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Aspects of hydrothermal alteration assemblages around Bakwani-Bagwa, Northwestern Nigeria: Insights from multifractal analysis of measured thresholds for mineral exploration

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ABSTRACT

This study is aimed at identifying highly altered zones by applying the concentration area (C-A) fractal model technique on Landsat ETM+ image of the area around Bakwani-Bagwa, Northwestern Nigeria. The multifractal analysis was used to quantify the degree of alteration on satellite images processed using the Crosta technique. A log–log plot was used to display the multifractal characteristics of clay and iron altered images and identify threshold values. Maximum and minimum threshold values obtained from the fractal analysis are 1.74 and 4.01 for clay altered images and 0.607 and 3.04 for iron altered images. High clay and iron alteration zones account for 5.89% and 7.84%, covering an area of 22.28km^2 and 29.65km^2, respectively. Delineating highly altered zones from these images reveals higher alteration largely within silicified sheared rocks and areas around faults. The current study proved that the multifractal processing techniques are valuable mapping tools for geological reconnaissance which can be extended to a large area of the Nigerian basement and provide preliminary hydrothermal alteration maps that are accurate as well as cost-effective and time-saving.

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1. Introduction

The study area lies within the Nigerian basement complex for which many authors have extensively described the origin, petrology, structure, and mineralization (Fitches et al., 1985; McCurry, 1976; Rahaman, 1988). The favorable geological characteristic of Nigeria could support broader economic growth through the mineral sector. There is, however, an incomplete understanding of the full mineral endowment, and technical specialists note that the currently available stock of mineral assets, either in production or available for production, represents a small percentage of the total (Igualada et al., 2017). Preliminarily, the integration of remotely sensed images on geological structures is done using potential inexpensive tools to constrain anomalous areas for further exploration (Ciampalini et al., 2013; Rajesh, 2004).

As precious metals and base metals cannot be detected directly by remote sensing, its use in mineral

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exploration depends heavily on the identification of hydrothermally altered areas on satellite imagery (Testa et al., 2018). A well-processed satellite imagery can display variations in the hydrothermal alteration from dark (low) to light (high) tone (Ciampalini et al., 2013). Quantifying these variations in alteration can be essential in mapping the most favorable areas for mineralization. The idea behind this quantification is to identify anomalous value also called the threshold from processed satellite imagery with alteration intensity (e.g., Ganne and Feng, 2017; Haihui et al., 2018).

In a remotely sensed mineral exploration perspective, "threshold" is a term used to signify a specific value that effectively separates threshold anomalies of fundamentally different characters on images, which reflect different causes (Chen, 2019). It distinguishes upper or anomalous datasets from the lower background set on the principal component (PC) image (Chen, 2019; Haihui et al., 2018). Different statistical methods have been applied to identify threshold values from the geological incline dataset (Asl et al., 2014). The main advantage of the multifractal technique over other traditional statistical methods is that it is spatial and allows modeling of spatial autocorrelation (Chen, 2019).

In Nigeria, not much has been achieved using geospatial technology in mineral exploration. Much of the work on remote sensing has been targeted at hydrogeological applications (Anudu et al., 2011; Bala et al., 2001). Talaat and Mohammed (2010) used digitally processed Landsat 5 imageries to characterize gold mineralization in the Garin Hawal area, NW Nigeria. Abubakar (2012) used a combined Landsat and aeromagnetic map to map and delineate structures in the Kushaka Schist belt. In the present contribution, we used multifractal analysis to calculate threshold values for the identification of hydrothermally altered zones within the study area.

1.1. Geological background

1.1.1. Regional geology

The Nigerian Basement Complex is a part of an Upper Proterozoic—Lower Phanerozoic Pan-African mobile belt situated between the West African and the Congo Cratons (Fig. 1). The belt is made up of two sectors the Tuareg shield and the Togo-Benin Shield. The Nigerian Basement complex essentially consists of three lithological units: the Migmatite gneiss, older granites, and the Schist belts. Although there are imprints of early thermo-tectonic events corresponding to Liberian (2,700 Ma), the Eburnean (2,000 Ma), and the Kibaran (1,100 Ma) (e.g., Ajibade et al., 1988), the dominance of Pan-African ages (600 ± 150 Ma) from U-Pb

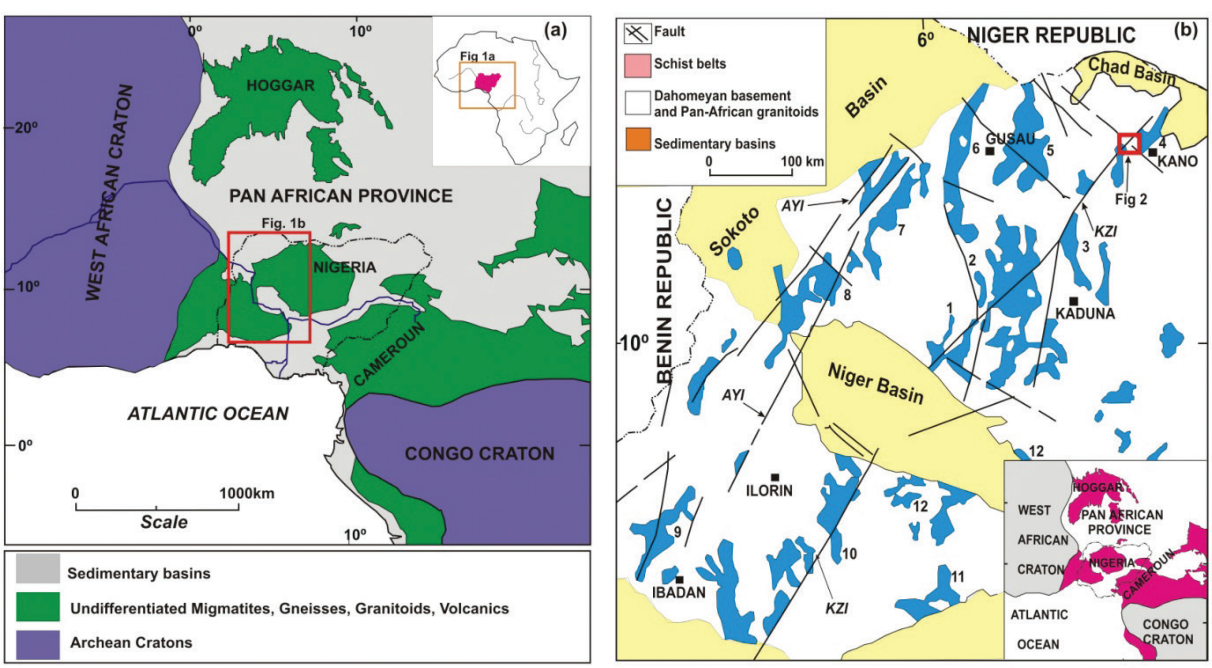

Figure 1. (a) Geology of the Pan African Belt (after Ajibade et al., 1988); (b) Study area (solid red square - not ro scale) within a simplified geological map of the Northern and Southern part of the Western half of Nigeria, showing the distribution of the schist belts and the locations of major lineaments (redrawn from Danbatta, 2008). The schist belts are 1. Zungeru-Birning Gwari, 2. Kushaka, 3. Malumfashi, 4. Kazaure, 5. Wonaka, 6.Maru, 7.Anka, 8.Zuru, 9.Iseyin-Oyan River, 10. Ife-Ilesha, 11. Igarra-Kabba-Lokoja, 12. Toto, AYI = Anka-Yauri-Iseyin fault system. KZI= Kalangai-Zungeru-Ifewara fault system

geochronology coupled with new petro-structural and lithostratigraphic data led Caby and Boese (2001) to propose the Pan-African event did not only "rejuvenate" older polyorogenic domain, but it represented the major tectono-metamorphic episode, as shown in central Hoggar (Fig. 1) (Caby and Monie, 2003).

1.1.2. Local geology

McCurry (1976) observed that the Paleozoic and Precambrian rocks in northern Nigeria can be divided into four major groups: the Basement Complex, "Younger" Metasediments (Schist belts), Older Granite series, and the volcanic rocks. Metamorphism is generally in the amphibolites to granulite facie grade. The gneisses and migmatites are so intimately associated such that they are hardly separated in the field, are commonly seen, and form the bulk of the rocks in this group. Relics of ancient metasediments (commonly feldspathic quartzites) associated with them are correlated with the Birrimian metasediments of Ghana (McCurry, 1976; Rahaman, 1988).

The Nigerian Schist belts occur in a 300 km wide zone, predominantly west of longitude 80°E, which trends NNE, parallel to the boundary between the Pan-African and the West-African Craton (Fig. 1a). The Older Granites include a suite of discordant, intrusive, late-tectonic to concordant, syntectonic bodies varying from small sub-elliptical plutons to large batholiths (Ajibade et al., 1988; McCurry, 1976; Rahaman, 1988). They constitute about 40%–50% of the basement complex outcrop and vary in composition from tonalite

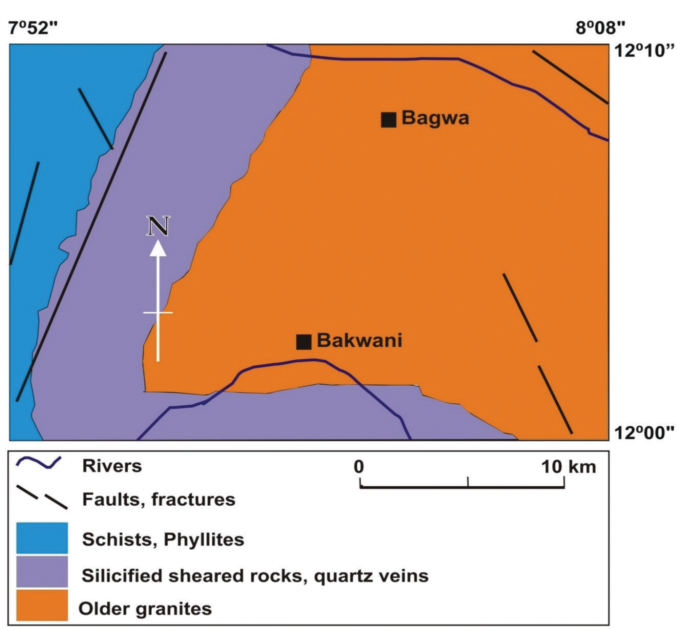

Figure 2. Geological map of part of area around Bakwani-Bagwa, northwest Nigeria (redrawn from NGSA, 2009).

through granodiorite, gabbro, and charnockite to granite and syenite. Structurally, two major regional (transcurrent) fault systems (Anka-Yauri-Iseyin-AYI and Kalangai-Zungeru-Ifewara-KZI fault systems) trending NE-SW were present in Nigeria and these were probably developed during the late Pan-African orogeny (Garba, 2000) (Fig. 1b). These fault systems are dextral wrench faults with displacements in the order of tens of kilometers and have associated with locally developed conjugate sinistral faults (Danbatta, 2008).

2. Materials and Method

Satellite images were downloaded from a global land cover facility website of the University of Maryland. These images were subsetted, and selective PC analysis was carried out to enhance iron and clay alteration distribution within the study area.

2.1. Principal component and multifractal analysis

The PC transformation (Crosta technique) selects uncorrelated linear combinations (eigenvector loadings) of variables in such a way that each successively extracted linear combination or PC has a smaller variance (Singh and Harrison, 1985). The analysis was performed on bands 1, 3, 5, 7 to enhance clay alteration while selective PC analysis was performed on bands 1, 3, 4, 5 for iron alteration mapping (Fig. 3a and b).

Also, the multifractal analysis was carried out on negated PC4 images for iron and clay alteration. This is aimed at the segregation of highly altered zones. From the processed negated iron and clay PC4 images, pixels values were extracted and arranged from maximum to minimum using MS Excel software. The cumulative frequency was calculated from these pixel values. A binary plot (Fig. 4a and b) was constructed using the digital number (pixel values) and the number of pixels (cumulative frequency) using Minitab 17 software.

3. Results and Discussion

3.1. Clay alterations

From the resultant PC images, PC1 images display albedo, PC2 images display the difference between short wave infrared and visible ranges, PC3 images display information on vegetation, and PC4 images display clay alteration as dark tone. The PC4 image was negated to map clay alteration as light tone (Fig. 3a) and also variation from color composites of Landsat ETM+ bands (Fig. 4a).

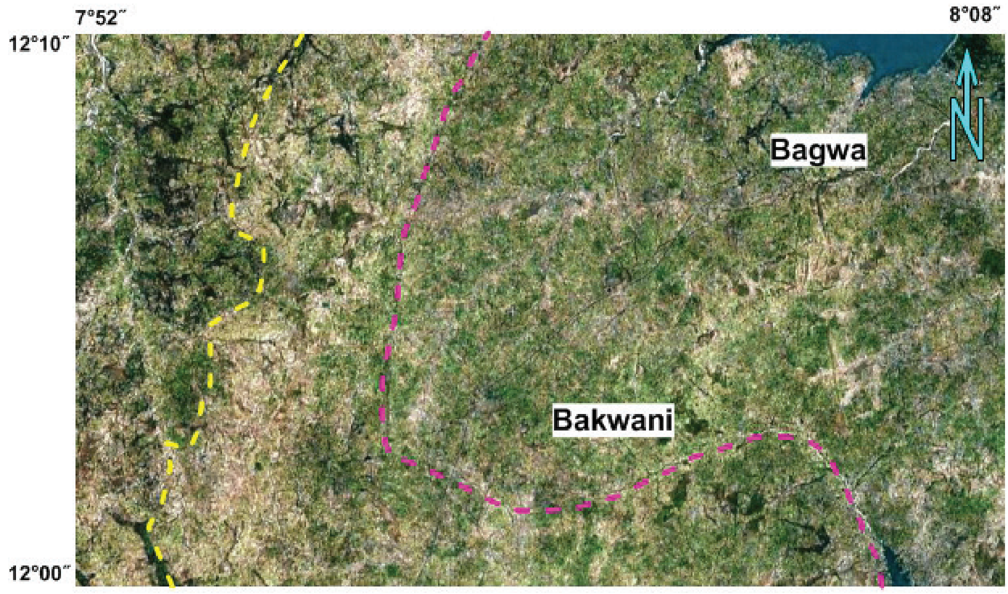

Figure 3. Zoom Earth satellite image showing the varied green colouration for vegetation, traces of lineaments and inferred lithologic boundaries in areas around Bakwani and Bagwa.

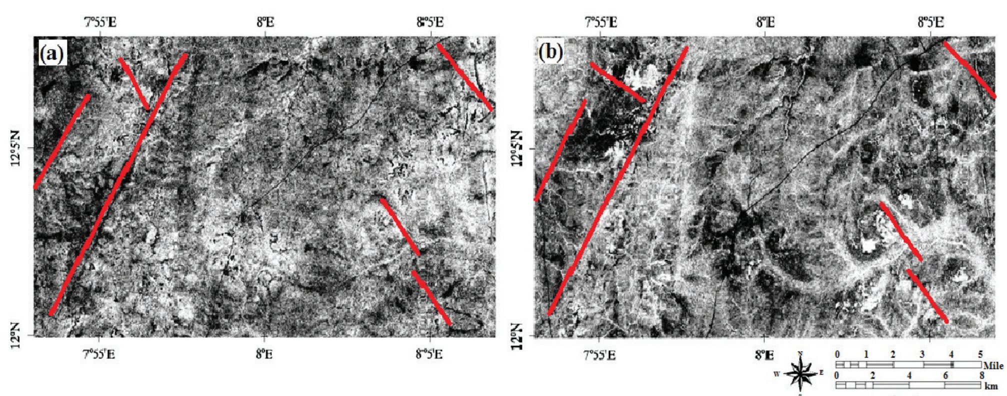

Figure 4. (a) Negated PC4 image displaying clay alteration zones as light tone. (b) Negated PC4 Image display iron alteration as light tone.

Table 1. Statistical analysis for clay and iron alteration.

Intensity	Iron Alteration		Clay Alteration	
	Area	**% cover**	**Area**	**% cover**
Low	228.6889	60.51731	286.2502	75.74962
Moderate	119.5484	31.63576	69.35464	18.35313
High	29.65276	7.84693	22.28511	5.897247
Total	377.89	100	377.89	100
	Min Threshold	Max Threshold	Min Threshold	Max Threshold
	0.607	3.04	1.74	4.01

For processed clay altered images, minimum and maximum threshold values of 1.74 and 4.01 were obtained. Areas of high clay alteration covered a total area of 22.8 km^2 and accounted for 5.89% of the study area (Table 1). On satellite imagery, high clay altered zones were observed in the Central, North Central, and Eastern parts of the study area, while moderately altered zones occurred in the North Central to Eastern part. It accounts for 18.36% of the study area and covers a total surface area of 69.35 km^2 (Table 1). Areas of low clay alteration spread throughout the study area account for 75.74% of the study area and cover a total area of 286.25 km^2 (Table 1).

3.2. Iron alterations

Resultant PC images display albedo on PC1, the difference between short wave infrared and visible ranges on PC2, vegetation on PC3, and iron alteration (dark tone) on PC4. PC4 was negated to display iron alteration within the study area (Fig. 3b). The variations are also checked from color composites from the Landsat ETM+ bands (Fig. 4b)

Iron altered images had minimum and maximum values of 0.607 and 3.04, respectively (Table 1). Areas of high iron alteration occur in the Southwestern to Northcentral and Eastern parts of the study area. This area accounted for 7.84% of the study area and has a total area cover of 29.65 km^2 (Table 1). Areas of moderate iron alterations are located in the western part of the study area; it covers a total surface area of 119.54 km^2 and accounts for 31.63% of the study area (Table 1). Areas of low iron alteration are spread throughout the study area. This area has a total surface area of 228.68 km^2 and accounts for 60.5% of the total surface area (Table 1).

3.3. Multifractal analysis

Preliminary fractal analysis was performed to study how a change in the altitude threshold would affect the fractal dimension. Several altitude thresholds were applied to the Landsat ETM+ data to extract the set of points with an altitude equal to or less than a certain value. On this plot, points of breakage were considered as minimum and maximum threshold for both clay and iron altered images (Aguado et al., 2014). Using the image classification techniques and the obtained minimum and maximum threshold values, areas of low moderate and high alterations for both clay and iron altered images were outlined and delineated as shown in Figure 5a and b.

3.4. Statistical analysis

Although the areas of alteration largely appear disseminated across the whole area, a closer visual assessment look indicated a higher tone around lithological boundaries and faults. The statistical analysis is presented in Table 1.

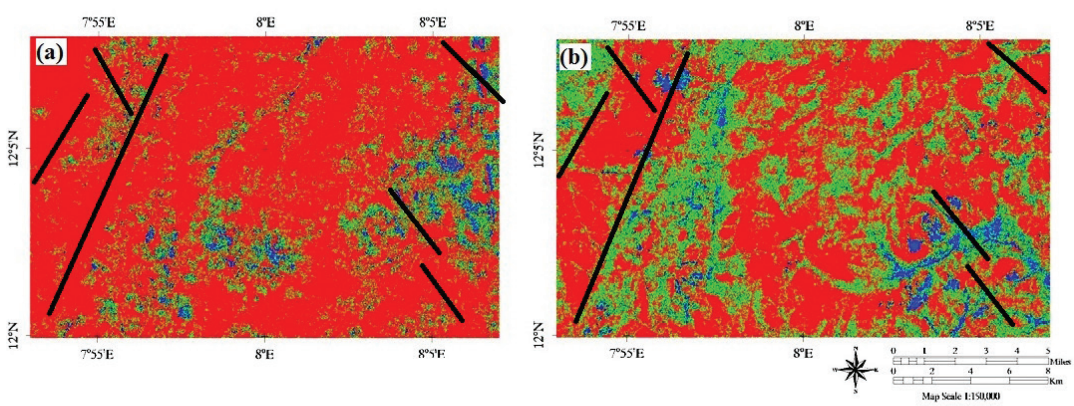

Figure 5. (a) Variation in clay alterations within the study area: red = low, green = moderate, blue = high. (b) Variation in iron alteration within the study area: red = low, green = moderate, blue = high.

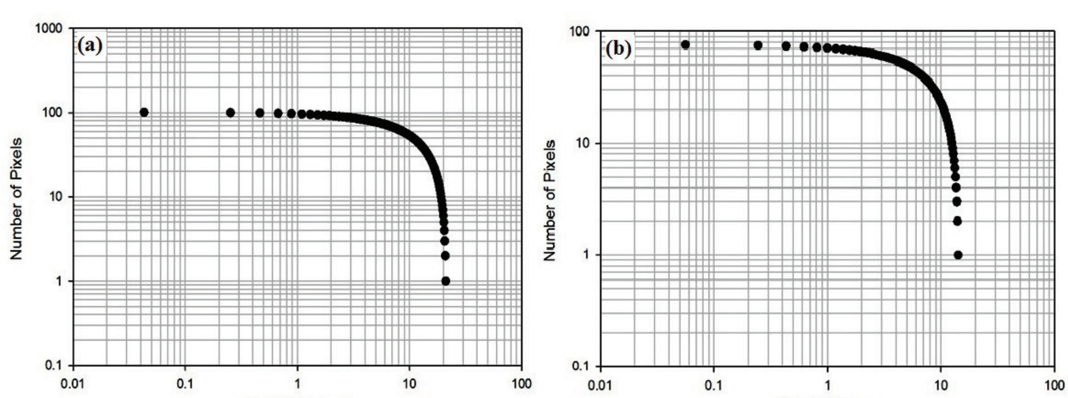

Figure 6. (a) Fractal plot for clay altered images. (b) Fractal plot for iron altered images. (after Clark et al., 1993)

4. Discussion

4.1. Potential strengths

The described enhancement techniques demonstrate the usefulness of multispectral imagery for the detection of alteration zones to preliminary lower target prospective areas for further exploration. As such, it can contribute to database for mineral resource potential (Ciampalini et al., 2013). The application of an inexpensive remote sensing tool—Satellite imagery—allowed the identification of an area of about 54 km^2 from an area that spanned over 375 km^2. A similar procedure was applied to constrain 72 km^2 prospective area for the exploration of iron deposits in Western Sahara and Southwest of Algeria (Ciampalini et al., 2013).

Mining is a capital intensive industry, with new mine developments typically requiring extensive ground preparation, provision of facilities (Humphreys, 2012), as such remote sensing is a low-cost technique that can be applied in an analogous geological framework and integrated with other techniques including dedicated field campaign geophysics and geochemistry for exploration site development (Ciampalini et al., 2013; Ganne and Feng, 2017).

In summary, the recognition of spatial patterns of alteration from processed satellite images makes the "remote sensing technique" one of the standard procedures in exploration geology, due to its high efficiency and low cost (Bodruddoza Mia and Fujimitsu, 2012).

4.2. Implications of the clay and iron alteration indices

Although the correlated tones from the inversed PC with the lithologic variants of the study area (Fig. 2b) clearly show that the areas of clay and iron alterations were disseminated, the light-toned areas are largely higher within the silicified sheared rocks and areas around faults (Figs. 3 and 5). One of the limitations of the present study on specific OH-bearing clay mineral paragenetic sequences is low-resolution hyperspectral mapping since certain alteration clay minerals are associated with hydrothermal ore deposition (Meunier et al., 1983). Nevertheless, hydrothermal alteration features highlighted by each image presented on the main lithologies are illustrated. Similar limitations were reported from ASTER imagery on lithological and hydrothermal alteration mapping of epithermal deposits in the Argentine Andes district (Testa et al., 2018).

4.3. Structural controls

The highly altered areas are largely within the margins of silicified sheared zones and areas around traces of faults. The faults are subsidiaries to the main KZI fault (Fig. 2a and b). Aside from other features, it has been documented that fold-to-fault control, where fault-controlled mineralization is generally confined to second-order faults related to major structures, is the prominent geological character of Phanerozoic mesothermal gold deposits (Nesbitt, 1991). The gold mineralizing fluids in Nigeria were channeled to depositional sites via the subsidiary brittle fault which is a NW–SE trending subsidiary structure that was linked to the transcurrent Anka fault (Garba, 2003; 2000). Also, the lineaments (minor fault systems) mapped from the Kushaka Schist belt, which is located to the southeast of the present study area, are associated with important mineralization. The belt hosts gold and rare earth metal pegmatite mineralization (Abubakar, 2012).

5. Conclusion

Determination of the threshold using a multifractal method was able to identify and segregate high iron and clay alteration regions within the study area.

1. Processing of remotely sensed Landsat ETM+ images is a powerful and cost-effective tool applicable during the first stage of mineral exploration. Its integration with other techniques has become a key additional procedure during the exploration stage or discovery of new deposits.
2. The use of multifractal techniques in processing satellite images for mineral exploration further enhances the potential of remote sensing for exploration-related activities.
3. Areas of high iron and clay alterations are favorable targets for mineral prospecting; the study area covers about 378km^2 and the probable anomaly is constrained within 54km^2.

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