The Application of Landsat-8 Imagery and Airborne Gamma-Ray Spectrometric Data for Lithological Mapping of Gabal Nuqara Area, Central Eastern Desert, Egypt

Ismail M. Abdel Ghani

Abstract: This paper examines the integration of the spectral analysis of Multispectral Landsat-8 data and the airborne gamma-ray spectrometric survey followed by detailed field work and petrographic studies for geological mapping and locating radioactive anomalous zones at Gabal (G.) Nuqara area, central Eastern Desert, Egypt. The Dokhan Volcanics of G. Nuqara are characterized by their heterogeneity, complexity, toothy nature of their summits, steep slopes and very rugged topography. Depending on traditional means, geological mapping of this rock unit is very difficult. The promising results of Landsat-8 image processing, including Colour Band Composites and spectral transformation techniques (Principal Component Analysis, Minimum Noise Fraction and Band Ratios) and the results of airborne gamma-ray spectrometric data processing are verified and confirmed in the field by identification of the different lithological units and alteration types; the integrated work is validated further through petrographic studies. The results of these techniques are integrated and combined to construct a precise geological map (scale 1:50,000) for the study area. Accordingly, G. Nuqara Dokhan Volcanics are classified into two members: 1) the lower intermediate member comprising andesite, dacite and quartz-dacite and their equivalent tuffs, and 2) the upper felsic, which is also classified into rhyodacites and their equivalent tuffs and the rhyolites with their equivalent tuffs. In addition, the younger granites are discriminated from the older ones. The radio element maps are correlated with the processed Landsat-8 images in order to delineate possible radio element potentialities at the G. Nuqara area. Uranium anomalies are encountered at G. Mohamed Rabbah, the area around Wadi El-Barud and sporadic zones in felsic Dokhan Volcanics.

Keywords: Landsat-8, Principal Component Analysis; Minimum Noise Fraction; Lithologic Mapping, Airborne Gamma-Ray Spectrometry, G. Nuqara, Dokhan Volcanics
تطبيقات صور لاندساسات 8 وبيانات الطيفية الجوية لأشعة جاما، تحليل المركبات الأساسية، الحد الأدنى لتجزيء التشويك، طيف أشعة جاما المحدودة جوياً، جبل نقارة، وسط الصحراء الشرقية، مصر

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ملخص: تجمع الدراسة الحالية بين التحليل الطيفي لبيانات القمر الصناعي لاندساسات 8، وتحليل أشعة جاما المحدودة جوياً، متبعاً بالعمل الحالي التفصيلي، وتكريتوسكوبية بحثية التحليل الجيولوجي لمنطقة جبل نقارة، وسط الصحراء الشرقية، مصر. والجدير بالذكر أن عملية التحليل الجيولوجي لمنطقة جبل نقارة اعتماداً على البيانات التحليلية باللغة المصرية، نظرًا لما تميزه بها هذه الوحدات الصخرية من عالم منتج وتقني، إضافة إلى الطبيعة المتنوعة من صخور الدخان، وتحتوار الدخان، والصخور الشمسية، وكذلك النظريات التي تدعم هذه الوضعية، مما يؤدي إلى رسم الخرائط القليلة الدقة، خاصة لمثل تل تلك القمم العالية، واللغزية.

لقد أظهرت كل من نتائج تقنيات المعالجة صور الملاحة، ودراسات الميكروسكوبية الاختلافات الطيفية بين الوحدات الصخرية بمنطقة الدراسة، مما سهل التحليل الجيولوجي لها، كما تعنيه أمكنك وأنواع نطاقات التحليل والتغير بالمنطقة. كما تم تجريب صورة الدخان بمنطقة الدراسة إلى نوعين: (1) عبارة عن تدريزات ومصادر، وكوارتز مذاب وصخور السداسية يتألفون منها، والصخور الطبيعية خاصتهم. (2) عبارة عن صخور ذات نماذج، وشعاب الأشجار، والصخور الطبيعية خاصتهم. ويمكن تبخير الجرانيت الأحمر بصورة واضحة، جاعلًا صور جزئيات الصخور الفردية قيدية.

نجوم عن تصوير البيانات خرائط المسح الإشعاعي أيضاً جبل محمد رباح (فانتوريزوي) في جبل الصخرة، لما له من محتوى عالي من اليوانووس، وتحتوارات تبقية لكل من الثوريوم والبيوتونيوم، وكذلك لاحتواره على طبقات الجواء التي تتواجد في حالة تبادل أو تغطي صخور الحجر الرملي الناعم، ومن طبقات الدخان، خصوصاً على المنطقة المحاذية لبواز فارود في صخور الجرانيت الحديث، وكذلك أكثر من صور في صخور الصخور في الدخان.

كلمات مفتاحية: لاندساسات 8، تحليل المركبات الأساسية، الحد الأدنى لتجزيء التشويك، طيف أشعة جاما المحدودة جوياً، جبل نقارة، بركانيات الدخان.

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1. INTRODUCTION

Using multispectral image processing and Geographic Information System (GIS) techniques, a number of highly accurate projected thematic maps representing geomorphologic and morphometric characteristics of hydrologic system, radiometrically and atmospherically corrected satellite imagery (Landsat 8 data), band colour combinations, band ratios, principal component analysis, minimum noise fraction, image classification, etc., that reflect the ability of these powerful tools in different geologic aspects saving time, efforts and cost. Remote sensing data involving satellite and airborne types provide quick and cheap tools in geological mapping and radioelement potentiality. The potential of using remote sensing accompanied by GIS in geology and geomorphology has long been discussed in the principal literature (e.g. Drury, 2001; Gupta, 2003; Jensen, 2005; Lillesand, Kiefer, & Chipman, 1999). Geological mapping and mineral exploration are some of the main responsibilities of remote sensing applications. Today, remote sensing data is usually utilized for lithological mapping, structure analysis and mineral exploration around the world, particularly in arid and semi-arid regions (Abdeen and Greiling, 2005; Rowan, Mars, & Simpson, 2005; Acharya and Mallik, 2012; Arnow and Sultan, 2014; El-Said, 2014; Sweiha, 2014; Badr, 2017; Sultan, El-Shafei, & Arnous, 2017). Furthermore, the digital image processing of the spaceborne data has a lot of potential in providing several solutions, especially ones used to overcome the difficulties and limitations associated with geological field mapping and mineral exploration (especially in inaccessible and rugged terrain, such as the G. Nuqara area in central Eastern Desert, Egypt).

Egyptian basement rocks in the Eastern Desert and Sinai comprise Neoproterozoic juvenile crust developed in the northwestern-most Arabian Nubian Shield (ANS; Stern, 2002). The ANS is composed of mostly low-grade metasedimentary and metavolcanic rocks that were derived from oceanic island arc volcanism (Collins and Pisarevsky, 2005; Hargrove, Stern, Kimura, Manton, & Johnson, 2006; Stern, 2002, 2008; Ali, Stern, Manton, Kimura, Whitehouse, Mukherjee, Johnson, & Griffin, 2010; Stern and Johnson, 2010). The shield was cratonized during the collision between East- and West-Gondwana following the closure of the Mozambique Ocean around 750-630 Ma (Stern, 1994; Abdeen and Greiling, 2005; Cox, Lewisa, Collins, Halverson, Jordan, Foden, Nettie, & Kattan, 2011; Abu-Alam, Santos, Brown, & Stüwe, 2013). After cratonization, the Neoproterozoic crust was injected by the eruption of K-rich volcanic rocks (Dokhan Volcanics) and emplacement of granitoid intrusions (El Shazly, Dixon, Engel, Abdeen-Meguid, & Stern, 1980; El-Bialy and Streck, 2009; Eyal, Litvinovsky, Jahn, Zanvilevich, & Katzir, 2010; Farahat and Azer, 2011; Johnson, Andresen, Collins, Fowler, Fritz, Ghebreab, Kusky, & Stern, 2011; El-Bialy; Hassen, 2012). The Dokhan type‐volcanics refer to a varicoloured thick sequence of non‐metamorphosed lava flows and pyroclastics with a wide range of (mafic to felsic) composition in association with ignimbritic rhyolites (El-Ramly, 1972; Basta, Kob, & Awadalla, 1980; Heikal, Higazy, & El Rahmany, 1980; Stern & Gottfried 1986 and Abdel Rahman 1996). Generally, the Dokhan Volcanics have been investigated petrologically, geochemically and even chronologically since the early 20th century by many authors (e.g. Basta et al., 1980; Akaad and Noweir, 1980; Stern and Hedge, 1985; Stern and Gottfried, 1986; Ragab, 1987; El-Gaby, Khudeir, & El-Taky, 1989; Abdel-Rahman, 1996).

The G. Nuqara study area, being a part of the ANS, is located in the central Eastern Desert (CED) in the west and southwest of Safaga City along the Red Sea coast. It is located between latitudes 26°35'29"N - 26°46'47"N and longitudes 33°45'50"E - 33°57'39"E covering an area of about 378.52 km² (figure 1A). The Dokhan Dokhan Volcanics assemblage with their relatively large geographic extent form a more or less circular outline of an area about 68 km². G. Nuqara is characterized by its very rugged topography with high peaks (834 m a.s.l.) and steep slopes. The drainage system representing the main Wadis (valleys) and the highest elevation points, as well as roads running through the study area are shown in figure (1B). The felsic rocks of G. Nuqara yield a Rb-Sr whole rock age of 581±7 Ma (Stern and Hedge, 1985), while the ages of the mafic rocks yield Rb-Sr whole rock of 686±28 Ma. Detailed geological studies and mapping
of the Nuqara volcanics, which form the topic of this contribution, are still controversial and sparse (Conoco Coral and EGPC, 1987; EGSMA, 1992; Ali, 1995; El-Mansi, Dardier, & Abdel Warith, 2003; Elbalakssy, Ali, & Elhusseiny, 2012). For example, two geological maps of scale (1: 50,000) are simplified after Conoco Coral and EGPC, 1987 and Ali (1995) (figure 2A) and EGSMA (1992) (figure 2B), to illustrate the variations and differences in the represented exposed rock units in geological maps, especially that of the Dokhan Volcanics. Controversial mapping extended even into the represented granitoid rocks in the two maps.

Figure 1A: Location map of G. Nuqara area, CED, Egypt.

Figure 1B: Physiographic map of G. Nuqara area, CED, Egypt.
Figure 2A: Simplified lithological map of G. Nuqara area, CED, Egypt, (Modified after Conoco Coral and EGPC, 1987 and Ali, 1995).

Figure 2B: Simplified lithological map of G. Nuqara area, CED, Egypt (Modified after EGS-MA, 1992).
The integration between the multispectral remote sensing data and the airborne gamma-ray spectrometry has been intensively used in lithological mapping to detect the potential radioactive zones in the Eastern Desert of Egypt (Nigm and Khameis, 2008; El-Sadek and Moussa, 2010; Sweha, 2014; Badr, 2017).

The present study aims to integrate and construct a detailed geological map of the G. Nuqara Dokhan Volcanics, and clarify the alteration zones and their potentiality for radioactivity. This is done by using Landsat-8 image processing and airborne Gamma-ray spectrometric data with fieldwork followed by laboratory work.

2. MATERIALS AND METHODS

A single Landsat-8 (LC81740422014188LGN00) L1T (terrain corrected) scene (path174/row 42), nearly cloud-free, covering the study area acquired on July 7, 2014, was obtained from USGS Earth Explorer site (http://earthexplorer.usgs.gov/). Landsat-8 data were collected by two-sensors, the Operational Land Imager (OLI) and the Thermal Infra-Red Sensor (TIRS). Respectively, these two instruments collect image data for nine shortwave and two longwave thermal bands. The pixel size of these bands was 15 meters for pan-chromatic, 30 meters for multispectral and 100 meters for thermal. The Landsat-8 image was radiometrically calibrated, atmospherically corrected using the Fast Line of Sight Atmospheric Analysis of Spectral Hypercube (FLAASH) and subset to fit the study area. In this study, only multispectral data (VNIR and SWIR) bands were used. The map projection was Universal Transverse Mercator (UTM) and the datum was WGS 84. Multispectral image enhancements comprising colour band combinations, principal component analysis, minimum noise fraction and band ratios were done. Alteration types resulting from band ratios were also investigated. ENVI software (version 5.3) was used in preprocessing and processing the scene.

The airborne gamma-ray spectrometric data of the study area was acquired in 1984. The survey was carried out along parallel flight lines oriented in a NE-SW direction at one km spacing, while the tie lines were flown in a NW-SE direction at 10 km intervals at a nominal flight altitude of 120m terrain clearance (Aerospace, 1984). All the aero-spectrometric data (TC, K, eU, and eTh values) were multiplied by 10. The data were processed and resulted in three radio elemental maps of eU, eTh and K besides four ternary maps used to clarify both lithological mapping and radioelements potentiality. These spectrometric data were also treated qualitatively and quantitatively to stand on the radioactive anomalies in the study area. The airborne gamma-ray spectrometric data were processed using Geo-sft Oasis Montaj software (version 8.4).

Digital elevation model and georeferenced data (geologic and topographic maps) were also used to extract the drainage system and topographic characteristics of the study area respectively. Statistical treatments for band ratios and radioelements data were done. The final products of the processed data were produced by Arc GIS software (version 10.5).

Fieldwork was carried out in several parts of the G. Nuqara Dokhan volcanics and its nearby areas to check the occurrence and spatial distribution of the lithological units. During the field work, the interpreted images were verified and sample collections of different varieties of the Dokhan Volcanics were carried out. The samples were petrographically studied to validate the image interpretations with the results of laboratory studies. Finally, accuracy assessment of the results of the field was checked and petrographic studies were done.

3. DATA PROCESSING

3.1. Landsat-8 Data Processing

3.1.1. Colour Band Composites (CBC)

The discrimination between different rocks in the area was achieved through an image combined bands 7, 5, 3 in RGB respectively (figure 3), the image represented different wavelengths (7 of SWIR, 5 of NIR, and 3 of visible green), hence it gave the highest variance (Jensen, 1986). This image discriminated the Dokhan Volcanics (lower and upper members) as a whole from the metavolcanics and younger gabbros. In addition, Phanerozoic sedimentary rocks were well discriminated and could be classified into two varieties: Cretaceous; Tertiary and Quaternary). However, it could not discriminate between the older granitoids and the younger granites.
3.1.2. Principal Component Analysis (PCA)

Principal component transformation is a multivariate statistical technique for simplifying a dataset by reducing multidimensional datasets to lower dimensions for analysis and for removing the redundancy of information that exists between the different bands to extract the pertinent information from them (Loughlin, 1991). Therefore, PCA displays the maximum contrast from several spectral bands with just three primary display colours, (Vincent, 1997). PCA is recommended as a good method in geological mapping (Crosta, Filho, Azevedo, & Brodie, 2003; Amer, Kusky, & Ghulam, 2010; Pour, Hashim, & van Genderen, 2013; Pour, Hashim, & Marghany, 2013; Rajendran, Nasir, Kusky, Ghulam, Gabr, & El-Ghali, 2013; Dawoud, Abdel Ghani, Elsaid, & Badr, 2017). PCA has been applied to the Landsat-8 scene and by checking the results of the eigenvalues of PC images, it was found that PC1, PC2, and PC3 contain total variance in the data. PC1 concentrate features common to all input bands (usually topography) often display important structural information. PC2 is orthogonal to PC1 in n directional space and highlights the spectral differences between visible and infrared spectral bands. PC3 includes the third most variability and is orthogonal to the other two PCs. The resulting PCA bands colour composite (Figure 4) delineates the metavolcanics and younger gabbros (greenish blue colour), the lower member (intermediate) of Dokhan Volcanics (yellowish green), the most upper member (rhyolites) of Dokhan Volcanics (dark blue colour) and Phanerozoic sedimentary rocks (both bright red and dark red colours) whereas the older granitoids and the younger granites can not be distinguished from each other (purple mottled with red colour).

Figure 3: False colour composite Landsat-8 bands 7, 5, 3 in RGB of the G. Nuqara area, CED, Egypt.

Figure 4: PCA colour composite of PC1, PC2 and PC3 in RGB of the G. Nuqara area, CED, Egypt.
3.1.3. Minimum Noise Fraction (MNF)

This method developed by Green, Berman, Switzer, & Craig (1988), is a principal component-like orthogonalization rotation that results in components ordered in increasing rank of random noise rather than decreasing rank of variance. So, the MNF transform is used to determine the inherent dimensionality of image data, to segregate and equalize the noise in the data, and to reduce the computational requirements for subsequent processing (R.S.I., 2003). In the multispectral image preprocessing stage, MNF and inverse MNF transformations were used for reducing noise in reflectance bands by avoiding Eigen images having eigen vector loadings less than unity, then recalculating surface reflectance data without noise. The first three Eigen images usually contain more than 98% of total eigen values and the colour composite of MNF1, MNF2 and MNF3 in RGB respectively provide a colourful image with least noise and highest variance (Figure 5). Regarding this image, two varieties of the Dokhan Volcanics are distinguished: 1) the lower member is composed of andesites, dacites, quartz-dacites and their related tuffs (dark purple colour), 2) the upper member including rhyodacite to rhyolite and related tuffs (purple colour). It was noticed that the third upper member of the Dokhan Volcanics (rhyolites and their equivalent related tuffs) could not be distinguished from the younger granites (reddish-orange colour) but they could be discriminated from the older granitoids (mottled yellowish brown colour). The metavolcanics appeared with mottled greenish blue colour whereas the younger gabbros exhibited with the mottled bluish green colour as their close similarity in mineral composition. The Phanerozoic sedimentary rocks are distinguished into two varieties; 1) upper Cretaceous (at G. Mohammed Rabbah and small outcrops capping the younger granites around Wadi El-Barud) with magenta colour and 2) Tertiary sedimentary rocks scattered along the eastern side of the area along the Red Sea coast (bright pink colour).

3.1.4. Band ratios

Band rationing is a data transformation technique used to enhance spectral differences between the image bands along with reducing topographic illumination effects (R.S.I., 2003). Dividing one spectral band by another produces an image that provides relative band intensities. Band ratios were widely applied in geological and alteration mineral mapping (Abrams et al., 1983; Sabins, 1987; El-Rakaiby, 1993; Abdelsalam et al., 2000; Abdeen et al., 2001; Rowan, Hook, Abrams, & Mars, 2003; Velosky, Stern, & Johnson, 2003; Xu, Lin, Shao, & Wang, 2004; and Badr, 2017). Band ratios of (B4/B2), (B5/B6) and (B6/B7) and their colour combination in RGB are created for the delineation of hydrothermal alteration zones (Figure 6). This composite image well distinguishes the younger granites (yellowish red and pink colours) from the older granitoids (brown mottled with magenta colour). In addition, the three varieties of the Dokhan Volcanics are well distinguished: 1) the lower member composed of andesites, dacites, quartz-dacites and their equivalent related tuffs (aqua marine and yellowish green colours), 2) the upper member including rhyodacite to rhyolite and their equivalent related tuffs (mixture of blue and magenta colours) and 3) the upper member are of rhyolites and their equivalent related tuffs (reddish brown colour). Band ratio B4/B2 enhanced iron oxides have absorption in Band 2 and show significant reflectance in Band 4. The threshold anomalies of this band ratio at 95% confidence (Figure 7) is exactly traced to the boundaries of both younger granites and Phanerozoic sedimentary rocks besides the younger granitic offshoots and felsic dykes cutting the other rocks, especially the older granitoids (northwestern part of the area) and the lower intermediate Dokhan Volcanics. Band ratio B5/B6 enhances ferromagnesian minerals and the threshold anomalies of this band ratio at 95% confidence (Figure 8) exactly trace the boundaries of the lower member Dokhan Volcanics and isolate them from the upper one and the other rock units of the study area. Band ratio B6/B7 enhances carbonates and OH-bearing minerals and the threshold anomalies of this band ratio at 95% confidence (Figure 9) roughly trace both the lower member Dokhan Volcanics and the Phanerozoic sedimentary rocks (especially G. Mohammed Rabbah) together.
(1) Metavolcanics; (2) Older granitoids; (3) Lower intermediate Dokhan volcanics; (4) Upper felsic rhyodacite Dokhan volcanics; (5) Younger gabbros; (6) Younger granites and Rhyolites (D.V.); (7) Phanerozoic Rocks (Cretaceous) and (8) Phanerozoic Rocks (Tertiary & Quaternary)

**Figure 5:** MNF colour composite of MNF1, MNF2, MNF3 in RGB of the G. Nuqara area, CED, Egypt.

**Figure 6:** Colour ratio composite of (B4/B2), (B5/B6), (B6/B7) in RGB of the G. Nuqara area, CED, Egypt.

**Figure 7:** Limonite minerals (Fe$^{3+}$) (B4/B2) of the G. Nuqara area, CED, Egypt (red zone is the expected threshold anomalies at 95% confidence).

**Figure 8:** Ferromagnesian minerals (Fe$^{2+}$) (B5/B6) of the G. Nuqara area, CED, Egypt (green zone is the expected threshold anomalies at 95% confidence).
3.2. Airborne Gamma-Ray Spectrometry

The airborne gamma-ray spectrometric data of the study area were processed and treated qualitatively and quantitatively. The qualitative interpretations resulted in three radioelement-maps as well as four ternary maps; whereas, the quantitative ones were used to clarify the radioelements contents of each rock unit.

3.2.1. Qualitative interpretation of the airborne gamma-ray spectrometric data.

Radioelements filled coloured contour maps comprising (eU in ppm), (eTh in ppm) and (K in %) are shown in Figs. 10 A, B and C. The concentration of eU (ppm), eTh (ppm) and K% may be classified into three levels. The younger granites, the Phanerozoic sedimentary rocks and the upper member felsic Dokhan Volcanics comprising rhyolites and related tuffs have the highest levels of eU, eTh, and K(31 to 52 ppm, 67 to 95 ppm and 25 to 32%, respectively). The older granitoids and the intermediate Dokhan Volcanics have intermediate levels of eU, eTh and K (15 to 30 ppm, 35 to 66 ppm and 13 to 24%, respectively) whereas the metavolcanics and the younger gabbros exhibit the lowest levels of eU, eTh and K% (5 to 14 ppm, 15 to 34 ppm and 5 – 12%, respectively). The Phanerozoic sedimentary rocks of G. Mohammed Rabbah are well discriminated as they have high eU levels and low levels of both eTh and K contents at the same time.
Figure 10A: Airborne radiometric contour map of uranium (eU in ppm) in the G. Nuqara area, CED, Egypt.

Figure 10B: Airborne radiometric contour map of thorium (eTh in ppm) in the G. Nuqara area, CED, Egypt.

Figure 10C: Airborne radiometric contour map of potassium (K %) in the G. Nuqara area, CED, Egypt.
Ternary maps are composite images which provide a simultaneous display of up to three parameters on one image and facilitate the correlation and delineation of areas based on subtle differences in the numerical values. In this case, the additive primary colours, red, green and blue (RGB) are used. The intensity of each colour depends on the concentration of the radio element. Black colour represents the low concentrations of all three elements while white colour reflects the high ones. These composite ternary maps are developed by the USGS (Duval, 1983).

Figure 11A shows the composite colour image of K%, eTh and eU in RGB, respectively. Blue colour represents high concentrations of eU and poor eTh + K%, green colour represents high eTh and poor eU+ K%; finally, red colour represents high K% and poor eU+eTh. It is clear that G. Mohammed Rabbah (Phanerozoic sedimentary rocks) has high concentrations of eU-content in addition to small spots in younger granites and felsic Dokhan Volcanics. This interpretation is confirmed by the uranium ternary composite image (eU, eU/eTh and eU/K in RGB) shown in Figure 11B.

The potassium composite image (Figure 11C) shows that the highest K-concentration (white colour) is only associated with the younger granites, felsic Dokhan Volcanics (rhyolites and their related tuffs) whereas the Phanerozoic sedimentary rocks show the lowest K-concentrations in the study area. The thorium composite image (Figure 11D) emphasizes the relative distribution of thorium and highlights areas of thorium enrichment. The highest eTh concentrations (white and red colours) are only associated with the younger granites and felsic Dokhan Volcanics. However, the Phanerozoic sedimentary rocks have the lowest eTh contents.

Figure 11A: Radioelements composite image (K, eTh and eU in RGB) of the G. Nuqara area, CED, Egypt.

Figure 11B: Uranium composite image (eU, eU/eTh and eU/K in RGB) of the G. Nuqara area, CED, Egypt.
3.2.2. Quantitative interpretation of the airborne gamma-ray spectrometric data.

The average equivalent uranium (eU) and equivalent thorium (eTh) abundances in felsic intrusive and extrusive rocks, such as granites and rhyolites, are 4.5 and 15.7 ppm, respectively (Boyle, 1982). The minimum, maximum and average of the eU (ppm), eTh (ppm) and K% as well as the ratios eU/eTh and eTh/eU of each rock unit cropped out in the study area are shown in Table 1 and Figure 12. It is clear that the average contents of the radio element distribution of all rock types are mostly within normal range. The meta volcanics and the lower intermediate member of the Dokhan Volcanics show relative high values of eU, eTh and K due to their location adjacent to the younger granites and the common presence of younger granites offshoots into them confirming uranium redistribution. Regarding the eU/eTh values, all the rock units have averages of about 0.5 except that of the Phanerozoic sedimentary rocks (G. Mohammed Rabbah) which has an average of more than 1.5. This may be attributed to the presence of Phosphatic bands intercalated with Nubian Sandstone and Dakhla Formation. This was also confirmed with the eTh/eU averages of the studied rock units.
Table 1: $eU$, $eTh$, $K\%$, $eU/eTh$ and $eTh/eU$ of the different rocks at the G. Nuqara area, CED, Egypt

<table>
<thead>
<tr>
<th>Rock type</th>
<th>eU (ppm)</th>
<th>eTh (ppm)</th>
<th>K %</th>
<th>eU/eTh</th>
<th>eTh/eU</th>
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<td><strong>Phanerozoic Sedimentary rocks</strong></td>
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<td>12.15</td>
<td>1.59</td>
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<tr>
<td></td>
<td>Maximum</td>
<td>65.07</td>
<td>124.48</td>
<td>31.16</td>
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<td>47.46</td>
<td>15.64</td>
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<td></td>
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<td>36.60</td>
<td>11.14</td>
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<tr>
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<td>Maximum</td>
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<td>32.39</td>
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<td></td>
<td>Average</td>
<td>29.74</td>
<td>69.89</td>
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<tr>
<td><strong>Rhyolites and related tuffs</strong></td>
<td>Minimum</td>
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<td>37.64</td>
<td>10.35</td>
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<tr>
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<tr>
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<td>Average</td>
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<td>71.46</td>
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<tr>
<td><strong>Rhyodacites and related tuffs</strong></td>
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<td>33.95</td>
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<tr>
<td></td>
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<td></td>
<td>Average</td>
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<tr>
<td><strong>Andesites, Dacites and related tuffs</strong></td>
<td>Minimum</td>
<td>1.96</td>
<td>19.84</td>
<td>6.27</td>
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<tr>
<td></td>
<td>Maximum</td>
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<td>180.77</td>
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<td>Average</td>
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<td>48.73</td>
<td>17.15</td>
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<td><strong>Older Granitoids</strong></td>
<td>Minimum</td>
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<td>12.35</td>
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<td></td>
<td>Maximum</td>
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<td>100.39</td>
<td>36.00</td>
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<td></td>
<td>Average</td>
<td>14.64</td>
<td>33.31</td>
<td>12.42</td>
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Figure 12: Bar diagrams showing the minimum, maximum and averages of eU, eTh, K%, eU/eTh and eTh/eU in the different rocks of G. Nuqara area, CED, Egypt.
4. FIELDWORK AND PETROGRAPHIC VERIFICATION

Based on fieldwork investigations, spatial distribution and contact relationships, the main rock units of the study area are represented by metavolcanics, older granitoids, Dokhan Volcanics, younger gabbrs, younger granites as well as Phanerozoic sedimentary rocks.

The metavolcanic association represents the oldest rock unit in the study area. It consists of a deformed succession of mafic to intermediate volcanic rocks and volcanoclastics (metabasalts, meta-andesites and their metapyroclastics) that have been regionally metamorphosed into green-schist facies. This metavolcanics are intruded by the older granitoids, the younger gabbros and younger granites.

The older granitoids are the dominant rock unit at the G. Nuqara area. They intrude the metavolcanics, carrying them as roof pendants, and contain several xenoliths of them. The younger gabbros and the younger granites intrude the older granitoids, where the intrusive bodies send offshoots into the skirting older granitoids. The syn-tectonic older granitoids are mainly represented by tonalite to quartz-diorite and granodiorite. This granite suite is coarse- to medium-grained, light gray in colour and encloses few mafic enclaves. Spatially, it is sheared and foliated.

The Dokhan volcanics (the main target of this study) are represented by G. Nuqara, which represents a conspicuous rock unit west of Safaga City covering an area about 68 km². They are characterized by their high relief with sharp peaks and steep slopes (Figure 13A) as well as conspicuous columnar jointing. The Dokhan Volcanics are intruded westward by younger granites where the shared contact is sharp and intrusive (Figure 13B). Along with their contacts, the younger granites send several offshoots of different thickness into them (Figure 13C) and host xenoliths of different shapes and sizes. On the other hand, the Dokhan Volcanics are unconformably overlain eastward by Phanerozoic sedimentary rocks. The studied Dokhan Volcanics can be subdivided into two subunits: the intermediate Volcanics and the felsic one. The intermediate subunit covers an area about 51.7 km² and is characterized by light to dark grey colours, while the felsic one covers an area about 16.3 km² with faint to reddish pink colours. The intermediate Dokhan volcanics are conformably overlain by the felsic volcanics (Figure 13D). The felsic subunit can be classified, according to the Landsat imagery processing results, into two varieties. The first one is characterized by its relics of tuffaceous structure which are scattered and cap the intermediate varieties, mostly south of Wadi El-Barud; whereas, the other one is characterized by flow structure and located north around Wadi El-Barud. Compared with the felsic Dokhan Volcanics, the intermediate ones are: 1) highly weathered particularly along the eastern periphery along the Red Sea coast, 2) possess several vesicles, especially near contacts, which sometimes are filled with carbonates, chlorite and quartz forming amygdales of different shapes and sizes, and 3) show conspicuous porphyritic textures. The pyroclastics of both subunits contain fragments varying in size from ash to lapilli and sometimes to bombs or huge rock fragments. Tuffs sometimes show kinked lamination; some of these laminae become brick red because of staining from iron oxy-hydroxides. Both Dokhan Volcanic subunits enclose xenoliths of different shapes and sizes from meta volcanics, especially near the southern contacts. It is worth to mention that the felsic varieties enclose xenoliths that are commonly of andesitic composition, suggesting that the felsic Dokhan volcanics are younger than the intermediate ones.

The younger gabbros intrude the older granitoids and carry several roof pendants of them. They are of limited distribution forming low terrains and are mainly represented by hornblende gabbros.

The younger granites occur as elongated belts bordering the Dokhan Volcanics from the south, west and north. They intrude all the previously mentioned rock units. This granitic belt is affected by a dextral fault running nearly E-W along Wadi Um Taghir. They are mainly represented by monzogranites and alkali-feldspar granites. All the earlier mentioned rock units are capped with the Phanerozoic sedimentary rocks, especially the Dokhan volcanics (Figure 13E) along the Red Sea coast as well as sporadic masses capping the younger granites.
along Wadi El-Barud, in addition to G. Mohammed Rabbah which caps the metavolcanics. All the Dokhan Volcanic masses as well as the surrounding rock units are dissected by felsic and mafic dyke swarms extending for several kilometers in NE-SW and NW-SE trends. The felsic dykes resist weathering more than the surrounding rocks and consequently appear as ridges and spines (Figure 13F). On the other hand, the mafic dykes are less resistant to weathering forming negative relief features.

**Figure 13:** Field characteristics of Dokhan volcanics of G. Nuqara area, CED, Egypt
A) G. Nuqara Dokhan Volcanics with its high relief, sharp peaks and steep slopes, B) Sharp intrusive contact between younger granites (YGR) and intermediate lower Dokhan volcanics (LDV), C) Offshoot of younger granites (YGR) cutting through the intermediate Dokhan volcanics (LDV) which capped with the Phanerozoic sediments (PHS), D) Felsic upper Dokhan volcanics (UDV) upon the intermediate lower Dokhan volcanics (LDV), E) Phanerozoic sediments (PHS) capping the intermediate Dokhan volcanics (LDV) and F) Quartz-feldspar porphyry dykes (QFPD) resist weathering more than the surrounding older granitoids (OGR) and consequently appear as ridges and spines.
The petrographic characteristics of the Dokhan Volcanics are discussed as in the following:
The lower Dokhan Volcanics member (intermediate) are mainly represented by andesites, dacites and quartz-dacites besides their equivalent tuffs. They show ophitic, sub-ophitic, porphyritic and sometimes show flow textures Figures 14A, B & C. The main mineral components of these rocks are plagioclase (An$_{20}$–An$_{35}$), pyroxene, hornblende, opaque and rare biotite and quartz. Their tuffs are crystal lithic to lithic crystal tuffs that sometimes show significant flow textures Figures 14D, E & F).

Figure 14: Photomicrographs showing the Petrographic characteristics of intermediate Dokhan volcanics and their related tuffs A) Sub-ophitic texture in porphyritic andesite, C.N., B) Plagioclase phenocrysts (PL) forming porphyritic texture in dacite, C.N., C) Plagioclase (PL) and quartz phenocrysts (QZ) in quartz-dacite, C.N., D) Quartz crystals (QZ) and dacitic lithic fragments (DC) in crystal lithic tuffs, C.N., E&F) Flow texture in lithic crystal tuffs of intermediate composition where the lithic fragments are of andesitic (AND) and dacitic (DC) composition besides quartz crystals (QZ), PL and C.N.
The upper felsic member is represented by rhyodacites, rhyolites and their related tuffs. They show porphyritic, micrographic and spherulitic textures (Figure 15A). The main mineral components of these rocks are k-feldspars (mostly sanidine with minor orthoclase), quartz, plagioclase (An\textsubscript{5} - An\textsubscript{15}), biotite and opaques. Common accessories are apatite, zircon and titanite (Figure 15B). The rhyolites are characterized by the common presence of spherulitic textures (Figure 15C). Some of these rocks are crushed especially along fault planes and near the younger granites contacts where titanite mineralis are predominant, especially around the opaques. In addition, along with fractured felsic volcanics, especially near the contacts with younger granites, radioactive minerals, such as uranophane is recorded (Figure 15D). The felsic tuffs show different sizes of crystal and lithic fragments ranging from lapilli to agglomerate. Some of these tuffs show banding and rarely show flow textures.

5. CONCLUSIONS

The spectral analysis of Landsat data at G. Nuqara area revealed results that prove the great capability of remote sensing techniques in lithological discrimination. The false colour composites (B7, B5, B3 in RGB) enhanced visualization of the lithological units in the study area. The Principal Component Analysis (PCA) highlighted the subtle spectral differences between different rock units within the study area. Band ratios 4/2, 5/6 and 6/7 are effective in delineating the hydrothermal alteration zones in the study area. Minimum noise fraction (MNF) transformation is also very successful in lithological discrimination in the study area through combining the MNFs whose highest eigenvalue percentages (1, 2 and 3 in RGB) as false colour composite images. The younger granites are well discriminated and appear as belts at the west of the Dokhan Volcanics. Landsat-8 processed data clearly mapped the different types of the exposed Dokhan
Volcanic rocks. The Dokhan Volcanics are discriminated into two members: intermediate Volcanics and felsicones, with three lithological varieties. The lower intermediate Dokhan Volcanics are mainly represented by andesites, dacites and quartz-dacites, besides their equivalent tuffs (crystal lithic to lithic crystal tuffs), are conformably overlain by the upper felsic volcanics. The felsic subunit may be classified, according to the Landsat imagery processing results, into two varieties. The first one is characterized by its relicts of tuffaceous structures which are scattered and cap the intermediate varieties, mostly south of Wadi El-Barud; whereas, the other one is characterized by flow structure and located north around Wadi El-Barud.

The airborne radiometric data participate in the lithological mapping of the exposed rock units. All the radioelement images can well discriminate the metavolcanics and the older granitoids as well as the younger gabbros (relatively lower radioactivity) from the other rock units (relatively higher radioactivity). K % image well discriminates the older granitoids and the metavolcanics from the other rock units (younger granites, the felsic variety of Dokhan Volcanics and most of the Phanerozoic sedimentary rocks) that exhibit relatively high to moderate K-content. eU (ppm) image has the ability to discriminate the sedimentary rocks of G. Mohammed Rabbah relative to the other radioelement images as it has a relatively high uranium content with low thorium- and potassium-contents. Also, the airborne gamma-ray spectrometric maps provide promising uranium potentiality at: 1) G. Mohammed Rabbah (Phanerozoic rocks) south of the study area which may be attributed to the presence of intercalated phosphatic layers with sandstone and shales or capping them, 2) the younger granites along Wadi El-Barud and 3) three sites in the felsic member of Dokhan Volcanics.

The integrated methods used in this study include Landsat-8 image and airborne radioelement processing followed by field investigations and detailed petrographic study that resulted in a geological map (figure 16) with an accuracy 88.43 % with a kappa coefficient value of 0.825.

The used integrated methods showed compatibility of the results for the rock units discrimination and their radioactive potentiality through locating the anomalous radioactive zones. This reflects the need of using multiple ways and methods to obtain confirmatory data and qualified results. Contribution of the remote sensing techniques with detailed geological and petrographical studies for the regions of the Egyptian Dokhan Volcanics is recommended.

Figure 16: The Constructed geological map of G. Nuqara area, CED, Egypt.
REFERENCES


El Ramly, M.F. (1972). A new geological map for the base-
ment rocks in the Eastern and South-Eastern deserts of Egypt, scale 1: 1,000,000 Ann. Geol. Surv. Egypt, 2, 1 -11.


