geophysical method was considered in the study to help identify pegmatites.

The aim of this study is to identify and characterize Lithium-bearing pegmatite dykes and granitoids of Paleoproterozoic ages. To this end, two field geology campaigns were carried out in 2018 and 2019. In addition, available aeromagnetic data were analyzed to identify potential lineaments that could link these formations. The lineaments have been ground followed through outcrop descriptions in the Bougouni area.

The Bougouni Pegmatite Province (BPP) is home to spectacular spodumene-bearing pegmatite dykes. The most of the pegmatitic bodies are located in the topographic map of Bougouni (**Figure 1B**). In the BPP about one hundred Li-rich and one hundred Li-poor aplite-pegmatite dykes of the LCT family are intrusive. Lithium is carried by spodumene. The spodumene is accompanied by alkali feldspar, plagioclase, quartz and a small amount of muscovite and biotite. The Li-poor are characterized by the same mineralogical group as the Li-rich dykes, except for spodumene. But, Li-poor contain garnet, which is absent in Li-rich. For geophysical point of view, the pegmatite facies of Bougouni have very low magnetic signature. But, they are contained in granitoids and metasediments which are bodies

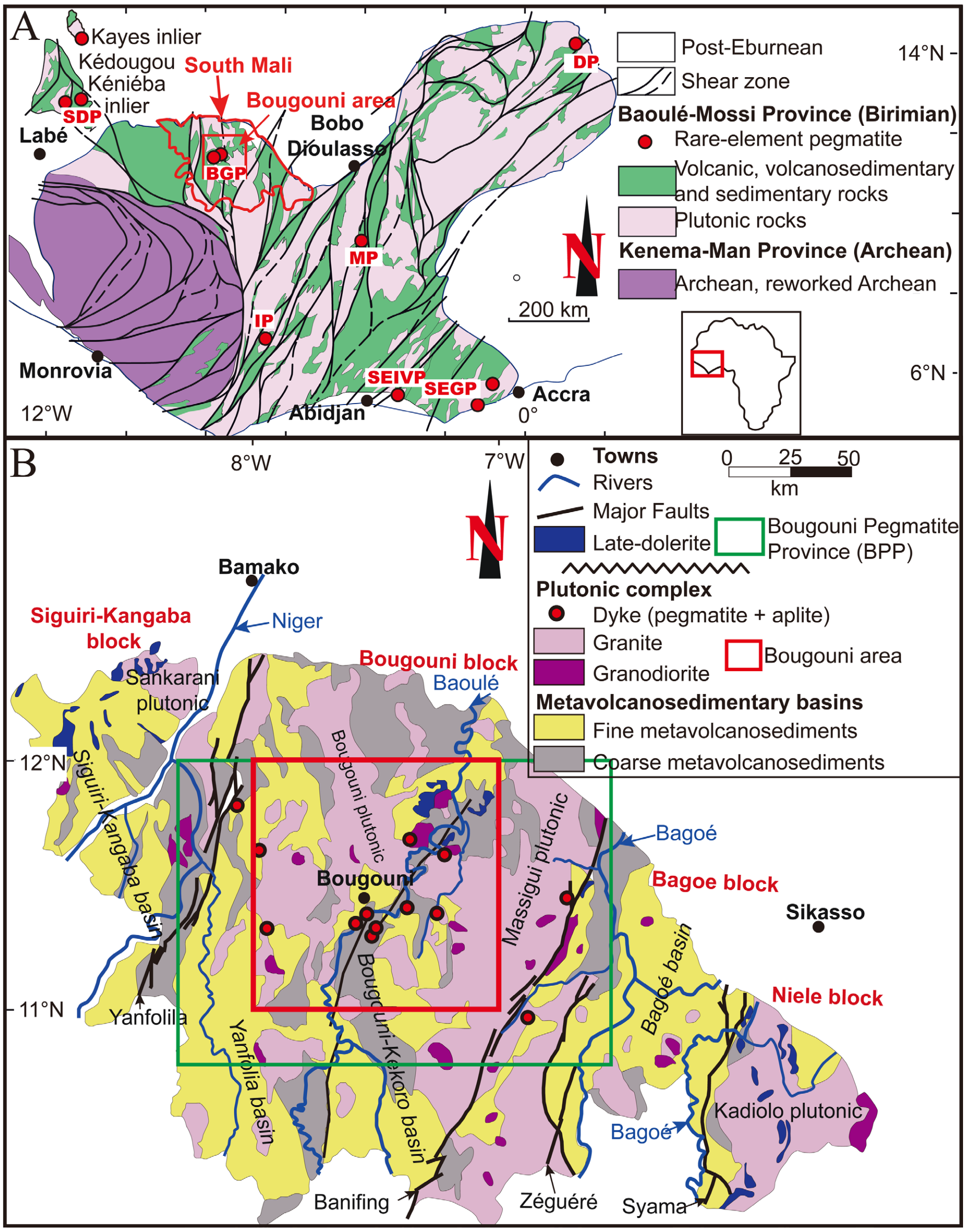

Figure 1. Simplified geological map: A-of the Southern West African Craton according to Chardon *et al.*, (2020); BGP: Bougouni-Goulamina pegmatite; MP: Mangodara pegmatite; SEGP: Southeast Ghana pegmatite; IP: Issia pegmatite; SEIV: Southeast Ivory Coast; SDP: Saraya-Dioumbalou pegmatite; DP: Dibilo pegmatite; B-of southern Mali, modified from [5]). The study area (100 km by 100 km) corresponds to the geological map of the Bougouni area.

with significative magnetic response. This has allowed indirectly to characterize pegmatites facies in the Bougouni Pegmatite Province (BPP) within southern Mali.

2. Geological Setting

In geological point of view, the study area is attached to west African craton (WAC). The WAC shelters two Shields (Reguibat and Leo-Man), two Inliers

(Kayes and Kedougou-Kenieba) and many Sedimentary basins (e.g., Tindouf, Taoudenit…). These shields and inliers are dated to Precambrian age [18]-[23] and the basins to Paleozoic. The last shield (Leo-Man) contains the study area (**Figure 1A**).

The Léo-Man Shield (**Figure 1A**), as southern outcrop of the WAC, is located in the south of Neoproterozoic to Paleozoic basin of Taoudenit. This shield is geologically divided into two domains separated by the Sassandra fault [8] [18] [24]-[26]: an Archean domain in the west namely Kénéma -Man and Paleoproterozoic one in the east called Baoulé-Mossi [5] [27]. The last one includes the Bougouni region (**Figure 1B**). The Baoule-Mossi domain of Mali is dominated by plutonic, volcano-sedimentary and metamorphic formations and outcrop in many places. Also, many pegmatite facies are known in the Baoulé-Mossi domain, as known as **Figure 1A**. In the Malian part, most of these pegmatites are located in BPP within Bougouni map sheet (**Figure 1B**).

The region southern Mali within the Baoulé-Mossi domain is structured by three major shear zones (Yanfolila, Banifing and Syama) and four major basins (Siguiri-Kangaba, Yanfolila, Bougouni-Kékoro and Bagoé) [5] [23]. The shear zones cross-cut the greenstone belts according to the latter authors. The Bougouni Pegmatite Province (**Figure 1B**) is framed by the Banifing and Yanfolila shear zones.

3. Used Data Presentation

Data analysis is focused on the analysis of aeromagnetic data and ground follow of identified lineaments and others outcrop of rocks.

3.1. Geophysical Data

The analysis of aeromagnetic data aims to identify structural lineaments able to tie pegmatite rocks in Bougouni region. Magnetic data analysis concerns the realization anomaly map and the application of mathematical transformations (e.g., reduction to the equator, upward continuation, analytical signal... etc.). These transformations allow to enhance the appearance of geological structures. Used aeromagnetic data were collected between February and December 2001 by Kevron Pty Ltd on behalf of the Malian government. The first processing was carried out by Fugro Airborne Surveys Pty Ltd [5]. The characteristics of the magnetic data survey are recorded in **Table 1**.

3.2. Outcrop Configuration and Dyke Measurement

Fieldwork expeditions were conducted in 2018 and 2019. A literature review was conducted prior to fieldwork. As a result, we identified a number of outcrops collected during previous campaigns and whose reports are available at the National Direction of Geology and Mines of Mali (DNGM). We were also able to study new outcrops not reported in the literature.

A local worker from Zantoulé (Kola community) was recruited to facilitate interaction with the people of his community. He also provided security and logistical support. During these campaigns, 200 outcropping levees were identified in 25 targets (**Figure 2**). All 200 outcropping pegmatite dykes were described macroscopically.

Table 1. Survey characteristics of aeromagnetic data [5].

Features	Descriptions
Date (year)	2001
Flight direction	135˚-315˚
Number of flight line	1080
Control line direction	045˚-225˚
Number of control lines	164
Equipment	Rockwell Aerocommander 500S VH-WAM, VH-EXS & Geometrics G-822A Cesium Vapor Magnetometer
Company	High Sense Geophysics Ltd/Aerodat
Flight altitude (m)	80
Line spacing (m)	400
Aircraft speed (m/s)	76.3 and 78.1
No measurement (m)	7m (0.1 second)

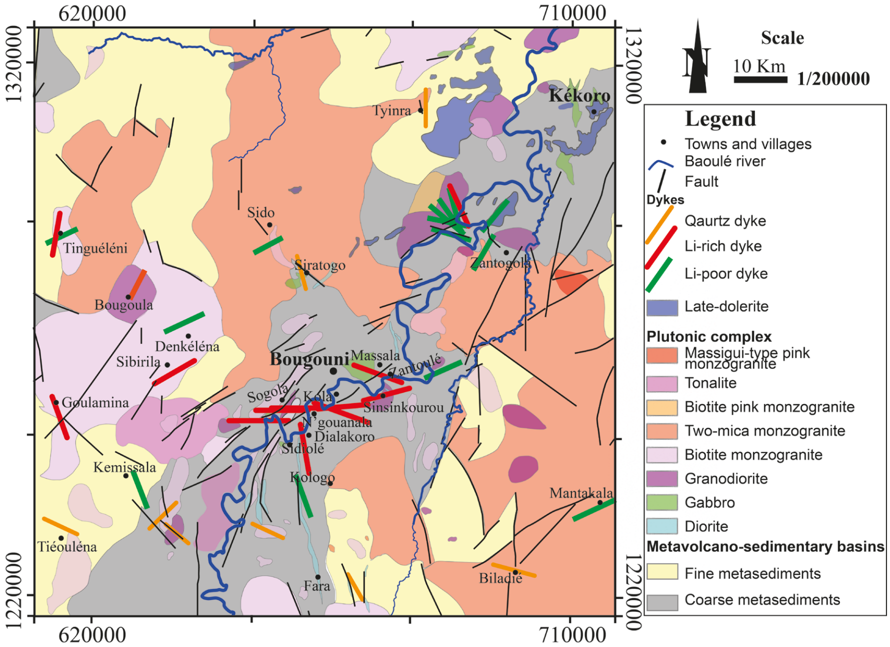

Figure 2. Bougouni geological map (modified from [5] presenting the direction of main pegmatitic dykes.

4. Data Analysis and Interpretation

4.1. Total Magnetic Intensity

The total magnetic intensity (TMI) represents the magnetic response of the underlying geological formations [2] [28]. It is an asymmetric anomaly with respect to the causative sources [29]. The TMI constitutes the response of the dominant magnetic bodies in the studied area. [3] and [4] qualify the TMI as allowing to define the variations in magnetic susceptibility contrast related to geological rocks rich in ferromagnesian elements and those poor.

The magnetic anomaly map of the Bougouni area shows numerous circular anomalies as well as magnetic lineaments. These anomalies are more dominant in the eastern part of the study area. They are marked by a magnetic contrast combining low and high values. This indicates the presence of circular bodies similar to massive geological formations such as crystalline rocks (magmatic and/or metamorphic). These geological massifs are smaller in size to the west and south of the Bougouni region (**Figure 3**). The observed magnetic lineaments are characterized by low magnetic signals. These lineaments are E-W; NW-SE; NNE-SSW to NE-SW directions. Many E-W directions are cross cut by NNE-SSW lineaments (**Figure 3**).

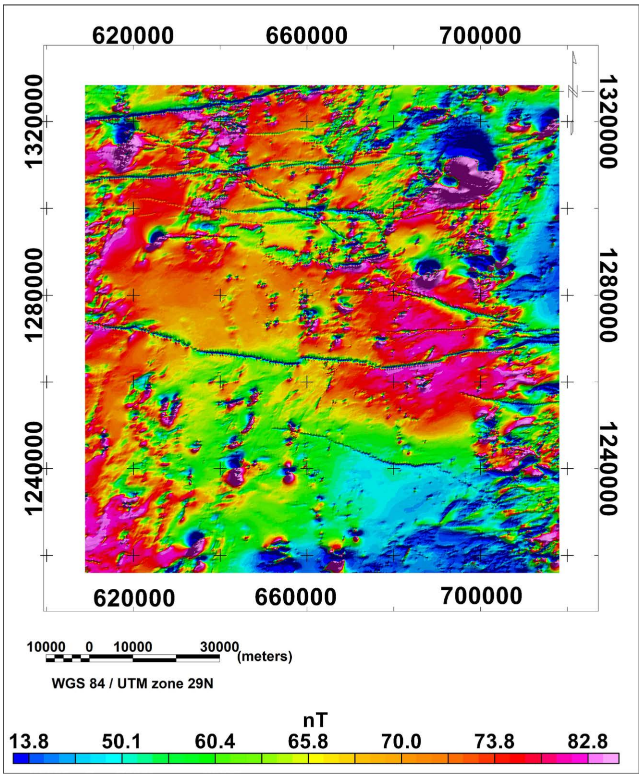

Figure 3. Total field anomaly map of the Bougouni area.

4.2. Reduction at the Equator (RTE)

The asymmetry of the anomaly constitutes an oblique magnetization [30] which complicates magnetic data interpretation. The reduction filters (pole or equator) can be removed this. In low-latitude regions such as Bougouni (<15˚ inclination), reduction to the equator (RTE) is more effective [2]. The RTE permits to bring the observed anomalies back to the vertical of the causative sources.

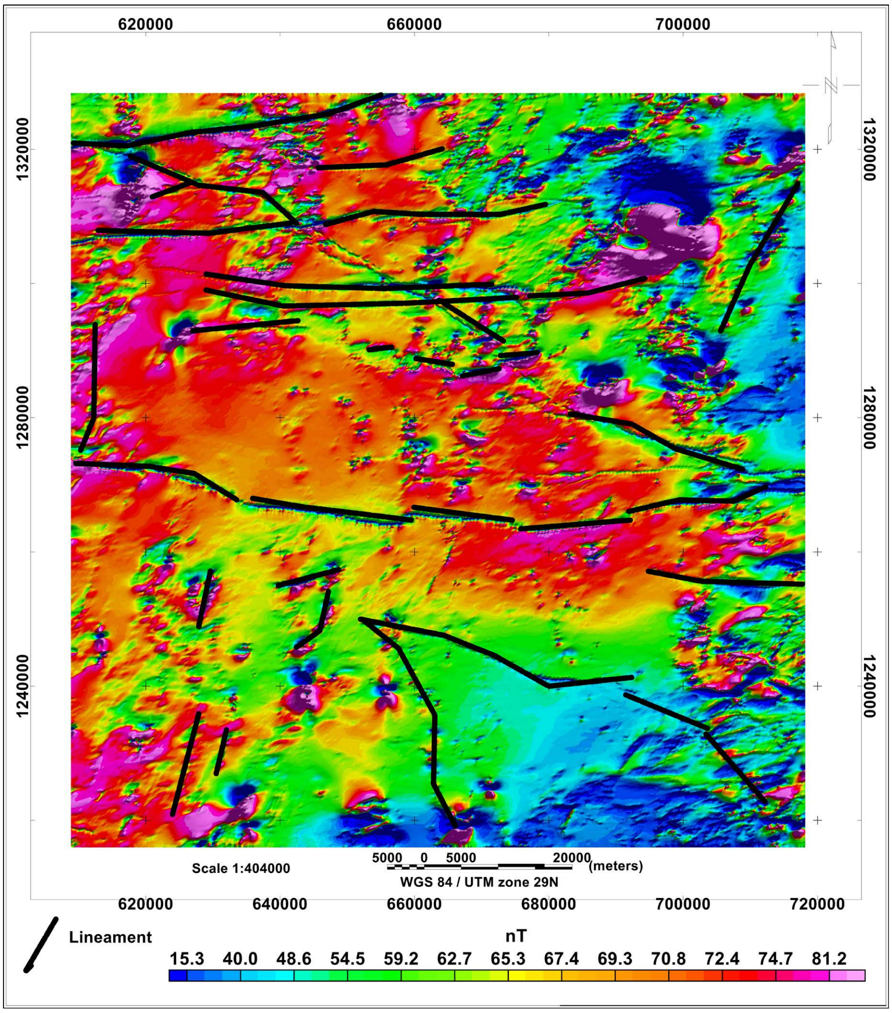

Figure 4. Map of the reduced field at the equator (RTE).

The application of the RTE in the Bougouni area is allowed to smooth the magnetic signal whose positive pole goes from 82.93 nT (**Figure 3**) to 81.2 nT (**Figure 4**). In this map, they are noted circular anomalies and lineaments. These lineaments have the same orientation in the TMI map. Also, NE-SW direction has a low magnetic signal compared to the others. The NE-SW are felt in places by the discontinuities of the EW and NW-SE lineaments (**Figure 4**).

4.3. Upward Continuation

The upward continuation (UC) is a mathematical transformation that has been widely discussed by [31]. It is the displacement of the measurement plane from a position P to a position P' (above) in order to assess the geometry and amplitude of the causative sources [2] [31] [32]. This transformation accentuates the effect of deep sources and attenuates that of superficial sources. The UC allow to classify sources according to their rooting.

The application of this transformation shows a progressive attenuation of the anomalies as a function of the UC distance (**Figure 5**). The signal amplitude of

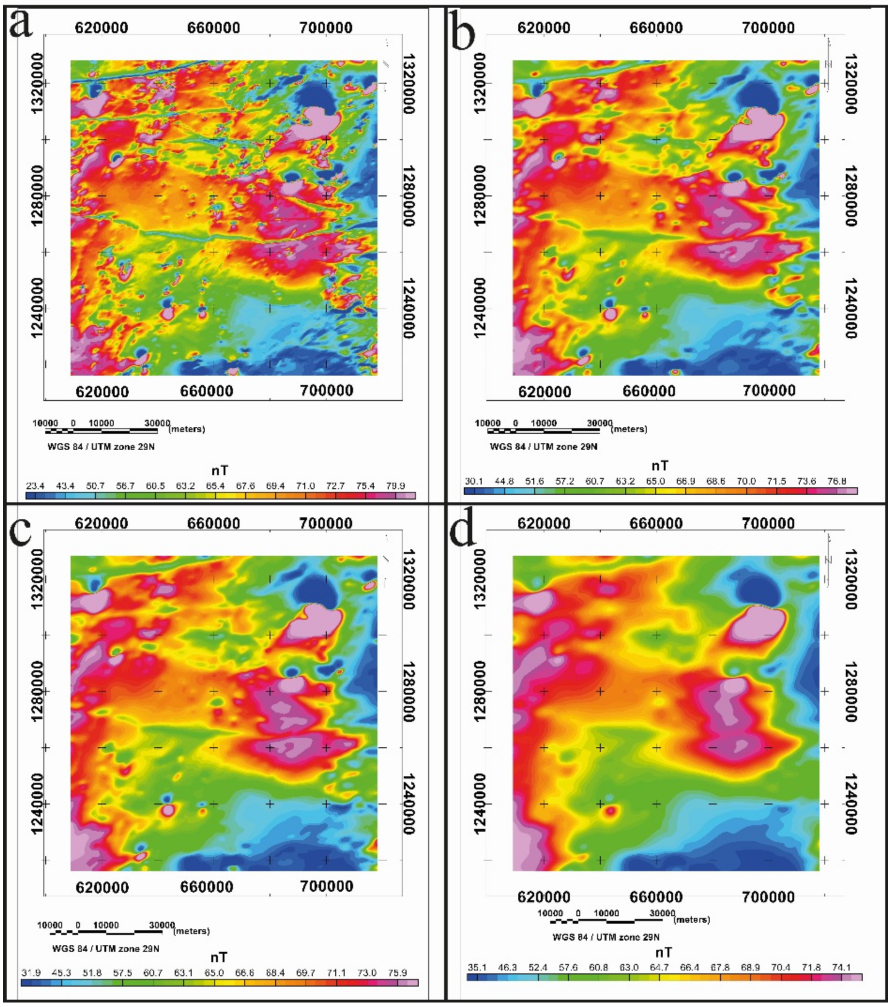

Figure 5. Map extended upwards by: a. 200 m; b. 800 m; c. 1200 m and d. 2500 m of the Bougouni area.

sources decreases with the increasing of UC distance. This allows to appreciate the degree of rooting of the anomalies observed in the Bougouni area. The lineaments are more attenuated towards 1200 m (**Figure 5c**). of extended distance while many circular anomalies still persist beyond 2500 m (**Figure 5d**). Thus, those anomalies can be qualified as deep sources.

4.4. Analytical Signal

The analytical signal is a transformation that enhances the bodies related to the disturbing sources of the observed anomalies [33]. It accentuates the shape of the anomalies above these disturbing sources [33]. It is also more effective to delimit the contour of anomalies related to geological bodies [32] [33]. This transformation is more appropriate in the determination of lineaments within crystalline terrain due to their non-negligible remanent and induced magnetizations [33].

The analytical signal map of Bougouni area more clearly defines the outline of observed circular anomalies and lineaments. The circular anomalies are expressed in positive magnetic signals (**Figure 6**) and are in places crossed by magnetic lineaments. The discontinuities (NW-SE) of the East-West lineaments are more accentuated by this transformation.

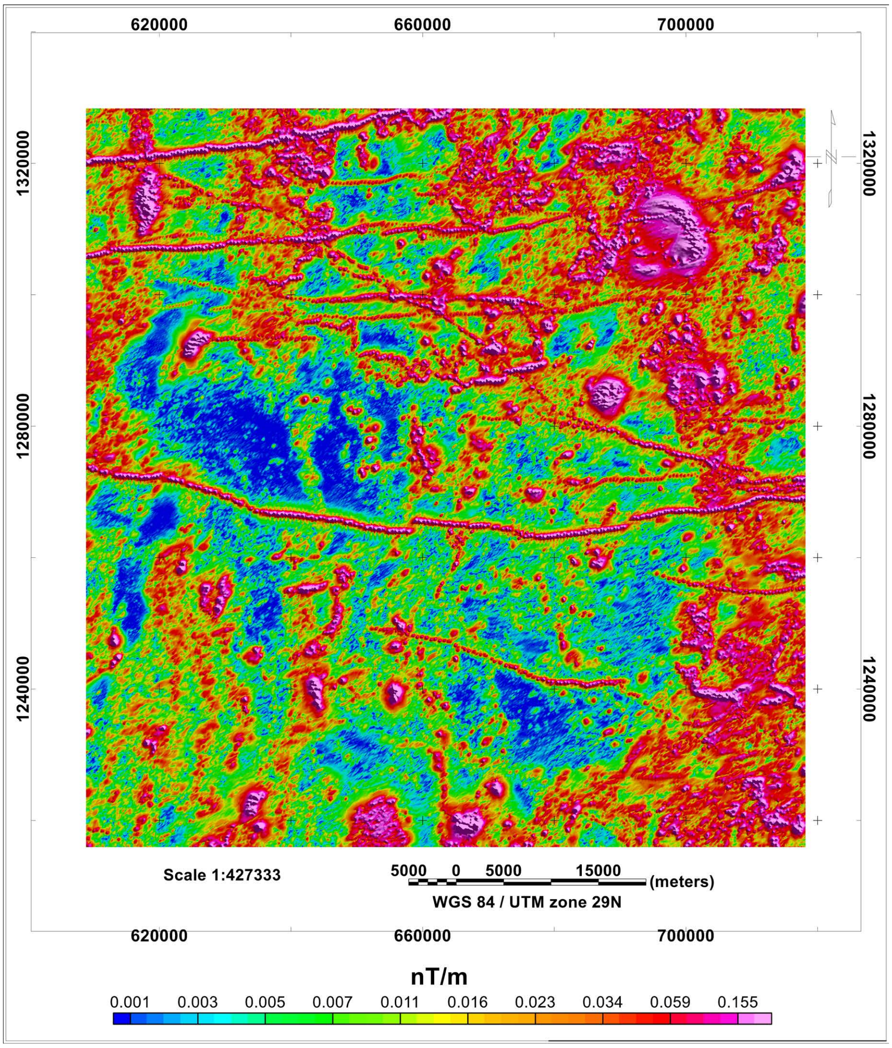

Figure 6. Analytical signal map of the Bougouni area.

4.5. Tilt Derivation

The derivative tilt transformation allows to enhance the amplitude of very short wavelengths related to a geological body [33]. [34] affirm that this transformation is able to represent all anomalies in a similar way even when they have very low signal amplitudes. The derivation processing consists of having a largely refined pushing in order to offer a multitude of lineaments oriented in all possible directions.

The map of the inclined derivative of the Bougouni area offers (**Figure 7**) many magnetic lineaments including those identified by the previous transformations. Many circular anomalies have their surface dominated by small lineaments. These lineaments are of very low magnetic intensity especially since they are only identified by this transformation of the inclined derivative (Figure 7). They are similar to the zones of discontinuities observed on surface of outcropping rocks.

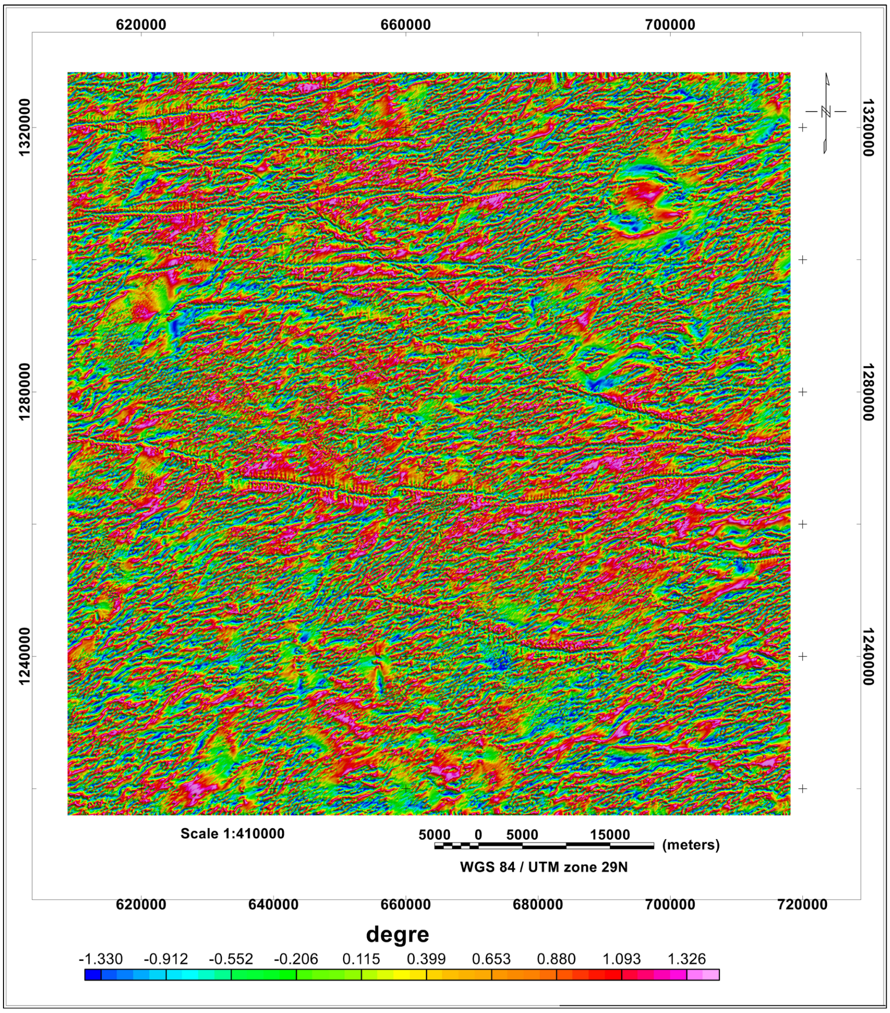

Figure 7. Map of the inclined derivative of the Bougouni area.

5. Lithological Characterization of Host Rocks Bougouni Pegmatites

The Bougouni Pegmatite Province (BPP) is composed of two main units: metasedimentary and granitoid rocks (Figure 2).

5.1. Metasedimentary Rocks

The metasedimentary rocks of the Bougouni area are located in Bougouni-Kékoro Basin (BKB). This basin occupies mainly the central part of the Bougouni Pegmatite Province (BPP). Metasedimentary rocks are intruded by several granitoidic plutons. They are divided into: i) coarse-grained metasediments and ii) fine-grained metasediments (Figure 1B & Figure 2). Subvertical to vertical stratification affects these rocks. Coarse-grained metasediments are most exposed and located many places around the Baoulé River. They are less weathering. The stratification of this formation is testified by the presence of metagreywackes and schists alternance. The stratification S0 and S1 (first phase of deformation) are locally sub-parallel to each other (**Figure 8A**). Concerning fine-grained metasediments, they dominate the BKB margins (**Figure 1B** & **Figure 2**). These formations are observed in a pit of gold artisanal mining site (AMS) in Tiéouléna village (**Figure 2**). They are highly altered.

5.2. Granitoids of Bougouni

The granitoids of the Bougouni area are composed of: i) the Massigui plutonic complex in the south-eastern part, and ii) the Bougouni plutonic complex in the northwestern part (**Figure 1B**). The petrographic composition of the Bougouni plutonic complex is various. They consist of: i) granodiorites, ii) tonalites, iii) biotite-bearing monzogranites and iv) two mica-bearing monzogranites (**Figure 2**). They are oriented NE-SW within the metasedimentary rocks of the Bougouni-Kékoro and Yanfolila basins (**Figure 1B**).

The granodiorites, as subcircular bodies, spread on tens of m2 to km2, those granodiorites commonly occur as flat slabs (**Figure 8F**). In some places, they occur as small metric "whale backs" with slight positive relief (**Figure 8E**). Tonalites outcrop in the west-central part of the study region (**Figure 2**) on about half a kilometer long. A network of quartz veins (1 to 2 cm thick) cuts the entire outcrop. Biotite monzogranites occur in many places, as batholiths and small circular plutons (**Figure 2**). They are often occurred as flat slabs and as whalebacks (**Figure 8G**). Two-mica monzogranites are the most abundant facies in the region (up more than 50% of the plutonic rocks). They are located in the northwest and in the southeast of the Bougouni area (**Figure 2**). These rocks occur as scattered decametric to hectometric slabs. They often occur as small plutons of a few meters to decameters in height. These facies dominate a large hill in Dogo and Tyinra in the north.

In addition to granitoids, there are some mafic rocks represented by quartz-gabbroic diorite and dolerite (**Figure 2**). On the field, they appear as scattered "balls" (**Figure 8H**). The dolerites are arranged in swarms of dykes. These last have been attached to post paleoproterozoic age. These facies appear as lenticular bands and cluster in areas of weakness, such as contact and fault zones (**Figure 2**).

6. Aplitic and Pegmatitic Dykes and Macroscopic Description

The outcrop characteristics of aplitic and pegmatic dykes are described in this section. The Bougouni pegmatite province (**Figure 1B** & **Figure 2**) is dominated by a lot of aplites and pegmatites dykes' outcrop. These dykes have been classed in two distinct groups of dykes: the Li-rich dykes (contain spodumene) and the Li-poor ones. However, on the field, pegmatitic facies are more strongly represented than the aplitic ones (less than 10 vol. % of aplite).

The ground follow shows that Li-rich dykes are more spectacular than Li-poor ones (**Figure 2**, **Figure 9** & **Figure 10**). Li-rich dykes are decametric to metric.

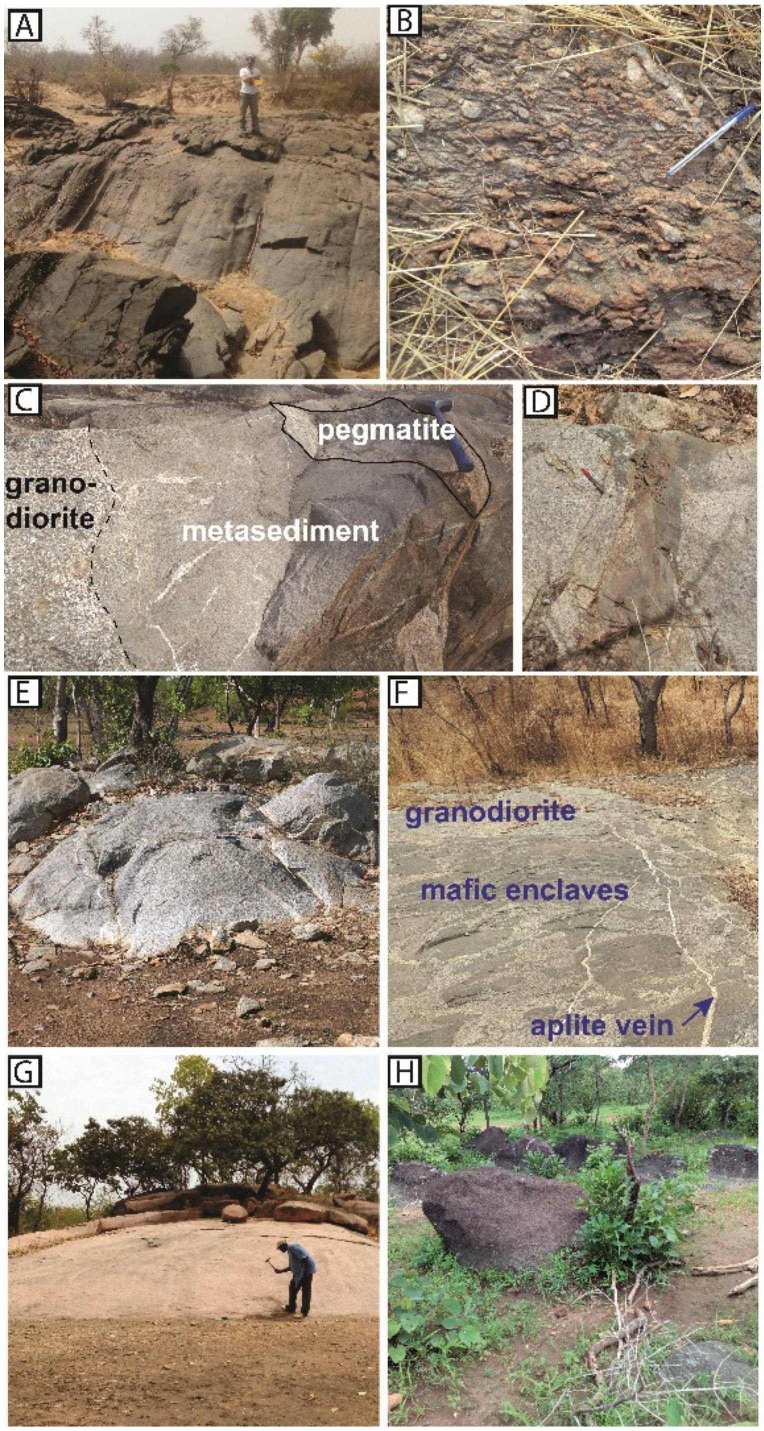

Figure 8. Field photographs of the coarse-grained metasedimentary facies in Bougouni area; A: outcrop of Sogola metagreywacke; B: outcrop of Sogola conglomerate; C: rounded contact zone between granodiorite and metasediment, the metasediment is cut by a Li-rich pegmatite (Massala); D: Metasedimentary enclave in granodiorite, the contact zone is diffuse and shows numerous lobes; field photos for the main plutonic facies of the Bougouni area; E: granodiorite with few lobes: E: granodiorite with few microdiorite enclaves from Diamana; F: granodiorite with numerous mafic enclaves crosscut by tardive aplitic veins from Sinsinkourou; G: pink monzogranite of the "Massigui" type from Tinkélini; H: quartz-gabbroic diorite "Boule" outcrop from Sinsinkourou.

Figure 10 shows the extent of targets with spectacular dykes. The pegmatitic and aplitic dykes are composed of light rocks (leucocratic facies). They are poor in ferromagnesian minerals (less than 1%). Altered biotite is recognized as the only Fe-Mg bearing mineral phase of these dykes. Macroscopic analysis of samples shows yellowish or pinkish crystals of altered alkali feldspar (Figure 9A, Figures 9D-9F).

6.1. Field and Macroscopic Descriptions of Li-Poor Dykes

In the field, Li-poor dykes are centimeter to decameter thick and a length varies from 5 to 500 meters. These dykes most outcrop in Diamana sector, Sido, Zantogola, Dialakoro, Bougoula and Madina sectors (Figure 2). These dykes contain the garnet mineral. This garnet occurs as circular crystal. It is light pink in the aplitic facies (Figure 9C) and reddish to brownish in pegmatitic one. Its size is variable from 0.1 to 1 cm (Figure 9B).

The pegmatitic and aplitic facies of the Li-poor dykes are distinctive dykes. Especially at Diamana (Figure 9A & Figure 10), aplites and pegmatites cut mutually. The aplites are generally organized in anastomosing veins (Figure 8F). The Li-poor dykes facies mainly host of feldspar and quartz with muscovite and some garnet with rare biotite (Figure 9B, Figure 9C & Table 2). The aplite facies are isogranular with a fine size (<0.1 cm) (Figure 9C). The pegmatites are heterogranular and characterized by medium to coarse crystals with size varies from 0.5 to 3 cm (Figure 9B). In outcrops, the difference between Li-poor dykes and ones of Li-rich is tied to this presence of garnet in the Li-poor rocks (Figure 9B).

The Li-poor dykes of Diamana sector are located 45 km to the northeast of Bougouni (Figure 2). The outcrops are located between 6 and 7 km around the village (Figure 10). Those dykes are host in the granodiorites. In 2018, somes of those dykes have been confirmed in 1 - 2 m deep trenchs done by National Geological Direction of Mali (DNGM). Within the pegmatites are enclaves of granodiorites.

The locality of Boundio is located 30 km in the municipality of Zantièbougou in at the eastern of Bougouni (Figure 2). The dykes of this sector outcrop near to granodiorite massif. The pegmatite dyke is around of 50 cm thick and oriented N65˚. Another dyke oriented N70˚ with 30 cm thick has been identified. This is divided into three ramifications to the west of first.

The target of Madina Kourlamini is located in 25 km to the southwest of Bougouni (Figure 2). It is an outcrop of granodiorite cut by pegmatites dykes oriented from N75 to N95. An N15 pegmatite dyke enriched in biotite has been identified within this target. Diorite and metasedimentary enclaves are also noticed in this sector.

The Sido target is located 34 km to the northwest of Bougouni (Figure 2). It is a 50 - 60 m diameter circular outcrop of biotite-monzogranite which is crossed by pegmatite veins and dykes. The contact with the host rock is unclear.

The Bougoula target is situated to 65 km west of Bougouni (Figure 2) and is composed of granodiorites. These granodiorites are spread over three small hills about 5 hectares area. They contain feldspar phenocrysts (2 to 5 cm) and are cut by outcrops of pegmatites and aplites. Some places, pegmatites and aplites present as veins. These dykes and veins are trending N30-50˚ and are between 5 and 50 cm thick. In same area, metasedimentary enclaves are noted within the granodiorite facies.

Dialakoro target is located on the right bank of the Baoulé River 25 km south of Bougouni (**Figure 2**). Here, pegmatite dykes' outcrop in a valley within the metasediments and have N170˚ orientation. They have 50 cm thick and are length to 200 m about. This dyke seems continued on the south in Kologo village where its outcrops in small body.

In Denkelena sector, pegmatite target is located at 40 km west of Bougouni. This target is near to Bougoula one (**Figure 2**) and composed of granodioritic facies. These facies are distributed in three outcrop areas covering 2.5 km^2. In this sector, pegmatite veins and dykes cut an outcrop of granodiorite and have a thickness between 5 to 20 cm.

6.2. Field and Macroscopic Descriptions of Li-Rich Dykes

The main targets of the Li-rich dykes' outcrop in: N'gouanala, Sogola, Goulamina, Kola, Sinsinkourou, Massala, Tinguéléni and Massafala (**Figure 10**). The pegmatite facies of Li-rich are mostly in lonely dykes. However, they are sometimes accompanied by aplite within the same dykes with a magmatic bedding structure (**Figure 9E**). This magmatic bedding suggests that dykes and their fluids use the same structural network. The metasedimentary rocks host mainly those Li-rich dykes (**Figure 2**). These dykes are lengths up to 560 m. Simalar to the Li-poor facies, these facies are composed of feldspar and quartz with occasional muscovite minerals. It is also noted an abundance of spodumene with rare biotite (**Figures 9E-9H**, **Table 2**). The aplite facies are heterogranular and some places isogranular and fine-grained (<0.1 cm) (**Figure 9D**). The pegmatites are also heterogranular, but characterized to crystals with medium to large grains (**Figures 9E-9H**). The abundance of spodumene is highly in these pegmatites (35% to 45% vol.). This mineral has a stick form (**Figures 9F-9H**) with a length between 2 and 20 cm long. Its mean size varies from 0.5 to 2 cm. In the field, spodumene is easily recognized by its prismatic and colorless appear. It is 90˚ double cleavage approximately (**Figure 9F**, **Figure 9G**). Fresh spodumene crystals are whitish and slightly translucent (**Figure 9G** & **Figure 9H**), whereas one's weathering, they become milky white, greenish, and brownish. Their differential alteration gives a brownish color (**Figure 9F**). Li-rich aplites also contain spodumene. However, they have small sizes (<0.2 cm) making them difficult to identify. It is important to note that Li-rich aplites contain millimetric crystals of tourmaline which make easy their identification. This can also distinguish this aplite to ones of Li-poor.

The Massafala target represents the fifth of Diamana sector and is located to the north of this village (**Figure 7** & **Figure 10**). It noted two granodiorite outcrops with different sizes. The smaller outcrop is crossed by some veins of pegmatite.

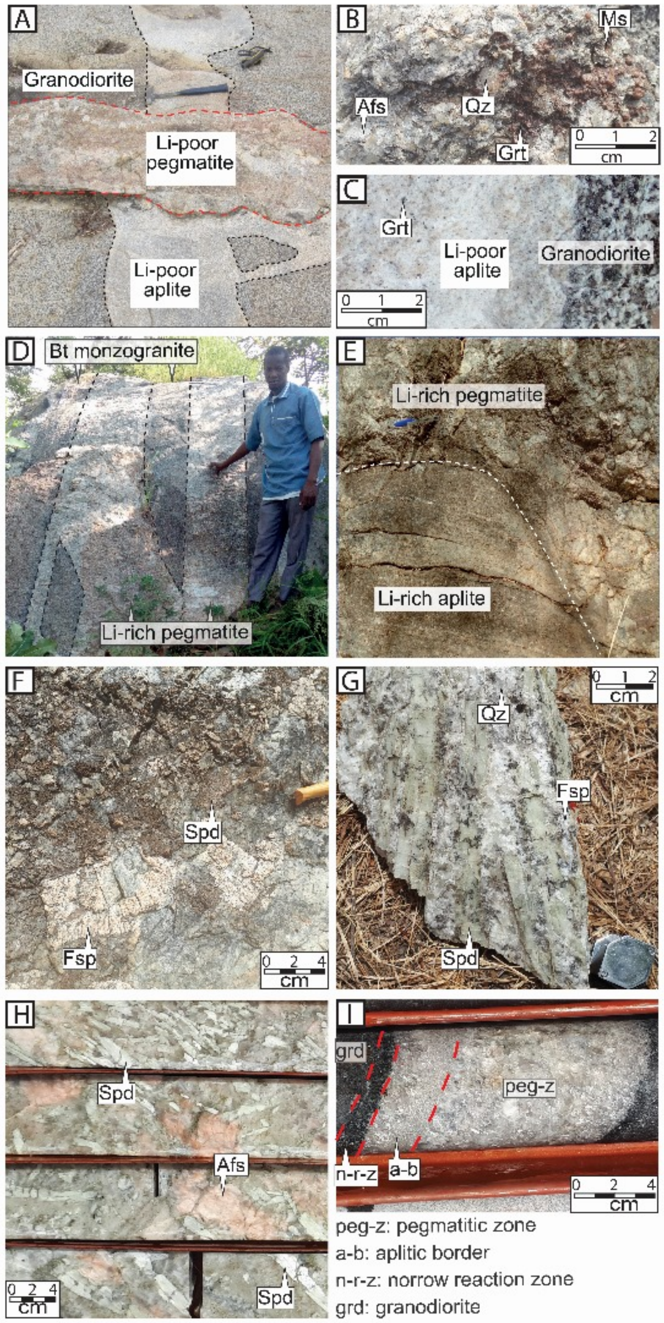

Figure 9. Field photographs of dyke facies of Bougouni area; A: granodiorite intruded by a Li-poor aplite, itself intruded by a Li-poor pegmatite from Diamana ; B: macroscopic view of Li-poor garnet-bearing pegmatite from Sinsinkourou; C: Sharp contact zone between granodiorite and Li-poor garnet-bearing aplite dyke; D: sharp contacts between biotite-monzogranite crosscut by pluridecimetric Li-rich pegmatites from Tinguéléni ; E: sharp contact between Li-rich aplite and Li-rich pegmatite from Goulamina ; F: weathered outcrop of Li-rich pegmatite from Sinsinkourou: Weathered outcrop of Li-rich pegmatite with typical brownish color and cleaved spodumene; G: fresh sample of Li-rich pegmatite with greenish pluricentimeter spodumene crystals from N'gouanala ; H: Core samples of Li-rich pegmatites with numerous centimeter-sized crystals of greenish spodumene; I: granodiorite-pegmatite contact with an aplitic edge and a narrow reaction zone; Grt = garnet; Ms = muscovite; Afs = alkali feldspar; Qz = quartz; Spd = spodumene.

Table 2. Summary of the macroscopic characteristics of the facies.

Facies	Color index	Color	Texture	Grain	Grain size
Metagrauwacke	Dark	Dark grey	Isogranular	Elements barely discernable	<1 mm
Conglomerate	Dark	Grey, white with reddish patina	Heterogranular	Figured elements + binder	mm-cm
Monzogabbro	Mésocrate	Dark	Isogranular	Coarse-grained	0.5 - 1 cm
Quartz-gabbroic diorite	Mélanocrate	Dark	Isogranular	Coarse-grained	0.5 - 1 cm
Granodiorite	Leucocrate	More or less dark	Isogranular	Coarse-grained	0.5 - 1 cm
	Leucocrate	More or less dark	Isogranular	Coarse-grained	0.5 - 1 cm
	Leucocrate	More or less dark	Heterogranular	Coarse-grained + medium grains	2 - 5 cm
Quartz microdiorite	Mésocrate	More or less dark	Heterogranular	Coarse-grained + medium grains	3 mm - 5 cm
Tonalite	Leucocrate	Greyish	Heterogranular	Coarse-grained	0.5 - 2 cm
	Hololeucocrate	Grey with a pinkish patina	Isogranular	Medium grains	2 - 5 mm
Biotite monzogranite	Leucocrate	Greyish	Isogranular	Medium grains	2 - 5 mm
	Leucocrate	Grey, milky white	Heterogranular	Coarse-grained + medium grains	3 mm - 5 cm
	Hololeucocrate	Pink-beige	Isogranular	Fine grains	<1 mm
Two-mica monzogranite	Hololeucocrate	Bright pink	Isogranular	Medium grains	2 - 5 mm
	Hololeucocrate	Pinkish grey	Isogranular	Coarse-grained	0.5 - 2 cm
	Leucocrate	Pinkish grey	Isogranular	Medium grains	2 - 10 mm
Li-poor	Hololeucocrate	White	Isogranular	Fine grains	<1 mm
	Hololeucocrate	White	Heterogranular	Coarse-grained + medium grains	mm-dm
Li-rich	Hololeucocrate	White	Isogranular	Fine grains	<1 mm
	Hololeucocrate	White	Isogranular	Coarse-grained	cm-dm
Quartz dyke	Hololeucocrate	White	Isogranular	Coarse-grained	cm-dm

These veins are of variable thickness and orientation. Also, it is noted the diorite enclaves within those granodiorites. These enclaves and pegmatites are not observed in the main outcrop. At the same place, a vein of pegmatite oriented N155 has been identified. This vein is 15 cm thick and 10 m long.

For the Goulamina target, it is located 68 km WSW of Bougouni town (**Figure 2**). This target is composed of an along relief outcrop (250m/40m) oriented N160 (**Figure 10**). Many pegmatites outcrop in this area. It is also noticed an alternation of pegmatitic and aplitic facies (**Figure 9E**). The pegmatitic facies are more dominant over the aplitic ones. The development of thick lateritic cover can be observed which often masks the contact between host rock and dyke. This target corresponds to "Leo Lithium" permit (now Ganfeng). Nowadays, this target is in exploitation phase.

The Sinsinkourou target is the magmatic outcrops located 12 km to the southeast of Bougouni (**Figure 2**). It is composed of a large batholith and the scattered diorite-granodiorite slabs which are crossed by pegmatite and aplite dykes. It is noticed metasedimentary enclaves in these outcrops. Also, a main pegmatite dyke is noted. It last, is oriented between N70 and N80, and has 2.5 - 6.7 m thick. This main pegmatite outcrops in 500 m + 40 m length running through the central of laterite hill (**Figure 10**). In the field, the enclaves of granodiorite (30 cm in diameter) are noted within this dyke. The crystals are coarser in the core and relatively finer at the walls of this dyke. The main dyke is connected:

- in the south, to a network pegmatite and aplite veins without spodumene (**Figure 10**). This network has all directions and variable thickness. It is important to note that many pegmatites cut aplites;
- to a series of sub-parallel pegmatite dykes to the north. These secondary pegmatite dykes, oriented N70 to N75, are more or less rich in aluminous minerals (garnet and muscovite). The pegmatite dykes thickness ranges from 15 to 55 cm;
- to laterite hill in the east of Sinsinkourou where outcrops basic facies of amphibole-bearing metagabbro in the form of lonely blocks 1 to 5 m in diameter (**Figure 8H**). These facies show dissolution structures on its surface;

The Sogola target is located 23 km to the southwest of Bougouni (**Figure 2**) around 1 to 1.5 km of Sogola village. This sector corresponds with Kodal Minerals exploration permit. The target contains four outcrops area of pegmatite. Generally, metasedimentary rocks are intruded by these pegmatite dykes. There are locally metasedimentary enclaves in these pegmatite:

- Outcrop 1: it is a small outcrop and occurrs about 600 - 800 m in southeast of Sogola village (**Figure 10**). It has a N145 orientation with 500 m long, 100 m wide and 20 to 30 m high. This outcrop is composed of four dykes of pegmatite with an average orientation of N85. These dykes are intrusive in quartz-diorite. it is noted one largest dyke up to 15 m thickness and three smallest which have each 30 cm ones. One of these small pegmatite dykes is composed of a mixture of coarse-grained and fine-grained facies. The latter one shows a magmatic structure as layers;
- Outcrop 2: not far from the first one (about 200 m to the south), it is a small outcrop with an N80 orientation, 200 m long, 40 to 60 m wide and 20 to 30 m high. It is also composed of four pegmatite dykes of with varying thickness (between 3 and 15 m). These pegmatite dykes are oriented from N75 to N90. They are hosted by quartz-diorite facies, both contained again by metasediments (metaconglomerates);
- Outcrop 3: located in the southern of the Sogola village, this outcrop appears in the Baoule stream. It is composed of a main pegmatite and another secondary one. They are hosted in metasediments. The main pegmatite is oriented N90 and the others from N50 to N60. The secondary bodies are between 3 and 40 cm thick;

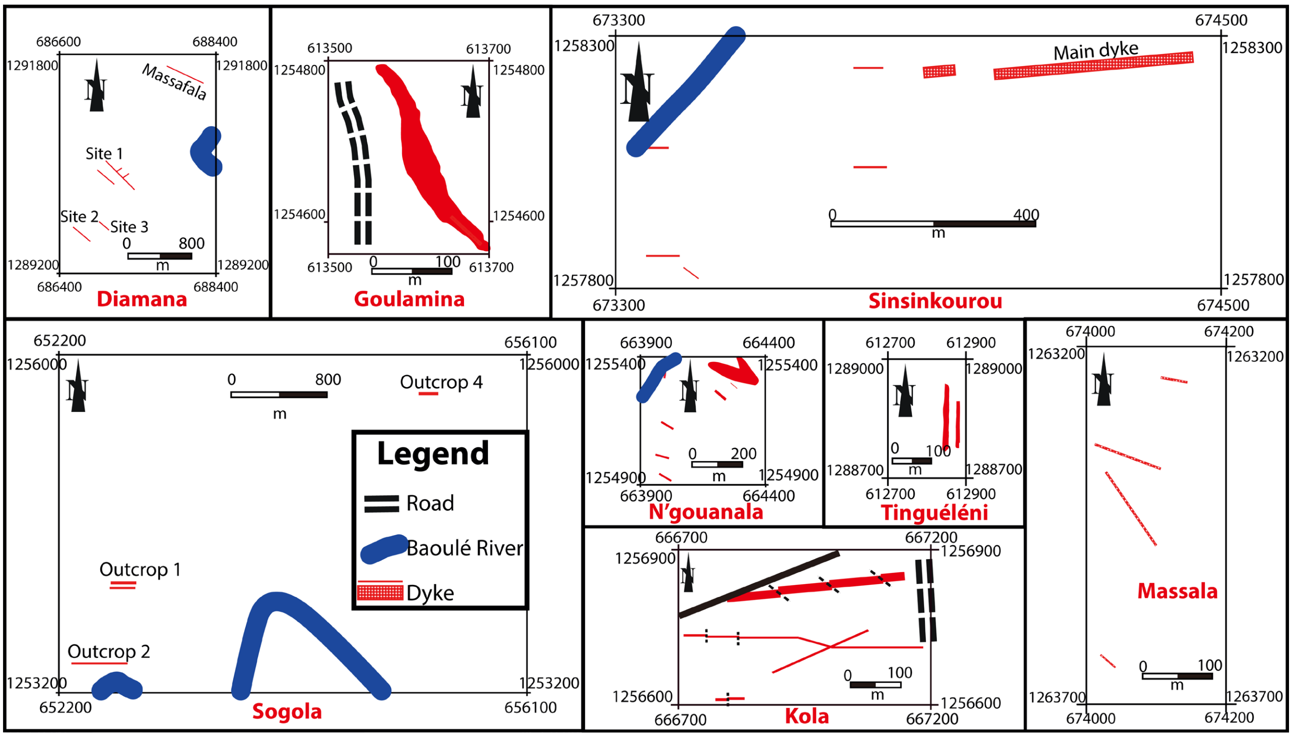

Figure 10. Simplified drawings of the most important outcrops of the spectacular dykes in the area of Bougouni.

- Outcrop 4: This outcrop is located to the northeast of the same village (Figure 10). It is also small, measuring of 150 m of long and 90 m wide. The outcrop is composed of a large pegmatite dyke oriented N90, with 10 m to 15 m thick. Its host rocks are the metasediments;

The N'gouanala target is located at 25 km in the south of Bougouni (Figure 2) no far from Dialakoro target (~4 km). The N'gounala target outcrops in Kodal Minerals permit. It is organized as a patchwork of pegmatite dykes intruded into the metasediments. The main body (pegmatite) is a hill-shaped dyke (200 m × 50 m). In west, this main dyke is divided into two ramifications (N160 and N110). In addition, there are many other pegmatite dykes trending from N105 to N130 with a thickness up to 4 m (Figure 10).

The Kola target is also in the south at 7 km of Bougouni (Figure 2). This target corresponds to an exploration permit held by Kodal Minerals. It presents many similarities with the N'gouanala target and outcrops are organized as small hills again. They consist of pegmatite dykes included in metasedimentary rocks. The contact between pegmatite dykes and host rock is sharp and very micaceous. The outcrop is composed of four pegmatite dykes (Figure 10) while three (3) are sub-parallel with N85 and N110 trending. The thickness varies from 1.2 to 10 m. The outcrop length ranges from 50 to 560 m. The central dyke is cut by the fourth dyke, trending N60 - 70 with 1.5 m thick and 200 m length.

The Tinguéléni target is located about 70 km to the west of Bougouni (Figure 2). The outcrop contains a massif of biotite- monzogranite with 200 m along and 100 m wide. It is approximately flat slabs shaped. It is noticed shows biotite enrichment on its edges, in contact with pegmatite and aplite veins and dykes that cross it. In the outcrop area, it is noted a series of parallel pegmatite dykes while two are N10 - trending. They are about 50 cm thick (**Figure 10**). The crystals are generally oriented perpendicular to walls of pegmatite dykes. Without spodumene, a pegmatite dyke and an aplite's vein are both associated with main pegmatite bodies. The first is oriented N65. For the last, it is N25 orientation and contains crystals of tourmaline and garnet, especially in its core.

The Massala target is located about ten kilometers to the east of Bougouni (**Figure 2**). The target consists of a metasedimentary and quartz-granodiorite complex. It is cut by pegmatite veins and dykes (**Figure 10**). Pegmatite dykes are often fragmented and tilted. Mostly of *in situ* pegmatite dykes, are intruded in quartz-granodiorite. Pegmatites of Massala are enriched in spodumene and depleted in muscovite from north to south.

The Zantogola outcrop is located to the northeast of Bougouni (**Figure 2**). Pegmatite dykes are at two outcrops (Koleba and Faradiècourou). Koleba Outcrop is a Li-poor pegmatite dyke trending N40 with 200 m long and 4 m thick. No far from this dyke, it notes dolerite outcrops. For Faradiècourou outcrop, it appears in massive with a dimension 400 × 100 m. It is cut by veins and pegmatite dykes Li-rich. These dykes have different orientations.

The target of Foulaboula is located 16 km in south-west between Bougouni and Sogola (**Figure 2**). In field, it is noticed two outcrops highly altered pegmatites. The first outcrop corresponds to shred of pegmatite appearing in the bed of the Baoulé River and is intrusive within metasediments. The second corresponds to pegmatite dyke with N90 trend. It is 5 m thick and 50 m long. This dyke outcrops at the edge of a valley not far from Baoulé River.

Located at 45 km in west of Bougouni not far from Bougoula (**Figure 3**), Sibirila target is a small outcrop of spodumene pegmatite. It is oriented N60, with a thickness of 3 m and length of 50 m. It is intrusive within a biotite-monzogranite.

7. Geophysical Implication to Pegmatites Dyke's Characterization

Aeromagnetic data analysis shows an absence of magnetic response to pegmatite dykes. Those dykes seem to have a very weak magnetic signature. However, magnetic data interpretation has allowed to identify many circular anomalies in Bougouni area which coincide to magmatic body areas such as granitoids and dolerites. Within these anomalies, it is noted many lineaments with very low magnetic responses. These response types within circular anomalies testify the presence of very weak magnetic linear bodies in that ones. The tilt derivative map (**Figure 7**) confirms this hypothesis in highlighting a lot of very low magnetic lineaments within the circular anomalies. They have all possible orientations. Between these circular anomalies, lineaments with low to moderate magnetic response can also be observed. These two categories of lineaments identified are generally oriented E-W, NW-SE and NNE-SSW to NE-SW. These directions have been ground prove in many pegmatite dykes' outcrops. This remark underlines that pegmatites dykes can be identified by geophysics only if they are contained in geological formations with moderate magnetic response. Some lineaments have a similarity with many measured directions in the field (Figure 11):

- in Tingueleni, measured trends N10 correspond to NNE-SSW lineaments and ones of N65 to NE-SW lineaments;
- in Massala, the WNW –ESE trends have been identified as N90 to 110;
- in Sinsinkourou, ENE-WSW magnetics lineaments concide to N70 –N80 direction.
- in Kologo NNW-SSE magnetic lineaments have been measured as N160;
- and in Dialakoro, it has been noted a N170 orientation which corresponds to NNW-SSE geophysical lineament.

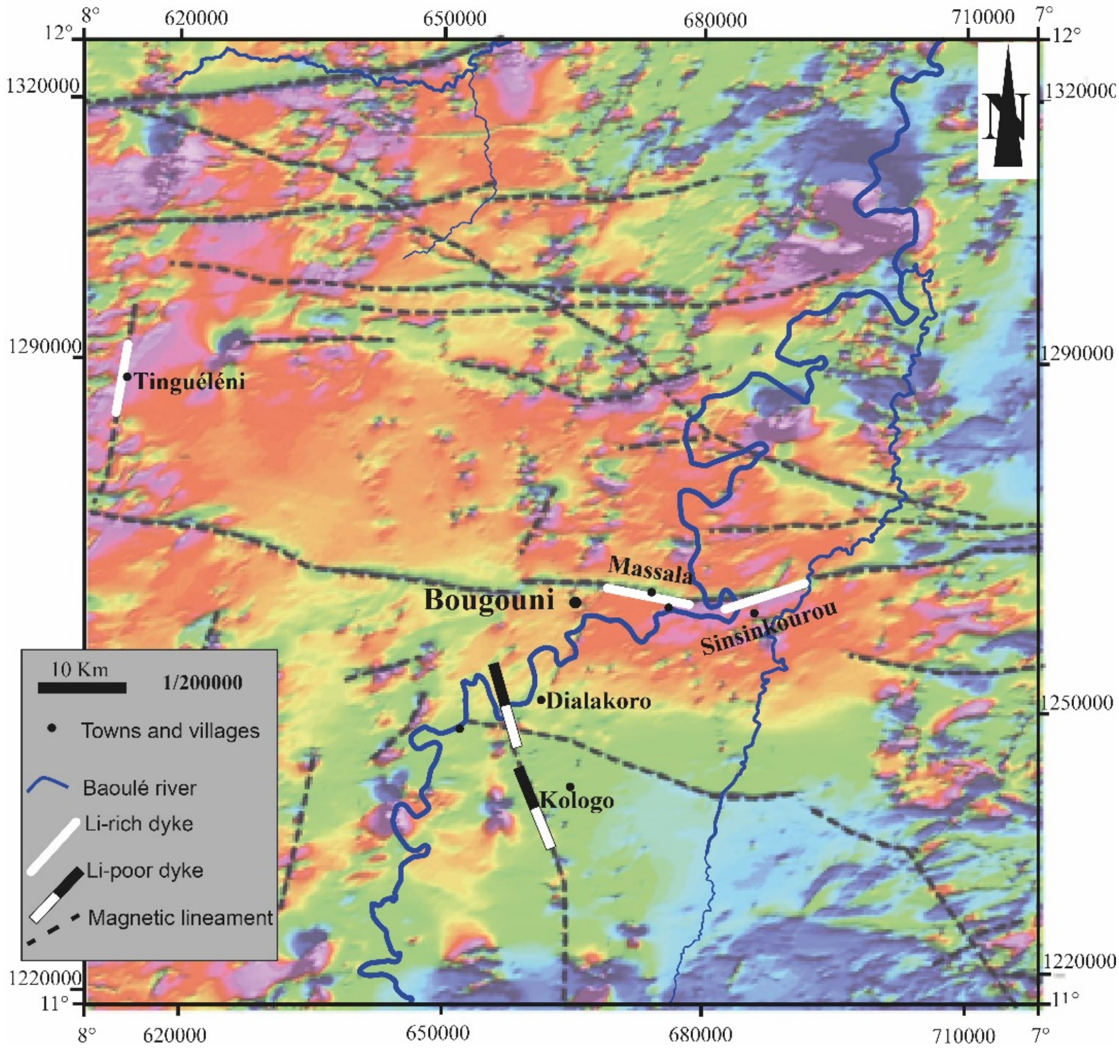

Figure 11. Some lineaments similar with many measured directions in the field.

8. Discussions

This study has characterized many pegmatite rocks areas which some are Li-poor and others Li-rich. These pegmatite facies are marked by a very low magnetic signature, or even an absence. Indeed, the pegmatite dykes of Bougouni area, as highly evolued rocks with weak thickness, are difficult to identify using aeromagnetic data analysis. The acidic character and the fine thickness of pegmatite dykes are known as make difficult the differentiation between contrasts of pegmatites physical properties and their hosting rocks [35]. This is supported by previous studies [35]-[39] which prove that geophysical methods fail to identify pegmatite dykes. But, the presence of pegmatites can be detected indirectly by the geophysical, in the right geological environment such as areas of granitoids and metasediments. This study has highlighted all the potentially Lithium-bearing targets (**Figure 10**) following a prelimenarly geophysical data analysis. Therefore, it can conclude that pegmatites facies of Bougouni are, generally, difficult to characterize using aeromagnetic data analysis.

In Bougouni area, field observations underline the presence of pegmatite facies within granitoid and metasedimentary rocks as dykes or veins. These granitoid and metasedimentary rocks correspond to circular anomalies composed of an association between low and high magnetic intensity [2]-[4]. Thus, aeromagnetic data analysis of Bougouni area underlines a significative magnetic response for these formations and for dolerites. The dolerites correspond to circular and lineament anomalies both. With their moderate to high magnetic response, Bougouni granitoids and metasediments constitute a ensure way to characterize pegmatites using the magnetic method. However, contacts between pegmatites and host rocks in Bougouni zone are more difficult to delineate through this geophysical method. This has been verified in other regions [36]. Those authors have used aeromagnetic data to identify the favorable structures for pegmatite emplacement through hosting rocks. The linear structures identification such as pegmatite dykes and veins in this study supports this hypothesis. Those lineaments coincide with zones of pegmatite dykes and veins in the surface geology. This implies that magnetic method can be a tool for indirectly mapping pegmatites through their hosting rocks.

Field geology testifies that the hosting rocks of Bougouni pegmatite facies are the metasedimentary and granitoids (**Figure 8C**, **Figure 9A**, **Figure 9C**, **Figure 9D** & **Figure 9I**) [7] [15] [17] [39]. These facies are intrusive as pegmatite dykes and, veins and have a sharp and brittle contact with their hosting rocks. These relationships between these hosting rocks and dykes show that the Bougouni dykes and these ones are not contemporaneous. The presence of metasediment enclaves in the granitoids (**Figure 8D**) implies to the fact that the latter post-date to metasediments. In the field, the cross-checking relationships between the Li-poor aplites and pegmatites Li-poor (**Figure 9A**) suggest that their emplacement is not contemporaneous. Furthermore, the Li-rich aplites and pegmatites use the same fluid emplacement networks for both types of pegmatite dykes (**Figure 9E**) suggesting there are contemporaneous. However, without direct emplacement relationships between the Li-poor and Li-rich dykes, it is difficult to interpret the posteriority of one in relation to the other. For the BPP pegmatites, the genetic relationship between Li-rich and

Li-poor remains unresolved. An open question is, what are the genesis relationships between the Li-rich and the Li-poor dykes in a close spatial proximity?

9. Conclusions

This paper aims to provide the distribution of pegmatites facies and their spatial relationships with the host rocks in the Bougouni Pegmatite Province (BPP) using aeromagnetic data analysis and field observations.

Geophysical interpretation testifies that pegmatites of BPP, as highly evolved rocks with weak thickness, are low or even non-existent magnetic response. However, these pegmatites are hosted within rocks (granitoids and metasediments) which have an appreciable magnetic signature. This allows to confirm that pegmatites facies of Bougouni can be detected indirectly by geomagnetic method only through their hosting rocks.

This study shows that Bougouni Pegmatite Province (BPP) is composed of many rocks among which granitoids and metasediments host pegmatite dykes. In the field, these dykes show clear and brittle contacts defining a close relationship (centimeter scale) with hosting rocks. Identified pegmatite facies are composed of Li-poor and Li-rich dykes. Li-poor dykes are characterized by the presence of garnet (almandine and spessartine type) and one's Li-rich by the presence of spodumene (main lithium-bearing mineral in BPP).

This study has allowed to establish another approach for pegmatites characterization using geophysical methods. This approach consists of identifying the geophysical signature of probably hosting rocks of pegmatites and ground following the last ones.

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Conflicts of Interest

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

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