Gamma-ray spectrometric survey for mineral exploration at Baljurashi area, Saudi Arabia

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ABSTRACT

Mineral resources exploration in the Kingdom of Saudi Arabia became an important target for the Saudi government. Nowadays, the economic vision of the country is to move away from oil-based country to multisource energy-based country. In Baljurashi area there were ancient mines for Copper, Cobalt, Magnesium, Zircon, and some other minerals. In the current study, we aim to evaluate the Baljurashi area in terms of mineral resources using the advanced technique. Consequently, we carried out ground gamma ray spectrometry survey in an area of about 50 km², elevation variation ranges from 380 m to 2280 m above the sea level. We used the RS-700 system to collect the gamma ray spectrometry data. In addition, we used the existing geochemical analysis results for this area and integrated the results to map the most important minerals. The integration work indicates that the area of Baljurashi is rich in mineral resources. The mineralization zones are located in the eastern part of the area where elevation is high (e.g., east of the escarpment). We also found that these mineralization zones are structurally controlled. Important mineral maps were produced (e.g., Cu, Cr, Mn, and Zr). We highly recommend more geophysical studies to evaluate the Baljurashi area for mineral identifications and quantifications.

1. Introduction

Mineral exploration in the Kingdom of Saudi Arabia became a major target for the Saudi government. It has a significant role in moving Saudi Arabia away from hydrocarbon-based economy. The media sector announced that Saudi Arabia will invest around 3.8 USD billion to enhance access to geoscience data and reduce regulatory to boost mineral exploration (https://www.arabnews.com/node/1448011/business-economy). Saudi Arabia’s central and northern regions contain large amounts of bauxite, zinc, copper, magnesite, and kaolin deposits. It also hosted some of the world’s largest stock of phosphate and tantalum, and of up to 20 Moz of gold in known deposits.

The current research focused on using the ground gamma-ray spectrometric survey to evaluate the mineral resources in Baljurashi area. In that regard, on December 8–10, 2019, a teamwork from King Abdulaziz University (KAU) and King Abdulaziz City for Science and Technology (KACST) carried out ground gamma-ray spectrometric survey using the RS-700 gamma-ray spectrometer instrument in Baljurashi area, Al Baha region, Saudi Arabia.

Gamma ray spectrometric data are good indicators for minerals that contain radioactive elements (e.g., Uranium, Thorium, and Potassium). For example, phosphate deposits have high uranium concentration; they thus can be located by mapping uranium. Gamma-ray spectrometric surveys can be used for geological mapping (Charbonneau et al., 1997; Darnley & Ford, 1989; Graham & Bonham-Carter, 1993; Jaques et al., 1997), lithological mapping units (IAEA, 2003), and environmental monitoring (Aboud et al., 2019). It is a surface mapping technique, penetrating only the top 50 cm or so of the earth’s surface. It works by measuring the gamma-ray which the radioactive isotopes of these elements emit during radioactive decay.

The interpretation of radioelement distribution for mapping surface geology assumes that different rock types are composed of certain amounts of rock-forming minerals, which comprise specific quantities of radioactive elements (Elawadi et al., 2004). The relationship between the radioelement content of the surficial material and the composition of the bedrock must be inferred from consideration of complementary evidence, provided by geological maps, satellite imagery, or ground inspection.

In the current study, we covered the Baljurashi area with ground gamma-ray spectrometry survey using the RS-700 instrument. Fortunately, Greenwood...
Table 1. Radioactive minerals and occurrences (Telford, 1982).

| Potassium minerals | Occurrence (K) |
|--------------------|----------------|
| (i) Orthoclase and microcline feldspars [KAlSi3O8] |
| (ii) Muscovite [Al[Si3O10](OH)2] |
| (iii) Alunite [K2Al2(AlSi3O10)(OH)6] |
| (iv) Sylvinite, carnallite [KCl, MgCl2·6H2O] |

(1975a) collected 137 wadi sand/rock/vein samples and performed geochemical analysis too. Herein, these rock samples will be integrated with the gamma-ray results in map the economic minerals.

2. Gamma ray and mineral exploration

All rocks and soils contain radioactive isotopes, and almost all the gamma-ray detected near the earth’s surface are the result of the natural radioactive decay of the radioactive elements (e.g., Uranium, Thorium, and Potassium). The gamma-rays are packets of electromagnetic radiation characterized by their high frequency and energy. They are sensitive to a layer thickness of approximately 50 cm through rock and several hundred meters through the air. The common radioactive minerals are Uraninite (UO2), Monazite (PO4), Zircon (ZrSiO4) in granite rocks, feldspar ([40K], Muscovite [KAl2(Si2AlO10)(OH)6], Sylvinite (KCl) in acid igneous rocks, and radiocarbon (14C), and Thorite (ThSiO4), Cheralite (SiO2PO4) rich in Potassium. Table 1 shows the overview of radioactive minerals and occurrences. Exploration for these minerals by radiometric survey became important because of the demand for nuclear fuels and also for detection of associated nonradioactive deposits such as Titanium and Zircon.

3. Geological outlines

3.1. Location and topography

The Baljurashi quadrangle, sheet 19/41 B, is located between lat. 19° 30’ and 20° 00’ and long 41° 30’ and 42° 00’ as shown in Figure 1. It encompasses an area of about 3000 km² where the Baljurashi is the largest town. The rugged Red Sea escarpment divides the Baljurashi quadrangle roughly into halves. The area north and east of the escarp is a part of north ‘Asir province’ and that south the escarp is of the scarp mountains. The Asir province is a dissected plateau that slopes gently eastward, whereas the scarp mountains are a complex physiographic region including a dissected mature upland plateau at about 800 m altitude and broad youthful wadis at 380–600 m. Topography in the Baljurashi area varies in high range as from 380 to 2260 m above the sea level.

3.2. Geological settings

The geology of the Baljurashi area (Figures 2 & 3) was studied by Greenwood (1975a); Anderson (1977); Greenwood et al. (1980); Prinz (1983); Greenwood et al. (1986); Johnson and Woldehaimanot (2003); Al-Shanti
Metamorphosed basalt  
Meta-andesitic coarse clastic
Graywacke, and chert  
Baish and Baha Group
Greenschist facies  
Jiddah and Ablah Groups

Figure 2. Sketch map of the pre cambrian rocks in Baljurashi area, Saudi Arabia.

(2009). Herein, we summarized the general geology in the following section.

The Baljurashi quadrangle sheet is underlain by two major assemblages of Precambrian rock: 1) metamorphosed basalt, graywacke, and chert of the Baish and Baha Group, 2) a meta-andesitic coarse clastic assemblage consisting of two sequences, the Jiddah (sometimes written Jeddah) and Ablah Groups. The Baish, Baha, and Jiddah Groups are folded, metamorphosed to greenschist facies, and intruded by gabbroic to quartz dioritic plutons about 960 My ago during the Aqiq orogeny. Rocks of the Ablah Group were deposited unconformably on older dioritic and layered rocks. Dioritic to quartz dioritic plutonism recurred during early phases of the Ranyah orogeny about 800 My ago. Domal intrusion of granodioritic orthogneiss later during the orogeny resulted in amphibolite facies metamorphism in layered rocks on the flanks of the domes.

Late tectonic and post tectonic granitic plutons were emplaced during a waning phase of the Ranyah orogeny. The volcanism, sedimentation, tectonism, metamorphism, and plutonism observed in the Baljurashi quadrangle are features of the Hijaz tectonic cycle. The continental crust of the southern part of the Arabian shield appears to have been produced during the Hijaz tectonic cycle.

Cenozoic basalt flows and cinder cones are associated with local fissure of northerly trend. The basalts are slightly dissected, are younger than the erosion surface at an altitude of 800 m and occupy the present draining.

3.3. Mineralization in Baljurashi

Baljurashi area has several ancient mines and prospects, Bubir mine, Al Wakabah mine, Sha’ib As Sut and Wahdid prospect, Al Kutayn pit, Northeast unnamed pit, Iron formation prospect, Wadi Ranyah copper prospect, and A’dema Ash Shamran-Shaqiq-Thurayban prospect. Copper is the dominant element in these mineralized deposits. Some of the mineralized deposits are veins that cut the host rock (e.g., Bubir mine), but most are small, narrow deposits in and adjacent to beds and lenses of marble interbedded in the Qirshah andesites. Red jasper is commonly associated with the copper deposits and cobbles of eroded jasper in the Rafa formation indicate that the deposits are older than that unit. The deposits are parallel to foliation of the enclosing rocks; mineralization may be syngentic, although some of the mineralized rocks are along fracture zones, which suggests epigenetic replacement of the marble (Greenwood, 1975a).

4. Data source

During the current study, Gamma-ray spectrometry data using the RS-700 system were collected. The RS-700 is a self-contained gamma ray radiation detection and monitoring system. It can be used in land vehicles, helicopters, UAVs, or at a fixed location. The system has a built-in GPS receiver to accurately locate each measurement. It is also supplied with software for user control, monitoring and recording. The system is flexible enough to permit real-time monitoring with a computer or operate in a standalone configuration with the data being recorded internally and later retrieved. Figure 4 shows the RS-700 system while using in the field.

5. Data processing and interpretation

Once data exported from RS-700 system as excel sheets, it is ready for processing and interpretation. Data was simply processed as removing some spikes and out of range values. Then, radioelement maps (equivalent Uranium, eU; equivalent Thorium, eTh; and Potassium percentage, %K) showing the surface distribution of these elements are produced. We used Oasis montaj program (ver 8.5) to generate the radioelements maps. In addition, ratio maps (eU/eTh, eU/K, eTh/K) maps are also generated.

It is worthy to state that during the gamma-ray survey we were not able to cover the whole area as we were using carborne system. So, maps were generated using minimum curvature interpolation gridding.

5.1. Total count map, Tc

The TC map (Figure 5) shows the distribution of the whole radiometric elements (eU, eTh, and K) in Baljurashi quadrangle. It shows that high Tc values (>1500 cps) as pink color are in the central part of the study area toward the north. It also can be recognized that these high Tc anomalies are bounded by set of
geological faults (dimmed black lines in Figure 3) which implying that the Tc anomalies are structurally controlled. Geologically, these high anomalies are associated with intrusive rocks (e.g., metagabbro, diorite, orthogneiss, granite, and muscovite) while the low anomalies are associated with Cenozoic rocks.

5.2. Equivalent uranium (eU) map

The eU map is displayed in Figure 5. It shows that the maximum value of eU is >3.3 ppm where the minimum value is < 1.4 ppm. Uranium values are indicators for radioactive mineralization zones. The Baljurashi area in general can be divided into two parts, in terms of eU,

Figure 3. Geological map of the Baljurashi quadrangle area (modified after Greenwood et al., 1980). Three field photos show the varies sizable dikes in the area of study.
Figure 4. Upper left: The RS-700 system on the roof of the car; lower left: sketch of the design survey; upper right: live data recording system; lower right: histogram statistics of the collected data (Total count).

Figure 5. Upper left: Tc map for Baljurashi area. Black dimmed lines show the mapped faults from Greenwood (1975a). Solid line shows the escarpment edge. upper right: Equivalent Uranium (eU) map, lower left: Equivalent Thorium (eTh) map, lower right: Equivalent distribution of Potassium percentage (%K).
north-central and south-sideral part as high (pink color) and low (blue color), respectively. Two important anomalies, eU1 and eU2, with surface area of about 80 km$^2$ and 97 km$^2$, respectively.

### 5.3. Equivalent thorium (eTh) map

The eTh map is displayed in Figure 5. Concentration values of the eTh varies from 2.1 to 11.0 ppm and it looks like eU map (Figure 3). However, it looks as structurally controlled when have a look at Tc, eU and eU map. Three high thorium concentration, eTh1, eTh2, and eTh3 with area of 254 km$^2$, 26 km$^2$, and 25 km$^2$, respectively, are recommended for further studies.

### 5.4. Potassium (%K) map

Potassium percentage (%K) map is displayed in Figure 5. It shows that the concentration of radioactive potassium (40k) ranges from 1 to 4.4% in Baljurashi area which indicates that economic mineral may be existed. Most of this percentage is located along an area trending NW and similar like eU distribution (Figure 3). Four high concentration potassium anomalies, K1, K2, K3, and K4 with areas of 39, 42, 14, and 31 km$^2$, respectively, are recommended for more study.

### 5.5. Ratios maps

Ratios maps show the amount of radioelement distribution related to others. Figure 6 shows the ratio maps of eU/eTh, eU/k, and K/eTh for Baljurashi area. Careful looking to the ratio maps, it can be observed that eU related to eTh is much larger at the eastern and some patches in the western parts of the map. Also, when looking for eU with Potassium, eU is much larger than K in the eastern portion of the map. However, it can be recognized that potassium percentage on the western part of the map comparing with eTh is much larger.

### 6. Geochemical data

Greenwood (1975a) collected various samples types for geochemical analysis from Baljurashi area consisting
mostly of sampling wadi sand/rock/veins. A total rock/sand sample of 137 were collected as shown in Figure 1. These samples are 99 wadi sand samples, 28 rock samples, and 10 vein material samples. Semiquantitative spectrographic methods were used in the laboratory of the Ministry of Petroleum and Mineral Resources at Jiddah to obtain the mass concentration of 20 elements in ppm unit. The wadi sand samples were collected 14 to 28 cm below the surface and then sieved. Magnetite was separated magnetically from the sieved fraction and analyzed by standard colorimetric techniques for copper, zinc, and molybdenum. Herein, we are trying to re-analyze these samples using advanced technique and generate geochemical maps showing the distribution of the mineral deposits in the study area.

Based on the geochemical analysis of the samples, it can be recognized that most of the minerals are located at the eastern side of Baljurashi quadrangle where the elevations are very high (>2000 m). The most abundant minerals in Baljurashi quadrangle are Barium (Ba), Copper (Cu), Chrome (Cr) Manganese (Mn), and Zircon. Figure 7 shows the concentration of such minerals in the Baljurashi area based on the geochemical data. It should be stated that Mo mineral has a very limited ppm (<15). In addition, Figure 8 shows the maps of the above-mentioned dominated minerals.

7. Discussion and conclusion
The current study indicates that ground gamma-ray spectrometry survey with the help of geochemical data highly contributed to mineral exploration. It can be, in general, divide the area into two parts east and west of escarpment where the elevation varies from 380 m to 2260 m. This elevated ranges could be the main reasons for mineralization zones. From this study, the following remarks can be concluded:

1. The mineralization zones are structurally controlled as shown in Figure 4 where the high gamma ray anomalies are bounded by the main geological faults.
2. The occurrences of eU, eTh, and K are abundant in the area and located at few sites in Baljurashi quadrangle (northern, central). Table 2 shows the interested areas.
3. When looking at the ratio maps (Figure 5), it can be stated that eU occurrences related to K is much higher at the eastern side of the map. Similar results are shown in eU/eTh map. Ratio maps show which radioelement percentage is more than the other. When looking at K/eTh, it can state that the potassium percentage is higher than eTh percentage which reflects the rock types of that locality.
4. Geochemical statistics indicate that the area contains economic minerals (e.g., Copper, Chrome, Manganous, and Zircon) near the ancient mines which means these mines should be reevaluated.

5. Geochemical map (Figure 8) indicates that the area is enriched of Copper, Chromium, Magnesium, and Zirconium. Most of all these mineralization zones are located in the eastern side of the area where eU/eTh and eU/k are higher.

6. In terms of quantity, it can be stated that the Manganese is abundant all over the area, especially the eastern part of the escarpment.

8. Recommendations

This work was an idea between Geohazard Research Center (GRC) at KAU and National Center for Mining Technology (NCMT), KACST to overview the mineral resources in Baljurashi area. We covered the area of interest with ground gamma-ray spectrometry. Of course, some places were not accessible which means some interpolation in the maps were added. Based on that, we recommend airborne/drone magnetic and gamma-ray survey on the eastern side of the escarpment area where ancient mines are located. Also, detailed geochemical work is very important where collecting more than 500 wadi/rock/vein samples (e.g.,

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Table 2. The target anomalies of radioelements and its percentage of the area of study.

| Anomaly Factor | eU (ppm) | eTh (ppm) | K (%) |
|----------------|---------|---------|------|
| eTh1          | 80      | 97      | 254  |
| eTh2          | 254     | 26      | 25   |
| eTh3          | 39      | 42      | 14   |
| eTh4          | 14      | 31      | 4    |

| Size (km²)    | Total area (km²) | % of the study area |
|---------------|------------------|---------------------|
| 80            | 177              | 6%                  |
| 97            | 305              | 10%                 |
| 254           | 126              | 4%                  |

Figure 8. Map of Cupper (Cu), Chrome (Cr), Manganous (Mn), and Zircon (Zr) distribution in Baljurashi area as from the geochemical study of Greenwood (1975a). Large circle means more distribution.
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Disclosure statement

No potential conflict of interest was reported by the authors.

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