

Original Research Article

Mapping of Hydrothermal Alteration Minerals Related to Tongue Tonguey (Sirba, Niger) Gold Mineralization Using Landsat 8 Imagery

ABSTRACT

Remote sensing is an effective means of exploring for gold resources. One of Niger's main gold provinces is the Sirba greenstone belt. Gold mineralization in the Tongue Tonguey soils of the Sirba greenstone belt presents interesting anomalies, and it was necessary to identify and map the associated hydrothermal alteration. The aim of this work was to map hydrothermal alteration anomalies associated with gold mineralization. Band ratio technique was applied to Landsat 8 imagery of the study area to highlight surfaces rich in alteration minerals. Band ratios (4/2) and (6/7) were applied to the Landsat 8 image of the study area to highlight iron minerals (hematite, goethite, jarosite) and alunite/clay minerals (kaolinite, montmorillonite, illite) respectively. Gold anomalies and alteration mineral anomalies were extracted from raster images using the threshold method. Iron minerals and alunite/clay minerals alterations were well associated with the gold anomalies host rocks. Hydrothermal alteration anomalies superimposed effectively on the gold anomalies. The latter were located on meta-volcano-sediments, along regional faults and at lithological contacts. Gold anomaly zones where iron minerals and alunite/clay minerals alterations had developed constitute favorable zones for gold exploration at Tongue Tonguey.

Keywords: Sirba, Niger, Gold mineralization, remote sensing, Band ratio, hydrothermal alteration

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1. INTRODUCTION

Mineral exploration uses several prospecting methods such as geochemistry, geophysics, geological mapping, remote sensing and ground surveys to determine anomalies associated with mineralization (Chica-Olmo et al., 2002). Remote sensing technology is more cost-effective for geological applications due to its low cost (Chica-Olmo et al., 2002). This technique involves the acquisition, processing and interpretation of images and related data acquired from aircraft and satellites that measure the interaction between the earth's surface features and electromagnetic energy (Gabr et al., 2010; Massironi et al., 2008; Pour and Hashim, 2011). Remote sensing applications in mineral exploration focus on geological and structural mapping that controls the emplacement of mineralization and the recognition of hydrothermal alteration of rocks by their spectral signatures. The presence of altered rocks is the main indicator of the presence of a probable ore deposit (Rajesh, 2004; Sabins, 1999). Remote sensing techniques had been widely used for mapping geological structures, discriminating lithologies and hydrothermal alterations, and for mineral exploration (Amer et al., 2010; Gabr et al., 2010; Kujjo et al., 2018; Sabins, 1999; Sultan et al., 1987). Remote sensing reconnaissance of host rocks had been widely used for the exploration of gold and porphyry copper deposits (Bedini, 2022; Bedini and Chen, 2020). Although gold cannot be detected directly by remote sensing, the presence of minerals such as iron oxide clay minerals could serve as hydrothermal alteration zones associated with gold occurrences (Kujjo, 2010). Rock

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depend on the spectra of the constituent minerals and their textural properties, such as grain size, matrix and association (Clark, 1999; Sgavetti et al., 2006). In areas where bedrock was exposed, multispectral remote sensing can be used to identify weathered rocks because their reflectance spectra differ from those of unweathered bedrock (Sabins, 1999). Alteration zones are important guides to mineral exploration and are generally characterized by abundant minerals such as kaolinite, alunite, muscovite, chlorite, epidote, calcite, goethite, hematite, jarosite, etc (Mahboob et al., 2019; Pour and Hashim, 2015; Sabins, 1999). Many mines had been discovered by recognizing outcrops of altered rock, the best indicators of which were iron oxides (Sabins, 1999) and hydrothermal clays (Poormirzaee and Oskouei, 2010). The Landsat 8 satellite uses the "Operational Land Imager (OLI)" sensor which enable to map clay minerals, alunite and secondary iron minerals associated with gold mineralization (Abass-Saley et al., 2021; Kujjo, 2010). Numerous techniques had been developed to enhance image quality and highlight target minerals (Aliyu and Aliyu, 2020; Hajibapir et al., 2014; Kamau et al., 2020; Mahboob et al., 2019; Masoumi et al., 2017; Osinowo et al., 2021; Safari et al., 2017; Sheikhrhimi et al., 2019; Testa et al., 2018; Zhang et al., 2016). One of these techniques was the Band ratio, which was commonly used for mineral and lithological mapping (Hewson et al., 2005; Sabins, 1999). The Band ratio helps to distinguish the lithological units (Abdelsalam et al., 2000) and to extract information on hydrothermal alteration zones (Mars and Rowan, 2006). Band ratios had been widely used in mineral exploration to map alteration zones and their associated minerals (Khidir et Babikir, 2013; Kujjo et al., 2018; Masoumi et al., 2017). The aim of this work is to map the alteration mineral anomalies related to Tongue Tonguey gold mineralization using Landsat 8 imagery.

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Commented [AD7]: For writing Introduction you should follow: Firstly, give a general background about using remote sensing techniques for mineral explorations particularly gold alteration minerals (use recent references). Secondly, describe the major image processes on OLI following standards suggested by for example (van der Werff and van der Meer (2015), Ninomiya and Fu (2019), ...etc) for ferric, ferrous, and hydroxyl bearing minerals. For more details you can follow: [10.1038/s41598-023-34531-y](https://doi.org/10.1016/j.rsase.2024.101416) <https://doi.org/10.1016/j.rsase.2024.101416> After that you should give a detailed introduction about the recent studies done in your study area. Finally, describe you main objectives and the new method and techniques used to achieve these objectives and their novelty.

2. MATERIAL AND METHODS

2.1 Geological context of the study area

The Tongue Tonguey gold zone is located on the Sirba greenstone belt in Niger's Liptako. The latter corresponds to the NE end of the Léo-Man ridge (Milési et al., 2004) (Fig. 1a) on the West African craton (Machens, 1973). The Liptako geological formations (Fig. 1b) were Lower Proterozoic in age (Bessoles, 1977). They were formed by alternating greenstone belts and granitoids (Machens, 1967) with Neoproterozoic and Mio-Pliocene sediments (Dupuis et al., 1991; Machens, 1973; Pons et al., 1995). Greenstone belts consist of pyroxenite, amphibolite, chloritoschist, meta-basalt, meta-gabbro, meta-sediments, meta-volcano-sediments, meta-volcano-plutonites, tuffs and rhyolitic breccias (Ama Salah et al., 1996; Soumaila, 2000; Soumaila et al., 2004). The plutons were composed of granite, tonalite, trondhjemite and granodiorite (Soumaila, 2000), intersected by sills and basic dykes (Dupuis et al., 1991; Pons et al., 1995). Tongue Tonguey's geological formations consist of undifferentiated meta-volcano-sediments, acidic meta-sediments, enclaves of amphibolite, quartz diorite and granite, and locally amphibolitized basic volcano-plutonite, quartz diorite, meta-gabbro, dolerite dykes and quartz vein outcrops, locally overlain by lateritic Continental Terminal armour and Quaternary sand dunes (Fig. 1c) (Abdou et al., 1997).

Gold mineralization in the West African Craton was largely associated with greenstone belts (Augustin, 2011; Markwitz et al., 2016; Milési et al., 1989) with over 80% of the craton's gold reserves (Castaing et al., 2003). Most gold deposits were dominated by quartz veins in shear zones and disseminated sulphide types formed at the end of the Eburnian orogeny (Béziat et al., 2008; Markwitz et al., 2015). Gold mineralization in the Liptako was closely linked to major regional faults and to the nature of the rocks (Klockner, 1995). Two types of gold mineralization had been identified in Liptako (Jica, 1995; Saint-Martin, 1999): syn-sedimentary exhalative gold mineralization associated with graphitic clays (Jica, 1995; Saint-Martin, 1999) and quartz vein or stockwork gold mineralization controlled by fractures and faults (Jica, 1995; Klockner, 1995; Saint-Martin, 1999; St-Julien, 1992). Gold mineralization was also related to gabbro, quartz diorite and rhyolite dyke clusters (Saint-Martin, 1999). Minerals observed in quartz veins include silver-bearing native gold, pyrite, arsenopyrite, sphalerite, galena, chalcopyrite, hematite, goethite (Jica, 1995; Klockner, 1995; Poulin et al., 1987; Saint-Martin, 1999). Gold mineralization in the Sirba greenstone belt occurs mostly in quartz veins in association with sulfides that had transformed into iron oxides in zones that had disintegrated or altered (Saint-Martin, 1999). The Tongue Tonguey gold mineralization, like that of the Sirba greenstone belt, was associated with sulfides (pyrite, pyrrhotite, arsenopyrite, chalcopyrite) and their alteration products (hematite, goethite, etc.) (Jica, 1995; Saint-Martin, 1999).

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Introduction
Study area and geological context
Materials and methods
Results
Discussion
Conclusion
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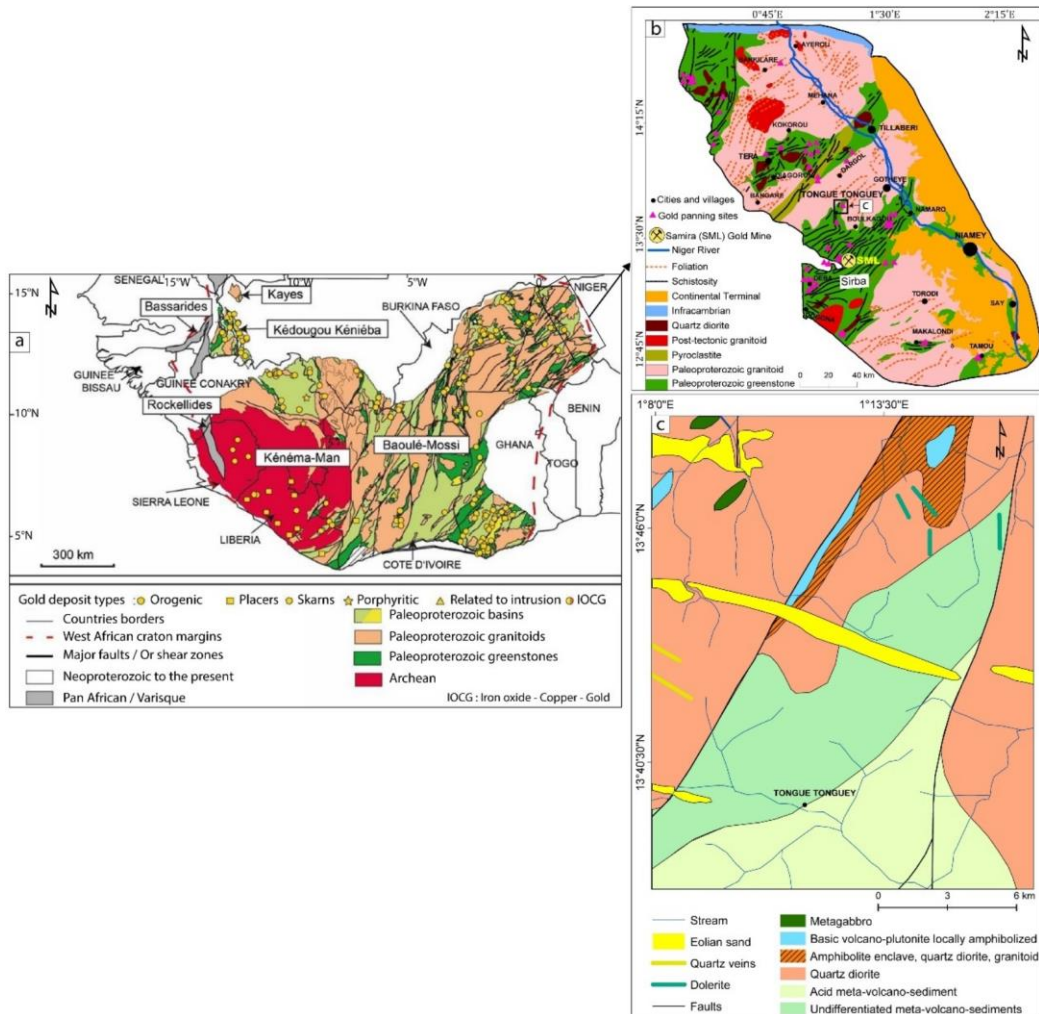


Fig. 1. Geological maps of the study area.

2.2 Data and process

Two types of data were used in this work: gold chemical analysis data from soil samples and Landsat 8 imagery of the study area.

The soil geochemistry data in this study come from the detailed geochemical prospecting campaign in the Sirba belt (1996-1997). Analytical results from 1,399 Tongue Tonguey soil samples were used. Gold analysis was performed by Chemex Labs Ltd. North Vancouver, B.C. Canada. The FA-NAA (Fire Assay Neutronic Atomic Absorption) method was used to determine the gold content of the soil samples after melting 10 g of sample. Fig. 2a shows the location of the soil sampling points (on the geological map).

A cloud-free level 1T (terrain-corrected) Landsat-8 image LC81930512018060LGN00 (path/row193/051) of the Tongue Tonguey area, acquired on March 01, 2018 was obtained from the USGS Earth Resources Observation and Science

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Center (<http://earthexplorer.usgs.gov>). Band designations, wavelengths and pixel sizes of the Landsat 8 imagery were given in Table 1, extracted from <https://www.usgs.gov/landsat-missions/landsat-8>. In order to improve the contrast of hydrothermal alteration minerals, Band ratio was applied to the Landsat 8 image of the study area using Envi software. The Band ratio was preceded by an image pre-processing phase. The pre-processing operations applied to the Landsat 8 image consisted of radiometric calibration, atmospheric correction, conversion of radiometric values to reflectance (Han and Nelson, 2014) and extraction of the study area image. After this step, the MNF (Minimum Noise Fraction) transformation was applied to the study area image to reduce the noise in the image (Berman, 1985; Dabiri and Lang, 2018; Frassy et al., 2013; Green et al., 1988; Shawky et al., 2019). Fig. 2b shows the true-color combination (Red-Green-Blue) of the study area OLI bands.

Table 1. Characteristics of the Landsat 8 OLI/TIRS bands.

Spectral Band	Band Name	Wavelength (μm)	Spatial Resolution (m)
Coastal/ aerosol	Band 1	0.435 – 0.451	30
Blue	Band 2	0.452 – 0.512	30
Green	Band 3	0.533 – 0.590	30
Red	Band 4	0.636 – 0.673	30
NIR	Band 5	0.851 – 0.879	30
SWIR 1	Band 6	1.566 – 1.651	30
SWIR 2	Band 7	2.107 – 2.294	30
Pan	Band 8	0.503 – 0.676	15
Cirrus	Band 9	1.363 – 1.384	30
TIR	Band 10	10.60 – 11.19	100
TIR	Band 11	11.50 – 12.51	100

NIR: Near Infrared; SWIR: Short-Wave Infrared; TIR: Thermal Infrared; Pan: Panchromatic

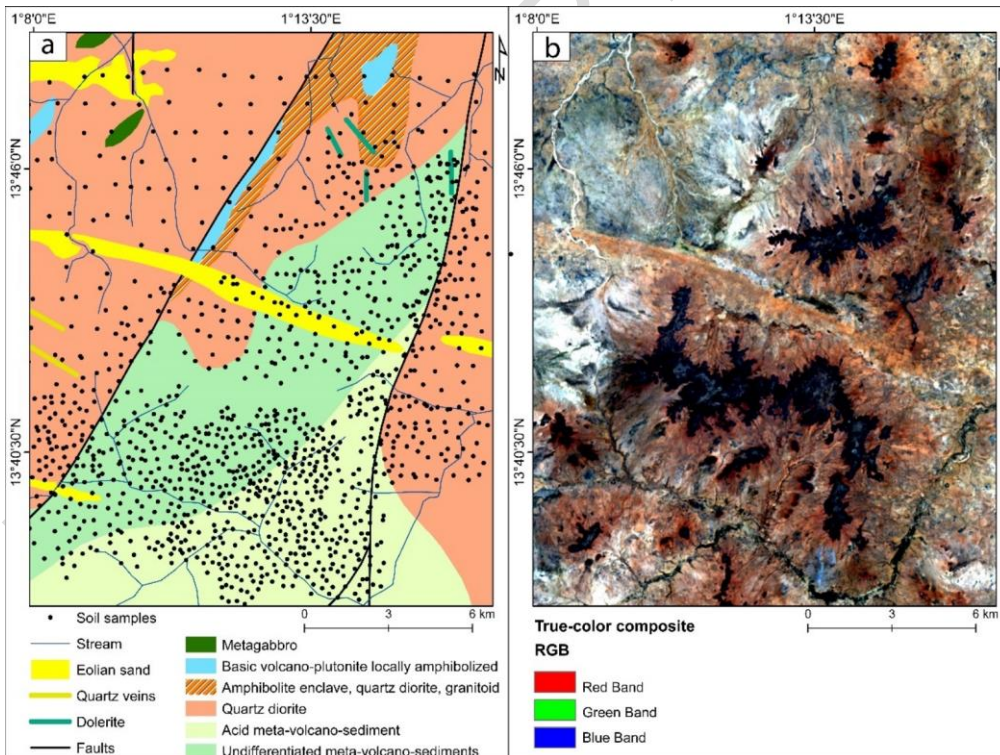


Fig. 2. Soil sampling points (a) and true-color composite of the study area Landsat 8 image (b).

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2.3 Spectral Band ratio

Band ratios improve spectral differences between bands and reduce the effects of topography (Sekandari et al., 2020). The ratio between two bands was calculated for each pixel digital number (DN values) in one spectral band were divided by the corresponding values in another band (Ali and Pour, 2014; Ghrefat et al., 2023). The resulting Band ratio image allows us to better distinguish hydrothermal alteration zones and lithological units (Abhary and Hassani, 2016; Frutuoso, 2015; Mwaniki et al., 2015; Ourhzif et al., 2019).

Iron minerals (hematite, goethite, jarosite) show similar spectral characteristics in the VNIR range due to their similar composition (Ge et al., 2020). They have low reflectance in the blue band (0.452-0.512 μm) and high reflectance in the red band (0.636-0.673 μm) (Table 1, Fig. 3a). Surfaces rich in these minerals will show high pixel values in an image with a Band 4 / Band 2 ratio (Kokaly et al., 2017; Pour et al., 2019; Traore et al., 2020).

Alunite and clay minerals (kaolinite, montmorillonite, illite) have a minimum reflectance in band 7 (2.107-2.294 μm) and a high reflectance in band 6 (1.566-1.651 μm) (Table 1, Fig. 3b). Landsat 8's Band ratio (6/7) highlights surfaces rich in clay minerals (kaolinite, illite, montmorillonite) and alunite through the presence of bright pixels (Kokaly et al., 2017; Pour et al., 2019; Pour and Hashim, 2015; Traore et al., 2020).

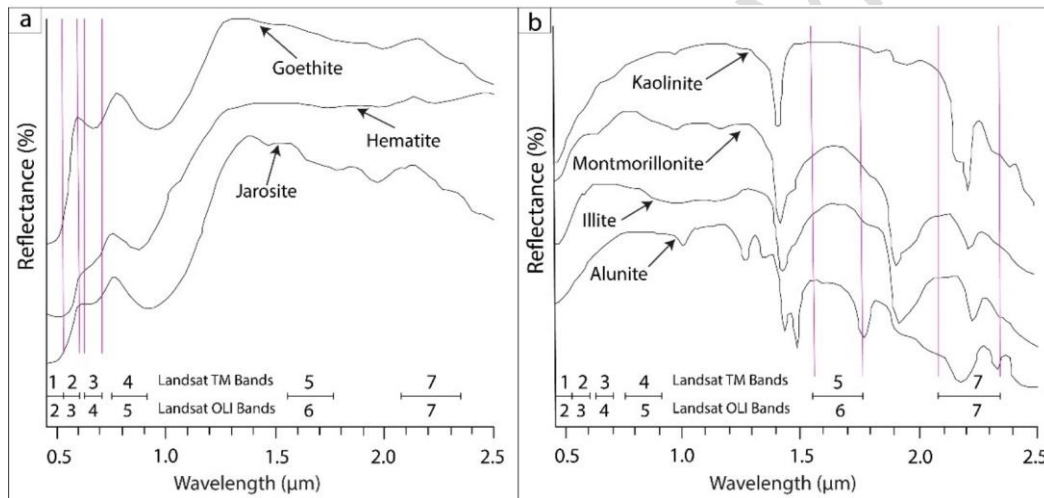


Fig. 3. Laboratory spectra of minerals (Clark, 1999; Sabins, 1999) with Landsat TM and OLI bands position.

2.4 Mapping of anomalies

Gold and alteration mineral anomalies were extracted from the raster images. The inverse distance weighted interpolation (IDW) method was applied to map gold concentrations. The interpolation map was converted to raster data with a 30 m spatial resolution. The image of gold anomalies and those resulting from band ratio (iron minerals, alunite and clay minerals) were recorded in grayscale (8 bits, 0 to 255). The threshold for each parameter was calculated from the DN values of each image (30 m spatial resolution) by applying one of the formulas: $\text{Thd} = \text{Mean} + 3 \cdot \text{Stdev}$ (98% of confidence) (1) or $\text{Thd} = \text{Mean} + 2 \cdot \text{Stdev}$ (95% of confidence) (2). Envi and ArcMap were used for anomalies extraction and mapping.

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3. RESULTS AND DISCUSSION

3.1 REMOTE SENSING RESULTS

3.1 Mapping of gold anomalies

Table 2 shows the statistical values of gold concentrations in Tongue Tonguey soil samples. Table 3 shows the statistical values of the raster image of the Tongue Tonguey gold anomalies. Fig. 4 shows the histogram and distribution curve of

gold concentrations in Tongue Tonguey soil samples. Fig. 5 shows the spatial distribution of gold concentrations around mean and standard deviation values (Fig. 5a) and the map of Tongue Tonguey gold anomalies (Fig. 5b).

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Table 2. Statistical values of gold concentrations (in ppb)

Element	Nt	Min	Mean	Stdev	Skewness	Max
Au	1399	0.5	85.78	403.70	24.33	13000

Nt: total number; Min: Minimum; Stdev: Standard deviation; Max: Maximum

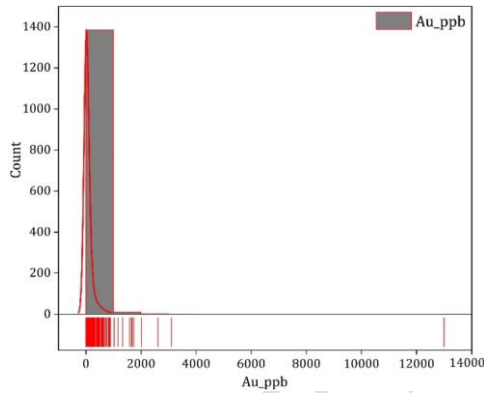


Fig. 4. Histogram and distribution curve of gold concentrations

Table 3. Raster image statistics for the Tongue Tonguey gold anomalies

Anomaly	Min	Max	Mean	Stdev	Thd	Conf
Gold (Au)	0	255	31.39	56.84	145.07	95%

Thd: Threshold; Conf: Confidence

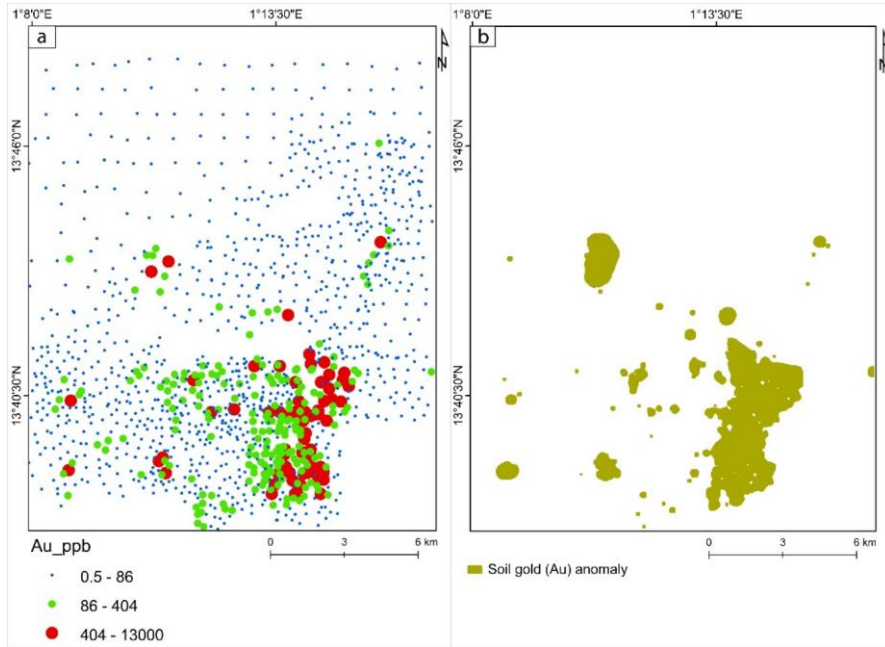


Fig. 5. Spatial distribution of Tongue Tonguey soil's gold anomalies

3.2 Mapping of hydrothermal mineral anomalies

Fig. 6 shows the Band ratio results for iron minerals (Fig. 6a) and for alunite and clay minerals (Fig. 6b). Areas in light pixels represent surfaces rich in iron minerals, clay minerals and alunite. Table 4 gives the statistics for iron minerals, alunite and clay minerals anomalies in the band ratio's raster images. Fig. 7 shows the spatial distribution of iron mineral anomalies (Fig. 7a) and alunite and clay mineral anomalies (Fig. 7b).

Fig. 8 shows the overlay of anomalies. Fig. 8a shows the overlay of iron mineral anomalies and alunite and clay mineral anomalies on the gold soil anomalies. Fig. 8b shows the superposition of iron mineral anomalies, alunite and clay mineral anomalies and gold soil anomalies on the Tongue Tonguey geological background.

Table 4. Raster image statistics of mineral anomalies from band ratios

Anomaly	Min	Max	Mean	Stdev	Thd	Conf
Iron minerals	0	255	117.75	63.41	244.56	95%
Alunite and Clay minerals	0	255	79.55	52.99	238.50	98%

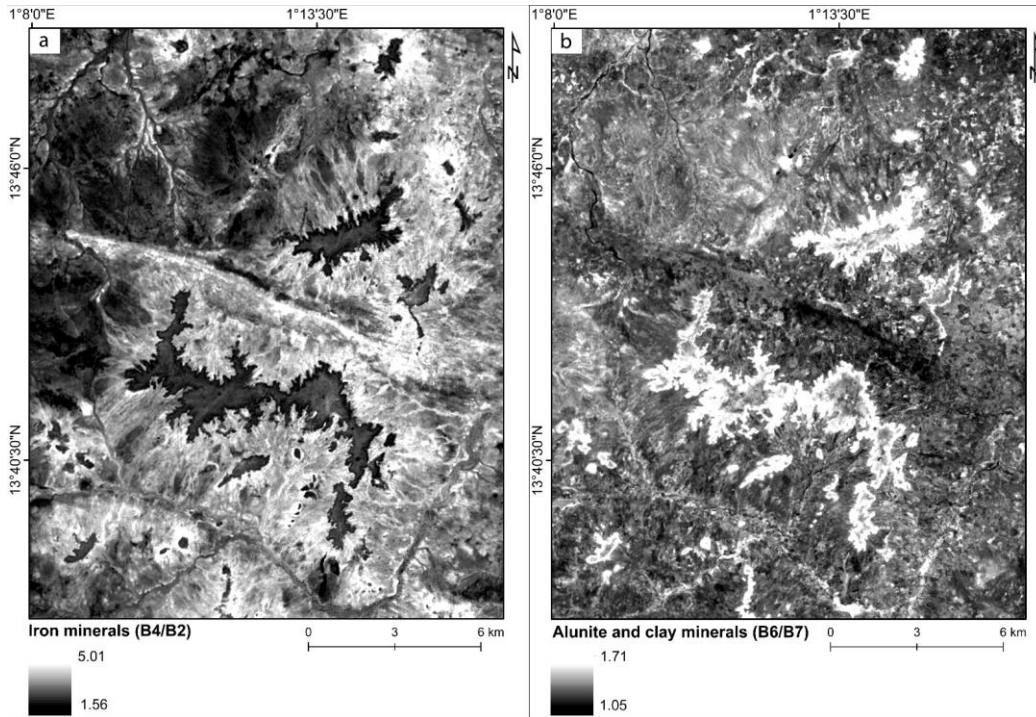


Fig. 6. Spatial distribution of hydrothermal alteration minerals

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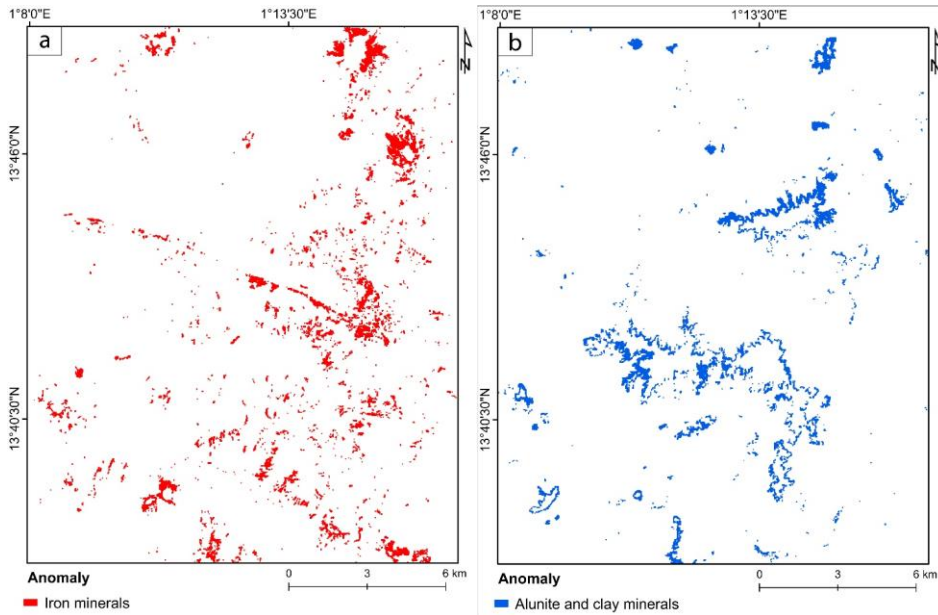


Fig. 7. Spatial distribution of hydrothermal alteration mineral anomalies

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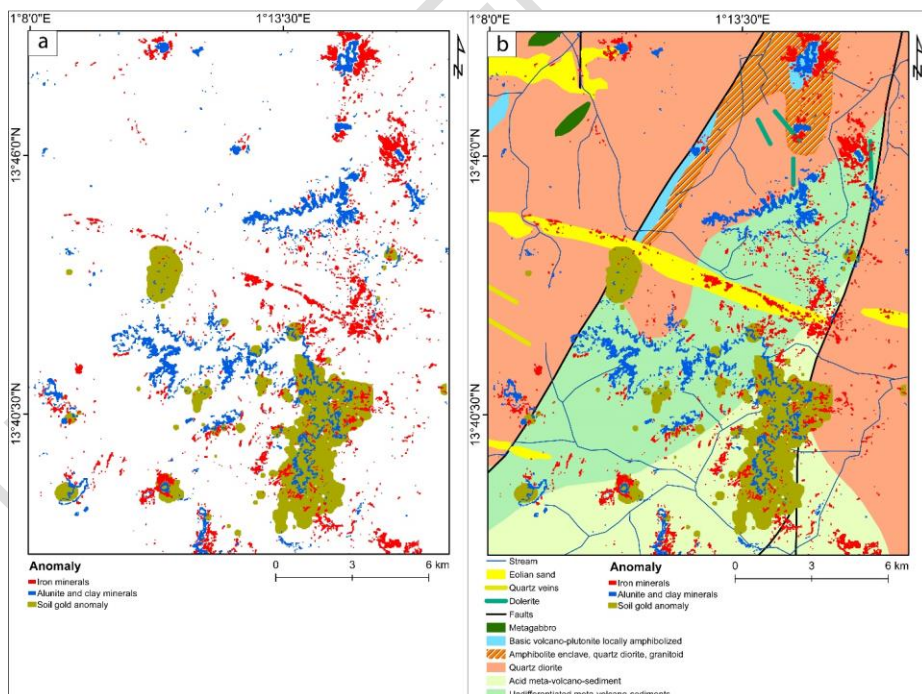


Fig. 8. Superposition of all anomalies on geological background

3.3 Discussion

Remote sensing satellite imagery had been successfully used to detect the hydrothermal alteration minerals associated with gold mineralization in metallogenic provinces (Boateng et al., 2018; Payamani et al., 2020; Sabins, 1999; Sheikhrhimi et al., 2019; Xu et al., 2019). In this investigation, spectral data derived from Landsat-8 sensor were used for detailed mapping hydrothermal alteration minerals in the Tongue Tonguey area, in the Sirba greenstone belt. Band ratios image processing technique was used to produce thematic maps of hydrothermal alteration minerals for indicating the high anomaly zones. Gold concentrations in Tongue Tonguey soils were very spread out (min = 0.5, max = 13,000, mean = 85.78) and highly skewed (skewness = 24.33). Most of the data were on the left, with a few extremely high values (outliers) on the right. The rocks hosting the Tongue Tonguey gold mineralization were subjected to hydrothermal alteration. The spatial distribution of alunite and clay minerals and iron minerals were mapped using the 6/7 and 4/2 band ratio of the Landsat-8 image. Gold anomalies were superimposed on hydrothermal alteration mineral anomalies (iron minerals, alunite and clay minerals). Iron mineral anomalies (hematite, goethite, jarosite) result from the alteration of iron sulfides. Iron sulfides (pyrite, arsenopyrite, pyrrhotite, chalcocopyrite) characterized the gossan and the ore zone (Sabins, 1999). When these sulfides were exposed at the surface, they oxidize to form secondary iron minerals such as goethite, jarosite and hematite, as also reported by Sabins (1999). Long et al. (1992) showed that alunite and jarosite derived from aluminosilicates and pyrite. Kaolinite derived from plagioclase and montmorillonite derived from volcanic glass (Kruse and Hauff, 1990). Kaolinite and montmorillonite characterized the argillic alteration zone (Sabins, 1999). Hydrothermal alteration had developed preferentially on meta-volcano-sediments and basic rocks. Gold anomalies were observed on meta-volcano-sedimentary rocks, along regional faults and at lithological contacts. This observation was made throughout the Liptako region by Jica (1995), Klockner (1995) and Saint-Martin (1999). These gold anomalies may represent favorable zones for gold exploration due to the high intensity of silicates and sulfides alteration in the source rocks. In fact, Jica (1995) and Saint-Martin (1999) had shown that the Sirba greenstone gold mineralization was associated with sulfides such as pyrite, chalcocopyrite and arsenopyrite, and iron oxides/hydroxides such as hematite and goethite.

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4. CONCLUSION

The Tongue Tonguey Gold mineralization was associated to meta-volcano-sediments, regional faults and lithological contacts. The host rocks of the gold mineralization had been subjected to hydrothermal alteration. The application of the band ratio technique to Landsat 8 imagery highlighted iron minerals (hematite, goethite, jarosite), and alunite and clay minerals (kaolinite, montmorillonite, illite) alteration. Both types of alteration had developed on the meta-volcano-sediments, preferentially on the gold anomalies. Gold mineralization at Tongue Tonguey was therefore characterized by iron minerals alteration and alunite/clay minerals alteration. These alteration minerals should constitute an excellent guide for gold exploration in the Tongue Tonguey area.

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DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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