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Title

Aeromagnetic and Spectral Expressions of Rare Earth Element Deposits in Gallinas Mountains Area, Central New Mexico, USA

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Keyword

New Mexico, Gallinas Mountains, Aeromagnetic, Landsat, 2D magnetic modeling

ABSTRACT

The Gallinas Mountains located in the conjunction of Lincoln County and Torrance County, New Mexico, USA are a series of alkaline volcanic rocks intruded into Permian sedimentary rocks. The Gallinas Mountains area is known to host fluorite and copper as veins containing bastnasite while hydrothermally altered rocks associated with iron oxides have been found in the area as well. In this study, multispectral band ratio method was used for surface mineral interpretation by processing satellite image, while aeromagnetic inversion method was applied using aeromagnetic data, digital elevation model and physical properties for 2-D subsurface structure modeling. Bastnasite has higher magnetic susceptibility than the host rocks and surrounding sedimentary rock whereas magnetization of iron oxides (magnetite & hematite) is much stronger than bastnasite; both of them can contribute to a positive aeromagnetic anomaly. Results of this study hypothesize the possible presence of mineralogies and lithologies among the Gallinas Mountains area, indicating the presence of a positive magnetic anomaly that is possibly resultant from both bastnasite and iron oxides.

INTRODUCTION

With the development of high-tech devices and the expanding demands in industrial production, rare earth elements (REE) have been playing an increasingly important role in global economy since several decades ago. Different types of REE serve irreplaceable functions in the high-tech industry, as well as in our exploration of developing sustainable energy and catalysis of manufacturing. Given that the global supply of REE once strained in 2009 (Long et al., 2010) but the demand is increasing, exploration for potential REE deposits

is necessary. Ten main regions containing REE deposits have been found in New Mexico in past years, therefore, research on reserves and mineral compositions of New Mexico's REE districts will have economic benefits in general.

The Gallinas Mountains district located in northern Lincoln County and southern Torrance County of central New Mexico is a series of alkaline igneous intrusions known to have bastnasite, a cerium-rich REE mineral, formed within fluorite-copper sulfide deposits in the Gallinas Mountains area. Four different deposit types have been identified in the Gallinas Mountains: Cu-REE-F hydrothermal veins, epithermal REE-F veins, REE-F breccia pipes and iron skarn deposits. All four types of deposit are related to alkaline to alkali-calcic igneous rocks (McLemore, 2010). Previous investigations on the Gallinas Mountains area have focused on geologic and tectonic formation, and geochemical studies; however, geophysical features of REE associated deposits and their host rocks remain relatively understudied.

Airborne magnetics and multispectral band ratio techniques are often useful for detecting mineral deposits having distinct physical features. An aeromagnetic anomaly is caused by lateral variations of Earth's materials that can be considered as a vector sum (total magnetization) of induced and remnant magnetization (Blakely, 1995). Igneous intrusions often correspond to high magnetic anomalies compared to country rocks. Multispectral band ratio imaging can remotely and economically detect minerals with specific spectral features linked to that material's absorption and reflection regions. In this paper, aeromagnetic data collected over central New Mexico south and Level 1T imagery from Landsat 8 are processed and interpreted.

The object of this study is to: 1) characterize specific geophysical features by using remote sensing technique (multispectral band ratioing) of satellite images, 2) conduct sensitivity analysis of subsurface structures using magnetic inverse modeling to fit the observed total field aeromagnetic anomaly, and 3) discuss the modeled subsurface features and suggest possible models for further exploration.

GEOLOGICAL BACKGROUND

The Gallinas Mountains mining district, located along the Lincoln County porphyry belt (LCPB), was formed by magmatic and volcanic activity. The LCPB belongs to the North American Cordilleran alkaline-igneous belt (Kelley and Thompson, 1964; Kelley, 1971; Allen and Foord, 1991; McLemore and Zimmerer, 2009). The belt of the North American Cordillera spanning Alaska, southern British Columbia, eastern New Mexico, Texas and Mexico (Lindgren, 1933) was examined to have numerous alkaline-related types of mineral deposits such as gold, silver, fluorite and REE (Van Alstine, 1976; Woolley, 1987; Clark, 1989; Mutschler et al., 1991). Important mineral deposits explored and exploited in the part of the North American Cordilleran alkaline-igneous belt in the LCPB of central New Mexico, are associated with Tertiary alkaline to subalkaline igneous rocks (McLemore, 2001, 2011). Early K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dating methods suggested that the Gallinas Mountains rocks in the LCPB alkaline belt were emplaced along the N-S trending Pedernal uplift around 38 to 30 Ma (Allen and Foord, 1991). Later K/Ar dates suggested that the Gallinas Mountains trachyte/syenite is 29.9 Ma, belonging to a younger magmatic event between 30 and 25 Ma (Perhac, 1970; Allen and Foord, 1991).

The Gallinas Mountains district consists of altered Proterozoic and Permian sedimentary rocks intruded by igneous rocks. The Lower Proterozoic gneisses and granites, the oldest units, are overlain by the unconformable Permian Abo Formation that is composed of arkosic conglomerate, arkose, and siltstone/shale. The Permian Yeso Formation, consisting of sandstone, siltstone, shale, limestone and dolomite, unconformably lies between the Abo Formation and sandstones of the Glorieta Formation. After the emplacement of the igneous intrusion (mainly trachyte and rhyolite), mid-Tertiary laccoliths formed which caused doming, faulting, and fracturing of the Lower Permian sedimentary rocks (Perhac, 1970; Long et al., 2010).

Principal deposits in New Mexico districts have been classified into four types of Great Plains Margin (GPM) deposits (North and McLemore, 1986, 1988; McLemore and Phillips, 1991; McLemore, 2010): Great Plains Margin-iron skarn deposits, Great Plains Margin-breccia pipe deposits, REE-F hydrothermal vein deposits and Cu-REE-F hydrothermal vein deposits. A geological map including locations of mines and prospects in the Gallinas Mountains area is shown in figure 1.

The REE-F hydrothermal veins and the Cu-REE-F hydrothermal veins in the Gallinas mining district were developed and mined for fluorite in the 1950s. The cerium-rich mineral bastnasite ($(\text{Ce}, \text{La})\text{CO}_3\text{F}$) was found deposited in fluorite-copper sulfides during recovery. The fluorite-copper-bastnasite deposits in the Gallinas mining district are mostly hosted in siltstones and sandstones of the Permian Yeso Formation except that two were found in porphyritic trachyte (Perhac, 1970; Long et al., 2010). The character of the alkaline trachyte intrusion indicates that the fluorite-copper-bastnasite deposits are epithermal, having formed occurred at

relatively low temperature and shallow depth (Schreiner, 1993; Long et al., 2010; McLemore, 2010). The fluorite deposits formed along fault breccias as hydrothermal veins and mineral-rich masses filling fissures and fractures. In F-REE and Cu-F-REE breccia deposits, fluorite is the dominant mineral that composes up to 60% of the rock in those fluorite mines (Soulé, 1946); other abundant and associated minerals include barite, quartz, galena, and bastnasite (Griswold, 1959; Perhac, 1970). In 1992-1992, U.S. Bureau of Mines calculated an inferred resource of 537,000 short tons with a grade of 2.95% total REE in the Gallinas Mountains (Schreiner, 1993). The main minerals in the study area are listed in Table 1. Even though previous geology data indicate that the REE-bearing fluorite fault breccia deposits exposed at the surface of the study site are low grade and lack of sufficient tonnage to support mining operation, information from a drill core of the Buckhorn deposit (east edge of the study area) presented that the REE minerals concentrated at depth lower than 445ft (Schreiner, 1993). In addition, data of other F-REE and Cu-F-REE mines and prospects in the study site presented that REE mineral, especially bastnasite, was found as tabular breccia zones in fluorite deposits, and the depth of currently known deposits ranges from several tens to several hundred meters.

Beside F-REE deposits, iron skarn have been found and mined during the past few decades in the Gallinas Mountains (figure 1, iron skarn deposits are on the left to the study site). The formation of iron skarn is one stage of hydrothermal formation system prior to the formation of F-REE vein deposits, and mild hydrothermal alteration and weathering of clay and iron oxides are commonly appeared at the deposits (Vance, 2013). Hypogene oxidation completely converted pyrite into hematite, goethite and limonite pseudomorphs in the iron mineral deposits. Some of the iron mines once had produced large amount of iron (mostly

hematite and magnetite) before 1943, whereas in 1943, trenching and sampling from New Mexico Bureau of Mines (NMBM) showed no additional ore can be produced from the mines. Carbonatite was also proposed to be associated with the hydrothermal F-REE veins and buried under trachyte intrusion, which suggested by previous studies (Perhac, 1970; Schreiner, 1993; McLemore, 2010; Vance, 2013). From the mineral samples collected at mines of the Gallinas Mountains area, fenitization was found, which is an alteration type associated with carbonatite.

DATA

Aeromagnetic Data

Aeromagnetic data is collected based on the measurement of Earth's magnetic field anomalies that result from induced magnetization (dependent on the external field) and the remnant magnetism field (independent of the external field) (Hinze et al., 2013). A series of digital data (3096C) were obtained from the 1976 U.S. Geological Survey (USGS) airborne survey over central New Mexico south, covering the Gallinas Mountains area (Kucks et al., 2001). The aeromagnetic data were collected along east-west flight lines with 1-mile spacing at a flight altitude of 8500 feet above sea level (Kucks et al., 2001).

Digital Elevation Model

DEM data were collected by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), which is an imaging instrument onboard the National Aeronautic and Space Administration (NASA) spacecraft Terra launched in 1999. The ASTER Global Digital Elevation Model Version 2 (GDEM2) data was released to the public by NASA

and the Ministry of Economy, Trade, and Industry (METI) of Japan on October, 2011. The ASTER satellite sensor produces multispectral images with resolution ranges from 15 to 90 meters, and the GDEM2 produces digital elevation models having a horizontal resolution on the order of 75m and an overall accuracy around 17m. An ASTER Global DEM Version 2 image ASTGTM2_N35W106 covering Gallinas Mountains was acquired from Earth explorer of U.S. Geological Survey (<https://earthexplorer.usgs.gov/>).

Remote Sensing Image

The Operational Land Imager (OLI) is one of the sensors onboard the Landsat 8 satellite that was launched on February, 2013. It has 9 different spectral bands which include 7 VNIR (visible-near infrared) and 2 SWIR (short wave infrared) bands, most bands have a spatial resolution of 30 m except that the panchromatic band is 15m. Spectral bands and other detailed characteristics of the OLI are presented in Table 2. A terrain corrected product (Level 1 T), cloud free Landsat-8 OLI/TIRS image (WRS path 33, row 36) covering the Gallinas Mountains area was downloaded from the U.S. Geological Survey (<https://earthexplorer.usgs.gov/>). This OLI/TIRS image LC80330362016294LGN00 was acquired on October 20th, 2016.

METHODS

Aeromagnetic inversion method

The aeromagnetic inversion method is based on processing of the total field magnetic anomaly. Total magnetization is the rock property associated to its magnetic anomaly and geologic origin (Reynolds et al., 1990) in the direction of the Earth's field. Aeromagnetic measurement including the vector sum of: a) the induced magnetic field caused by the

interaction of the Earth's internal magnetic field and a rock's magnetic susceptibility, b) the remnant magnetic field that related to the nature of a rock's formation, and c) the changing of Earth's interior magnetic field measured by International Geomagnetic Earth Reference Field (IGRF). The International Geomagnetic Earth Reference Field (IGRF) is a mathematically global magnetic model providing Earth's magnetic main field and its secular variation. The IGRF of the study area has already been removed from acquired aeromagnetic data. Induced magnetization is the magnetic susceptibility proportional to magnetism in a material that response to an applied external magnetizing field; it disappears as the applied field is removed. Remnant magnetization is a permanent magnetization remaining in a material that reflects the geologic history and source of a rock's material. It is commonly not oriented to the ambient field and its magnitude is usually much smaller than the induced magnetization. The total field aeromagnetic anomalies include both induced and remnant magnetic fields, reflecting variations in the amount and type of subsurface magnetic minerals, and are thus important for geophysical prospecting of mineral resources. In this study, the magnetic modeling for subsurface interpretation will conduct by processing aeromagnetic data, digital elevation model and physical property of rocks and minerals.

After correction of the Earth's field, a total field aeromagnetic anomaly map was gridded over central New Mexico south using the digital data set 3096C (figure 2). The grid was generated with a cell size of 200m, interpolated by a minimum curvature gridding method, and displayed as a pseudo color map.

Multispectral band ratio

Spaceborne remote sensing techniques have been extensively used to explore for natural resources on Earth's surface. Mineral exploration is one of the important usages of multispectral imaging data. Each mineral or rock may have its own unique spectral pattern of scattering and absorption features known as its spectral signature. This spectral signature is often used to identify a target mineral remotely. In this study, since hydrothermal alteration and iron oxide are reported to occur in the Gallinas Mountains mining district (Perhac, 1970; Schreiner, 1993; McLemore, 2010), the remote sensing technique band ratioing and color composite imaging can help to emphasize spectral contrast and to map the iron mineral's distribution (Rawashdeh et al., 2006; Madani, 2009; Dehnavi et al. 2010).

Iron oxides and oxide-hydroxides are among the most common minerals in nature. Common iron oxide minerals include hematite (Fe_2O_3), goethite (FeOOH), and magnetite (Fe_3O_4). Iron minerals often present in altered rocks can produce unique spectral features, including hematite, goethite, magnetite, and jarosite. Spectral information of hydrothermally altered rocks and minerals is very useful due to their mineralogical association with valuable deposits. Spectral features displayed in a visible and near infrared spectrum (0.35 to 1.0 μm) are caused by iron cations through electronic processes of crystal-effects and charge-transfer absorptions (Singer, 1981), whereas features at wavelengths longer than 1.0 μm but less than 2.5 μm are caused by the vibrational transitions of hydroxyl-bearing minerals (Hunt & Ashley, 1979).

Previous studies (e.g. Hunt, 1971; Hunt and Ashley 1979; Singer, 1981; Morris et al., 1985; Drury, 1993; Gupta, 2013) have observed that ferric iron oxides display distinguishable absorption features in the spectrum ranges of 0.48 – 0.55, 0.63 – 0.71 and 0.85 – 1.00 μm . Ferrous oxides absorb light mainly in the spectrum ranges of 0.45 – 0.55, 1.00 and 2.00 – 4.80 μm , whereas hydrothermal clays exhibits notable absorption features at around 1.90, 2.35 and 2.50 μm (Elsayed Zeinelabdein and Albielyb, 2008).

Band ratioing is a straightforward and powerful remote sensing method that has been widely used in mapping alteration zones and their associated minerals such as iron oxides (Segal, 1983; Sabins, 1999; Shalaby et al., 2010; Dehnavi et al., 2010). It can enhance the contrasts between spectral reflectance curves and diminish the effect of topography and albedo (Sabins, 1999; Howari et al., 2007). Band ratios herein selected for mineral detection are OLI band ratio 4/2, 6/5, 6/4 and 6/7.

RESULTS

Band ratioing

By applying the theoretical method of the spectral features of iron oxides, which typically present reflectance in OLI band 4, 6 and absorptions in band 2 and band 5 (Ducart et al., 2016), OLI bands 4/2 and 6/5 were selected as band ratios for highlighting iron minerals in the study area.

Band ratio 4/2 is useful for detecting ferric (Fe^{3+}) iron oxides such as hematite and goethite as they often show red to yellow colors in visible band and are absorbed in the UV and

blue spectral regions (Rockwell, 1989; Knepper, 1989; 2010). Thus, band ratio 4/2 commonly enhances the reddish color from ferric iron minerals (Sabins, 1999; Dehnavi et al., 2010; Shalaby et al., 2010; Knepper, 2010) even if they are not present in high concentration. Area of ferric iron mineral occurring as coatings or disseminated on surfaces of hydrothermally altered rocks, sedimentary rocks and mafic related regolith at low grade can be identified with this ratio (Rockwell, 2013; Dehnavi et al., 2010). As a result, high pixel values in the study area (red rectangle in figure 3) represent rocks and soils associate with ferric iron oxides. The brightest zones in the study area are located at the central and middle left areas, a few bright pixels were observed at the bottom and top left areas also. These observations indicate the presence of soil or rock containing ferric oxides on the surface.

Another band ratio applied in this study is OLI band 6/5, an index proposed to detect crystal-field absorption features from possible ferrous (Fe^{2+}) mineral and ferric-ferrous iron oxide magnetite (Kaufmann, 1988; Wilford and Creasey, 2002; Rajendran et al., 2007; Dogan, 2008; Elsayed Zeinelabdein and Albiely, 2008; Ducart et al., 2016) since OLI band 5 coincides with the absorption feature of ferrous and ferric iron minerals whereas band 6 covers the high reflection peak for ferrous iron oxides, ferruginous saprolite, clays and hydrothermally altered rocks (Podwysocki, et al., 1985; Wilford and Creasey, 2002). This index highlights ferrous iron related rocks as shown in figure 4. The distribution of brightness zones are located very similar to those on band ratio image 4/2 but the high pixel values in the central region are a lot more than those of ratio 4/2. The brightness zones indicate the ferrous iron oxides mostly appear at the central and mid-left areas with a few in the top-left and bottom areas.

Based on the consideration of those two band ratio results above, a false color composite image using a combination of the OLI band ratios of 6/4, 4/2 and 6/7 in red, green and blue, respectively, has been obtained to detect alteration zones featured by iron oxides, hydroxyl-bearing minerals, and hydrothermal clays (Sabins, 1999; Elsayed Zeinelabdein and Albielyb, 2008; Knepper, 2010; Knepper, 2010; Ducart et al., 2016). A high ratio value of one color will display on the pixel as a primary color of red, green or blue; high ratio values of two colors will be presented in the pixel as a combination of two colors proportional to their values. High 6/4 values (red) give a high composition of iron oxides (both ferric and ferrous); large 4/2 values (green), as discussed before, represent a large component of ferric oxides associated soils; high 6/7 values (blue) represent the presence of hydrothermal clays since the band 6 covers the reflectance peak of hydrothermal clays whereas band 7 contains a reflectance trough of the clays. If 6/4 and 4/2 ratio values become similarly high in the same pixel, the color of the pixel will display as yellow, while if ratios of 6/4 and 6/7 display a same value in one pixel, the color of the pixel will be pink. As shown in figure 5, reddish pink zones and its surrounded yellowish zones mainly locate at the center of the study area marked by the red rectangular box, indicating the presence of hydrothermal altered clays containing of disseminated iron oxides.

Aeromagnetic distribution

The total-field aeromagnetic anomaly of area 3096C in central New Mexico is ranging from 52133.4nT (blue) to 52347.4nT (pinkish white) as displayed in figure 2. By adding the digital elevation model (DEM) data onto the aeromagnetic anomaly map (figure 6 left), the center of the study site occupies a total-field anomaly high (color pink). The magnetic anomaly decreases gently from the center to the margins. It is located right to a northwest-southeast fault

and around another southwest-northeast strike fault, both of which can be observed on the left of figure 6.

Magnetic profile modeling

Geological profile modeling is helpful in offering insights into subsurface geological structure and magnetic mineral distribution. Aeromagnetic data of several profiles through the study site have been extracted for magnetic modeling, out of which two were selected for detailed investigation (right panel of figure 6). By combining Global Digital Elevation Model V.2 (GDEM2) data from ASTER, 2011, aeromagnetic anomaly data sets along the selected profiles were put into GM-SYS for 2D modeling study. The physical property needed for the 2-D profile modeling is magnetic susceptibility. Although many rock types in the study area have their own features of magnetic susceptibility, based on a previous lithology study (Griswold, 1959; Perhac, 1970; McLemore and Phillips 1991; McLemore, 2010), two units are the most possible candidates that cause the local aeromagnetic high: 1) the REE mineral bastnasite and 2) iron oxides includemagnetite and hematite. Country rocks and REE host rocks with magnetic susceptibilities less than 0.001SI will not significantly contribute to the observed magnetic field anomaly. Based on the spectral ratio maps and previous geology study, the presence of hydrothermal alteration associated iron oxides on the surface of the study site indicate unexploited iron oxides, hematite and magnetite, will probably exist at depth during the formation of hydrothermal deposits Therefore, the iron oxide unit is reasonably assumed to be a mixture of magnetite and other colored iron oxides. The average magnetic susceptibility

of hematite and magnetite as a mixture is estimated from magnetic susceptibility index (Feral, 2010; Rosenblum and Brownfield, 2000) that proposed to be 0.2 SI and that of bastnasite is taken to be 0.009 SI. The mean magnetic susceptibilities are used for each geologic unit, boundaries of geologic units were adjusted to fit the modeled magnetic curve (black solid line, figure 7 & figure 8) to the observed total-field aeromagnetic anomaly curve (black dashed line, figure 7 & figure 8). The depth of mineralization was assigned to be within 1 km (around 400m) below surface as suggested by previous geology study and data from mines and prospects (Perhac, 1970; Schreiner, 1993; Long et al., 2010; McLemore, 2010). As previously data from mines and prospects around the study site reported, the bastnasite formed in fluorite deposits or breccia zones appears to be tabular, and the hydrothermally altered iron oxides have been found in the study site but the amount is unknown. Therefore, even though bastnasite in fault breccia deposits could be brecciated or disseminated, all bastnasite deposits can be seen as locating at a same average depth and the large amount of brecciated veins can be seen as a tabular layer in cross-sectional view, Therefore, the target mineral bastnasite and probable iron oxides are simplified as pure layers buried below surface. Figure 7 and figure 8 show the modeled subsurface mineralogical structures along the profiles A-A' and B-B', respectively, with different mixing situations.

The panels of figure 7 show four subsurface mineralogical models along a west-east profile A-A' (see Fig.6). Target minerals of bastnasite and/or iron oxides of hematite and magnetite are modeled as pure layer(s) surrounded by REE host rocks. In figure 7, bastnasite and iron oxides are presented as dark red and yellow, respectively, and the surrounding REE bearing rocks as pink, sandstone from Yeso Formation and granite with granitic gneiss as dark

green. The panels of figure 8 show the corresponding subsurface mineralogical models along a northwest to southeast profile B-B' (see figure 6). The first model assumes that the aeromagnetic anomaly high is caused by bastnasite only (dark red in figure 7 case 1). A layer of the target mineral about 80m thick for average fits well the observed magnetic anomaly, the calculated modeling result with fitting errors of 1.72% and 1.47% compared respectively on figure 7 and 8. The second mineralogical model deals with the case that the magnetic cause is a mixture of bastnasite and iron oxides (hematite and magnetite). In such case, due to the presence of iron oxides (average thickness 2m), the average thickness of bastnasite is about 13-15 m. Such a model fits the observed magnetic anomaly with errors of 1.32% and 3.12%, respectively. The third model assumes that the observed magnetic anomaly high is totally contributed by iron oxides at the same depth as in the first two cases. In this case, the thickness of the iron oxide layer is about 8m on average and the fitting error ranges between 1.62% and 2.79%. The last model assumes that the observed magnetic high is just due to magnetite with a magnetic susceptibility of 2.0 SI (Rosenblum & Brownfield, 2000). In such case, the magnetite appears as a layer (yellow in case 4 of figure 7 and 8) with a thickness ranges from 0.2m-2m (0.5m for average), the fitting errors for this case are 3.14% and 4.91%.

DISCUSSION

Surface interpretation

Result of Landsat 8 OLI band ratio 4/2, presented in figure 3, indicates a possible presence of altered and weathered ferric iron oxides in the top soil at the study area. In addition, the band ratio result also implies iron oxides are associated with hydrothermally altered rocks.

The OLI band 6 contents high reflection peaks of most types of rocks and soils include hydrothermal alteration rocks, ferruginous clays, and iron oxides while band 5 includes the absorption band for ferric and ferrous iron-bearing minerals (Wilford and Creasey, 2002), therefore, the high values of brightness can be resulted from altered rocks in association of iron oxides. Previous studies by Perhac (1970), North and McLemore (1986, 1988), Schreiner (1993), and McLemore (1991, 2010) show that there are four types of deposits in the Gallinas Mountains district while hematite and magnetite existed in prospects and mines of the four types of deposit. Hydrothermal alteration and the formation of iron deposits appeared before the formation of hydrothermal F-REE and Cu-F-REE veins. Therefore, iron oxides could be disseminated in the top soil with low concentration, and the high brightness values of band ratio result are probably caused by iron oxides and their associated hydrothermal clays. These results can be examined in the same ratio image as well: the bright zone on the left of the study area (figure 3 and figure 4) is a series of breccias intruded into Tertiary igneous rocks. The Tertiary trachyte contains mafic minerals which were altered to hematite and limonite and were stained by the iron-oxide-related mafic regolith. Those iron oxides, although in low concentrations, have spectral features that have been detected and represented as bright pixels in figure 3 and figure 4. In the study area (red rectangle, figure 5), false color RGB image displays yellow at the center, reddish pink at the top left surrounded by yellow. Refers to the color addition of color composition RGB image, yellow represents the presence of both ferrous and ferric iron oxides while pink represents the presence of both hydrothermal clay in association of iron oxides. The light grey to white zones on the ratio images (figure 3 and figure 4) inside the study area coincide with pink and yellow zones on the false color image (figure

5), dark grey to black zones on ratio images coincide with whitish zones on the RGB image. The RGB image matches the results of band ratio 4/2 and 6/5. Both single band ratio results and false color image indicates the altered iron oxides and hydrothermal alteration appear at the surface of the study site, these results indicate iron oxide can be deposited under the study site due to hydrothermal alteration.

Subsurface interpretation

The total-field magnetic anomaly over the Gallinas Mountains area reflects the distribution of magnetic minerals or magnetic mineral-bearing rocks. The positive magnetic anomaly observed within the study area (figure 2) and the geologic map (figure 1) show that iron oxides of hematite and magnetite, and bastnasite are the most probable minerals causing the observed magnetic anomaly. As is shown in figure 7 and figure 8, we interpret the observed magnetic anomaly using four possible mineralogical models, with the content of bastnasite varying from 100% to 0% and magnetite from 0% to 100%, respectively. Paramagnetic feature results in a thick layer of bastnasite by association of F-REE and Cu-F-REE depositional host rocks (figure 7 & figure 8). The paramagnetic feature of hematite and the ferromagnetic feature of magnetite contribute to the magnetic susceptibility of iron oxides by slimming the thickness of the bastnasite (figure 7 & figure 8, case 2). The magnetic anomaly was interpreted as being caused by a layered deposit of iron oxides including hematite and magnetite (figure 7 & figure 8, case 3), and magnetite only (figure 7 & figure 8, case 4). The presence of ferric oxides and magnetite decreases the amount of bastnasite. There are no known borehole constraints within the magnetic anomaly zone, the depth of all four types of the Gallinas Mountains deposits proposed by Schreiner (1993), Richards (1995) and McLemore (2010) is within 1km and

information of one drill core on the east edge of the study site showed REE mineral was found relatively concentrated at a depth of 445ft. The depth of the magnetic sources in the four subsurface mineralogical models shown in figure 7 and figure 8 matches the previous geology studies. In addition, the simplified layered models proposed in this study fit the observed magnetic anomaly better than those models with target minerals of narrower but thicker layer(s) which are not presented here.

Integration and future study

As is shown in the surface spectral analysis using multi-spectral OLI image, the presence of hydrothermal alteration and the altered iron oxides on the surface of the study area indicates that iron oxides may exist below surface to be a main magnetic source of the observed positive aeromagnetic anomaly. Aeromagnetic inversion along two intersecting profiles are made depending on the hypothesis that the significant magnetic susceptibilities were caused by iron oxides of magnetite and hematite, and the REE mineral bastnasite. The subsurface modeling is non-unique since the exact mixing situation is unknown. Geologically, the magnetic anomaly may be caused by concentrated zones of bastnasite, depositional zones of hematite and magnetite mixtures and bastnasite, alteration zones contain mixture of hematite and magnetite, or only deposits of magnetite. However, the existence of bastnasite, hematite, and magnetite within the study site has been reported in previous geological studies of the Gallinas Mountains depositional area (Perhac, 1970; Schreiner, 1993). The cross-sectional subsurface model having a mixture of iron oxides and bastnasite as the magnetic source (model 2 in figure 7 & 8) is a better match to the geological data. The model is simplified as pure layers of magnetic minerals of bastnasite and altered iron oxides that formed as a probable series of

tabular and brecciated deposits distributing around a same averaged depth, This subsurface model is worth further investigation in the future by combining geophysical methods with borehole data that is not yet available. Also bastnasite, iron oxides (hematite, magnetite), fluorite have higher specific densities of 4.95, 5.15, 3.18, respectively, than the country rocks (2.8-3.0 gm/cc) that can be detected by gravity anomaly. Additionally, bastnasite in breccia zones appears on the left side to the study site are formed by filling open space caused by fenitization (Griswold, 1959; Perhac, 1970; Schreiner, 1993; McLemore, 1991). This formation is usually associated with carbonatite that can be detected since carbonatite is often denser while its magnetic susceptibility is usually lower than the surrounding rocks. Borehole data, if available in the future, can help to constrain the depth and magnetic susceptibility value of the causative minerals for three dimensional modeling so that a more definitive and comprehensive 3D subsurface mineralogical model can be constructed.

CONCLUSION

Given the aeromagnetic anomaly, geologic mapping, magnetic properties, multispectral band ratioing and false color imaging, the presence of bastnasite and iron oxides in the study site, the southeastern Gallinas Mountains is interpreted. The study site in southeastern Gallinas Mountain district contains a series of breccias that have been found to have mineral deposits of fluorite, copper, and bastnasite. Hydrothermal alteration associated with iron oxides is also found over trachyte intrusions and detected herein by band ratio imaging. The positive aeromagnetic anomaly over the study site and data of surface mineral deposits show the possible existence of subsurface magnetic minerals. Four mineralogical models are proposed

to generate the observed magnetic anomaly. The geology of the four models is (1) bastnasite, a paramagnetic REE mineral, (2) a mixture of bastnasite and iron oxides including magnetite and hematite, (3) iron oxides of hematite and magnetite, and (4) only magnetite. Previous mineralogy and lithology studies indicate that the mineralogical model with a mixture of bastnasite and iron oxides including hematite and magnetite as the causative magnetic sources for the observed aeromagnetic anomaly is more likely the true case but a more detailed composition of the bastnasite and iron oxide mixtures need to verify. The other models are still possible candidates unless borehole data are available to eliminate the uncertainty.

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Table 1. Typical mineral composition in study area.

Deposit type	Mineral	Chemical Formula
F-REE deposits and Cu-F-REE deposits	quartz	SiO ₂
	fluorite	CaF ₂
	barite	BaSO ₄
	calcite	CaCO ₃
	pyrite	FeS ₂
	bastnasite	[Ce, La, (CO ₃)]F
	agardite	(Ce, Ca, La)Cu ₆ (AsO ₄) ₃ (OH) ₆ .3H ₂ O
	parisite	Ca(Nd, Ce, La) ₂ (CO ₃) ₃ F ₂
	xenotime	(Yb, Y, Er)PO ₄
	monazite	(Sm, Gd, Ce, Th, Ca)(PO ₄)
	hematite (trace)	Fe ₂ O ₃
	magnetite (trace)	Fe ₃ O ₄

Table 2. Landsat 8 OLI band features.

Spectral Band		Resolution (m)	Spectral range (um)
VNIR	Band1 - Coastal/ Aerosol	30	0.433–0.453
	Band2 - Blue		0.450–0.515
	Band3 - Green		0.525–0.600
	Band4 - Red		0.630–0.680
	Band5 - NIR		0.845–0.885
SWIR	Band6 - SWIR-1	30	1.560–1.660
	Band7 - SWIR-2		2.100–2.300
VNIR	Band8 - Panchromatic	15	0.500–0.680
	Band9 - Cirrus	30	1.360–1.390