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Ground Radiometric Method as a Tool for Determining the Surface Boundary of a Buried Bauxitic Karst

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استخدام القياسات الإشعاعية الأرضية في تعيين الحدود السطحية لخسفات البوكسايت المدفونة

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ملخص: تم أخذ 42 قياساً للخلفية الأشعاعية على طول 9 مسارات ضمن شبكة مستطيلة الشكل تقع مباشرة فوق أحد الخسفات البوكسايتية ضمن تكوين العبيد (الجوراسي الأسفل) في الصحراء الغربية من العراق. تم استخدام مطياف أشعة غاما ذي ألأربع قنوات، والمزود ببلورة يوديد الصوديوم حقلياً لقياس النشاط الإشعاعي الكلي في التربة السطحية. تم جمعت عينات من التربة السطحية عند كل نقطة قياس ، بالإضافة الى عينات لبابية تم جمعها من بئر اختباري يخترق الخسفة ، وحللت بأشعة غاما الطيفية. الهدف الرئيس من هذه الدراسة هو كشف بالبوكسايت الخسفي، وتحديد الحدود السطحية للخسفة. تراوح النشاط الإشعاعي على سطح الخسفة البوكسايتية من 60-80 عدة/ دقيقة، بينما تراوحت الخلفية الإشعاعية لتكوين العبيد الذي يحتضن الخسفة من 100 – 150 عدة/ دقيقة. عمليات التجوية الكيمياوية وخاصة الإذابة والشطف نقلت اليورانيوم - 238 والثوريوم-232 من صخور الغطاء باتجاه الأسفل. تبعاً لذلك فان هذه العناصر امتزت على اسطح المعادن الطينية والبوكسايت المدفون على عمق 5م تقريبا مما سبب اغناء هذا النطاق بالنشاط الإشعاعي. أصبحت صخور الغطاء المشطوفة ناضبة من العناصر المشعة ، لذلك كان نشاطها الإشعاعي أقل من مستوى الخلفية الإشعاعية. بين التحليل الطيفي لأشعة غاما أن قيم النشاط الإشعاعي لليورانيوم- 238 والثوريوم-232 في صخور الغطاء 0.5 – 3 بيكرل / كغم, في حين بلغت 240 – 260 بيكرل / كغم في البوكسايت وطبقة الطين الفلنتي على التوالي. بالاعتماد على تباين الشذوذ الإشعاعي على السطح ، رسمت خريطة تساوي الإشعاع ، ومنها تم تحديد قطر الخسفة البوكسايتية الذي يمثل الشذوذ الإشعاعي الأقل، والذي تراوح من 150 – 200 م. تبرهن الدراسة الحالية أن طريقة قياس الخلفية الإشعاعية الأرضية مفيدة جداً للكشف عن وجود الخسفات البوكسايتية وتحديد حدودها السطحية.

ABSTRACT: Forty two ground radiometric measurements along nine traverses within a rectangular network area were taken across a bauxitic karst within the Ubaid Formation (Lower Jurassic) in the Western Desert of Iraq. A 4-Channel Gamma Ray Spectrometer (GAD-6) with sodium iodide NaI (Tl) crystal (GSP-4S) was used in the field to measure the total radioactivity of the surface soil. Soil samples collected from the surface at each measurement point and core samples collected from a test well penetrating the karst were analyzed by Gamma ray spectrometer. The main objective of this study was to detect the hidden bauxitic karst and determine its surface boundary. The radioactivity on the surface of the karst was ranging between 60 and 80 count per second (c/s), while the background radioactivity of the Ubaid Formation, which hosts the karst, was ranging between 100 and150 c/s. Chemical weathering, especially dissolution and leaching moved uranium (^{238}U) and thorium (^{232}Th) from the overburden downward. Accordingly, these elements have been adsorbed on the surface of clay minerals and bauxite buried at a depth of about 5m causing enrichment with radioactivity. The leached overburden lack radioelements, so its radioactivity was less than background radioactivity level. The gamma ray spectroanalysis showed that the radioactivity of ^{238}U and ^{232}Th in the overburden was 0.5 and 3 Bq/Kg, whereas, in the bauxite and flint clay bed, it was 240 and 160 Bq/Kg respectively. Based on the radioactivity anomaly contrast on the surface, an isorad map was plotted and the karst diameter which represents low anomaly was determined to be ranging from 150 to 200m. The current study demonstrates that the ground radiometric method is quite useful for detecting the bauxitic karst and inferring its surface boundaries.

KEYWORDS: Radiation; Karst; Bauxite; Gamma ray; Ubaid formation; Isorad.

1. Introduction

Bauxite comprising 55% alumina is the principal source of aluminum. From a geological point of view, bauxite is a residual rock that formed intermittently throughout much of the Earth's history during periods of intense continental subaerial weathering. Bauxite deposits are usually classified according to their mineralogy, chemistry, and host-rock lithology (B'ardossy and Aleva, 1990). Of all known bauxite deposits, about 88% is of laterite type, 11.5% is of karst type, and the remaining 0.5% is of Tikhvin type (B'ardossy, 1995; B'ardossy and Aleva, 1990; Meyer, 2004).

In 2001, bauxite was mined in 22 countries. The 12 largest producing countries account for about 97% of the world production (Plunkert, 2001); Australia is currently the largest producer, with about 53.3 million metric dry tons (Mt) of bauxite, followed by Guinea (15.7 Mt), Brazil (13.9 Mt), Jamaica (12.4 Mt), China (9.5 Mt), and India (8.39 Mt). The bauxite ore is red colored because of iron content (10–25%). It also contains various amounts of water and silica (Abbady and El-Arabi, 2006). In Iraq, karst bauxite was discovered in 1989 within the Ubaid Formation in the Western Desert between Wadi Hauran and Wadi Al-Hussainiyat (Figure 1). Sediments formed essentially from bauxite with minor karst-filling sediments were named later as the Nuwaifa Formation.

Radiometric methods are used in the investigation of mineral deposits and ores in many parts of the world. Initially, radioactivity measurements in boreholes and airborne gamma spectrometry were used in petroleum exploration (Howell and Frosch, 1939; Lundberg *et al*. 1952; Kellogg, 1975). Darnley and Ford (1987) concluded that in many cases, the airborne gamma-ray spectrometry technique is probably more useful than any other single airborne geophysical or remote sensing technique for providing information directly interpretable in term of surface geology (Darnley and Ford, 1987). It is one of the most important methods that has been used as aid to geologic mapping (Darnley and Grasty, 1971; Kotel'nikov and Grigor'ev, 1972 ; Darnley, 1991; Shives, 1996; Rabie *et al*. 2000; Buccianti *et al.* 2009). Also, gamma ray measurements have been applied in investigation of mineral deposits (Constello and Norquay, 1967; Tixer and Alger, 1970; IAEA,2003)). In northern Canada, polymetallic mineralization was discovered using gamma-ray surveys (Charbonneau,1987; Gandhi *et al*. 1996). These surveys have resulted in exploration and production of significant Canadian deposit types that contain gold, cobalt, copper, bismuth and tungsten. Airborne gamma ray measurements were used for identifying serpentinized ultramafic rocks and associated soils in northern California which are characterized by high concentrations of Cr and Ni. Because ultramafic rocks and their soils are naturally lacking in radioelements, gamma-ray surveys can be used to produce quasi-geochemical maps that identify radiometrically deficient areas (Mc-Caffety and Van Gosen, 2009). Some other applications include underwater investigations. (Van Wijngaarden *et al*. 2002). Airborne gamma spectrometry surveys helped in exploring some bauxite deposits in Saudi Arabia (Al-Bassam and Mustafa, 1989). Also, there is some information about the radioactivity associated with bauxite deposits in Gant in Hungary, and Unterlaussa in Austria (Valeton, 1972). There is the chance of the association of uranium and thorium with bauxite and clay deposits (Samama, 1984), depending on the similarity of the geochemical environment during the deposition, and on the behavior of these elements (Al-Atia, 1993).

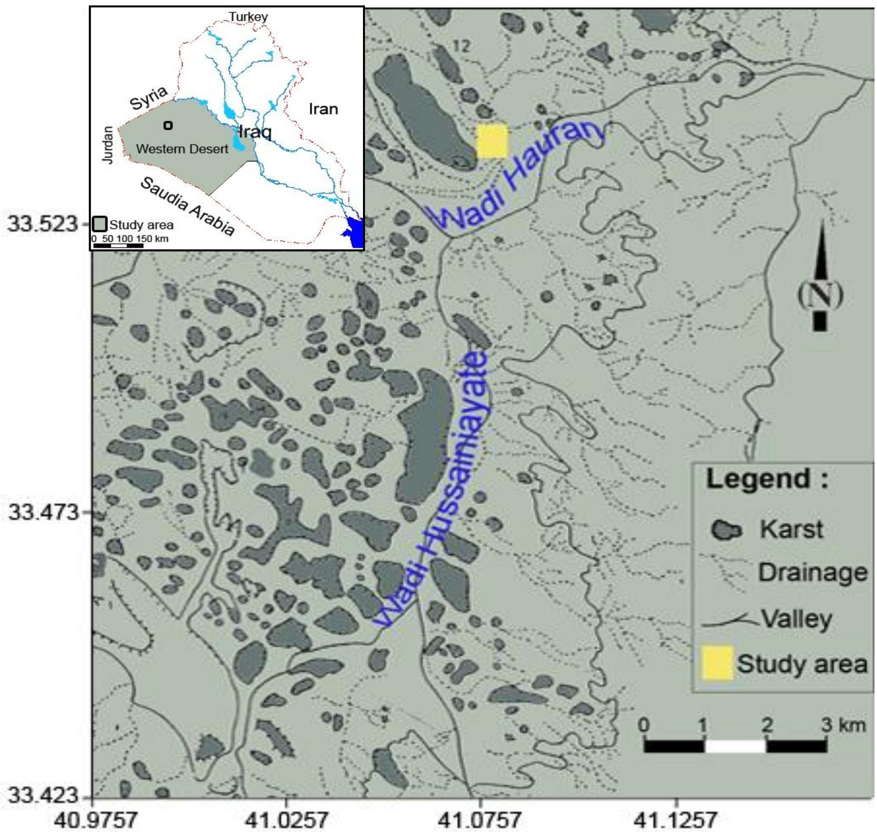

Figure 1. Location map showing the distribution of karsts and the study area in the Western Desert of Iraq.

Airborne radiometric measurements carried out in Iraq with a traverse interval of 2 km did not yield any radioactive anomalies as the surface area of the karst ranges between 0.2 and 0.4 km on average, and 34 m to 105 m depth (Al-Rubaii, 1997). However, the present work aims to discuss the capability of the ground radiometric method in detecting the surface boundaries of buried karst containing bauxite and clay minerals in the Western Desert of Iraq.

2. The study area

The study area is located in the middle of the Western Desert of Iraq near the crossing of Wadi Hauran and Wadi Hussainiyat. It is accurately determined with longitudes (41˚ 04′ 32″ - 41˚ 05′ 11″) and latitudes (33˚ 32′ 2″ - 33˚ 32′ 21″) (Figure 1). In the northwest of Wadi Hussainiyat, some sporadic karsts containing bauxite deposits (Mustafa *et al*. 1991) are scattered within dolomite of the Ubaid Formation (Lower Jurassic). The studied karst (Figure 2) has identification number 47 in the classification list that has been prepared by the Geological Survey and Mineral Investigation Company in Iraq (Al-Rubaii, 1997).

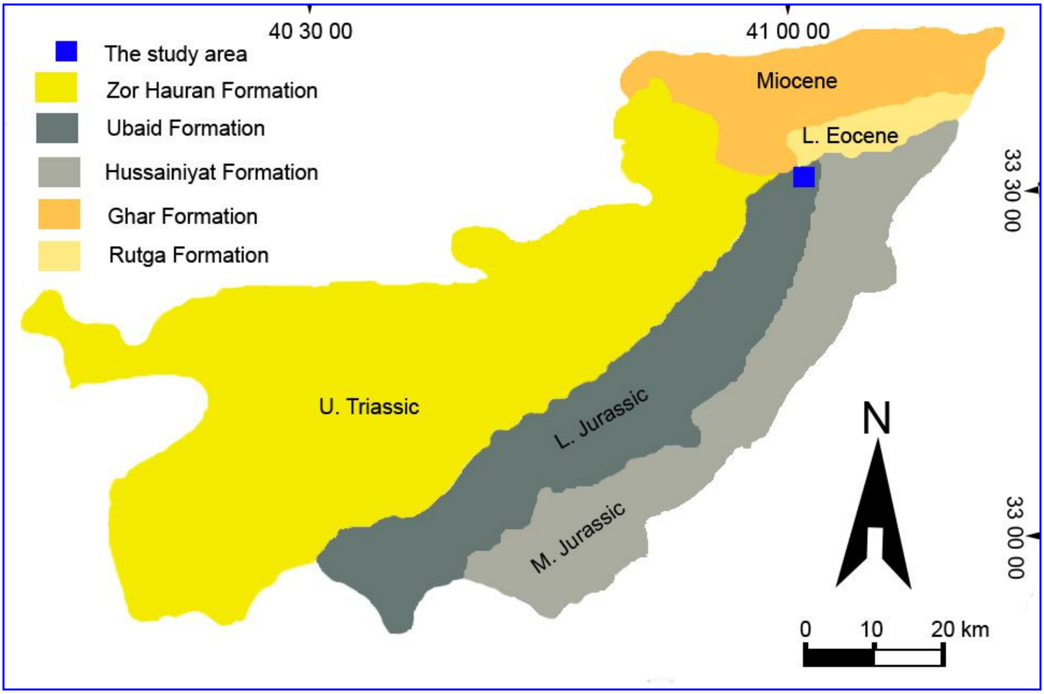

Figure 2. Simplified geological map showing Mesozoic and Tertiary formations exposed in the study area.

3. Geological setting

3.1 Geomorphology

Valleys, hills, plateaus, pediments and karstification are the common features that can be seen in the study area. Wadi Huaran and Wadi Hussainiyat, which are seasonal valleys, are important valleys in the region surrounded by hills formed from dolomite and dolomitic limestone and are mostly covered with black quartzite because of the desert varnish (Buday and Hack, 1980). Two main plateaus exist; the first is the Ubaid plateau, which appears to be a rugged plateau characterized by exposures of yellow dolomite of the Ubaid Formation (L. Jurassic) and hosts most of the bauxitic karsts; and the second one is the Ghar plateau, which is a low rugged plateau formed essentially from conglomerates of the Ghar Formation (Miocene) covered with calcrete. Some of the bauxitic karsts are covered partially with the sediments of the Ghar Formation.

3.2 Lithostratigraphy

Paleozoic, Triassic, Jurassic and Tertiary rocks are exposed in the Western Desert of Iraq. In the study area, the Paleozoic rocks are not exposed and are mainly covered with sedimentary rocks belonging to the Triassic, Jurassic and Tertiary ages (Figure 2). These formations are nearly horizontal, consisting mainly of carbonate and/or clastic rocks (Jassim and Goff, 2006). Several wadies have been filled with Quaternary deposits. A lithostratigraphic sequence could be described from oldest to youngest as in the Zor Hauran Formation (U. Triassic), which has a tidal to sub-tidal depositional environment composed of marl, marly dolomite, limestone, dolomitic limestone and with dolomite at the top (Buday and Hack, 1980). The Ubaid Formation (L. Jurassic) consists of chert interbededed with dolostone at the bottom; with light gray dolostone and greenish yellow shale containing secondary gypsum at the top of the formation. It conformably emplaces on

Zor Hauran Formation representing the first sedimentary cycle of the Jurassic with an average thickness of 65m (Al-Mubarak, 1983). Karstification is the most important feature in the Ubaid Formation (Al-Rubaii, 1997). The Hussainiyat Formation (M. Jurassic) deposited unconformably on the Ubaid Formation when the tidal environment changed to the continental environment. It is composed of a clastic unit at the bottom of the formation, whereas the top is composed of limestone. The clastic unit is comprised of sand, silt, kaolinite and iron oxide, which indicates a fluviatile environment (Jassim and Goff, 2006).

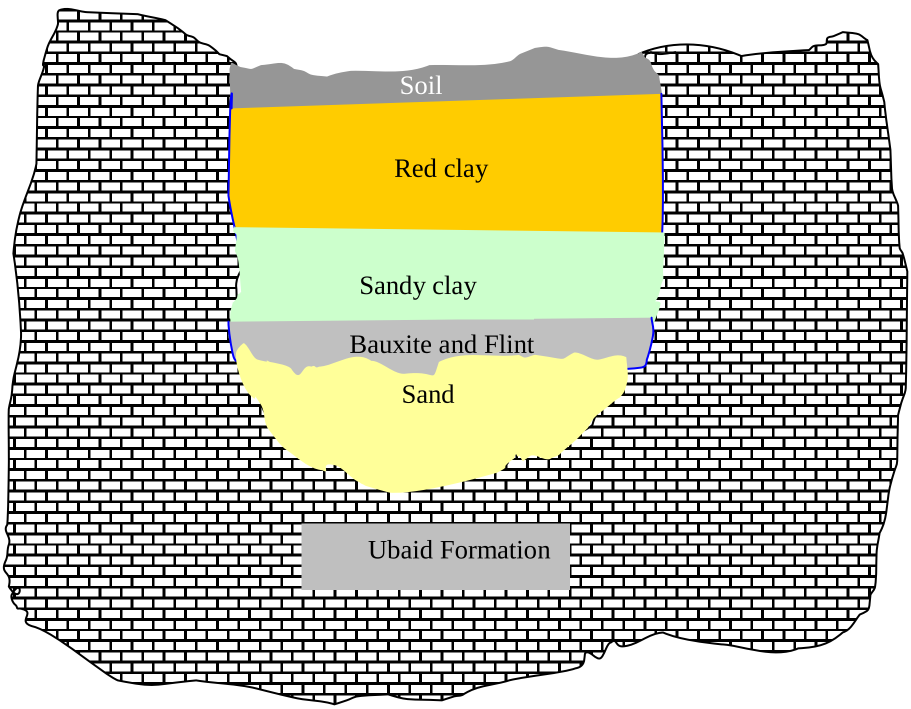

Figure 3. Sketch diagram of karst showing the stratigraphic column, vertical and horizontal dimensions without scale.

4. The nature of karst

According to Sweeting (1972) two features of karst are observed in the Western Desert of Iraq; the first is sink holes, which belong to the active karstification system, whereas the second feature is fossil karsts, which belong to the buried karstification system. The current study was conducted on buried karst. Chemical weathering of run-off water and ground water is considered an important factor forming karst in a humid climate. Karsts appear to be contemporaneously filled with sediments during karstification. The stratigraphic column in the studied karst could be described lithologicaly from the bottom to the top as sand, bauxitic clay and flint clay, sandy clay, red clay and soil (Al-Rubaii,1997) (Figure 3). Sand appears to be unconsolidated white sand fining upward with an average thickness of 3 m. Flint clay has a white to gray color with an average thickness of 8 m characterized by concoidal fractures containing kaolinite mixed with organic matters and pyrite surrounded by bauxitic clay. Bauxite existes as hard lenses within flint clay characterized by pisolitic texture. Sandy clay, red clay with soil representes the overburden of bauxite ore.

5. Materials and methods

Total radioactivity measurements were recorded at the surface of the probable buried karst in the region. Nine traverses, including forty two measurement points (Figure 4) were achieved with a portable GAD-6 NaI(Tl) scintillation counter (Sintrex, Canada). Readings were recorded in counts per second (c/s) after 300 second at each location.

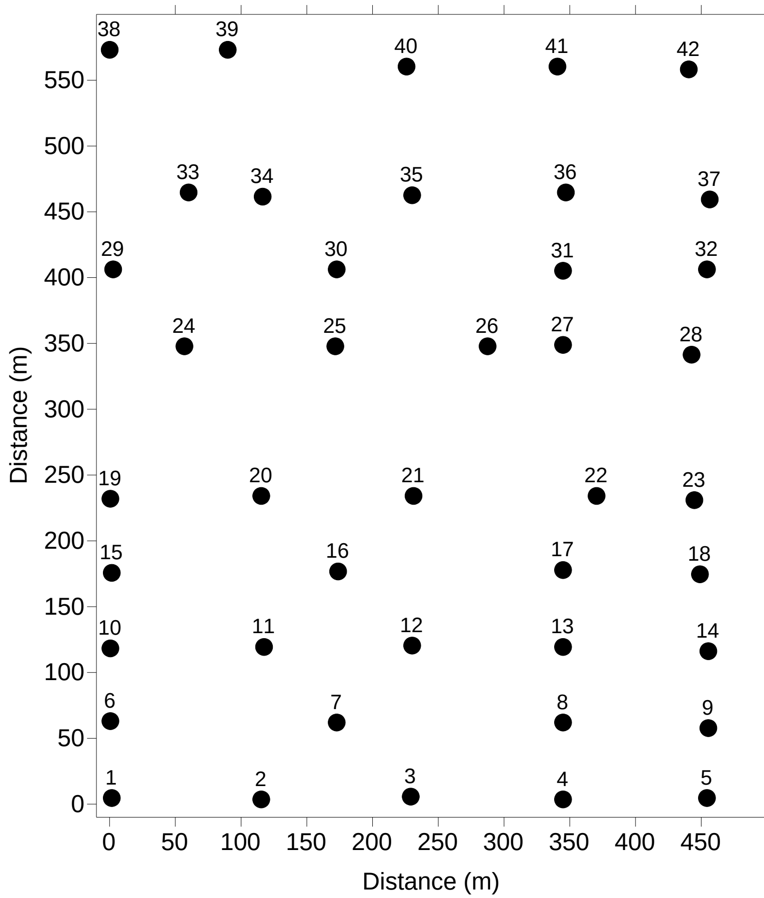

Figure 4. Network measurements on the surface of the probable karst.

Soil samples were collected from the surface soil at each measurement point, as well as the core samples that were collected from the test well (SM77, KARST 47). The nature and mineralogy of the core samples were identified according to the field observations (Al-Rubaii, 1997). Samples were overnight dried at 100˚C, crushed, sieved through a 1 mm mesh sieve and analyzed for Uranium (^{238}U), Thorium (^{232}Th) and Potassium (^{40}K) using a gamma spectrometric system based on a pure germanium detector with an efficiency of 40% (Tennelec, USA) attached to an 8192-channel personal computer analyzer. The activity concentrations of ^{238}U, ^{232}Th and ^{40}K were determined with the computer code GDR-4 (Nucleus, USA). Merinelli beaker geometry was used for the measurements. The energy and efficiency of measurement was calibrated by Europium-152 (^{152}Eu, IAEA, Vienna) standard source. Positional data were recorded using a portable GPS receiver.

6. Results and discussion

The total radioactivity count rates in the study area range from 57 to 147 cps (Table 1). It was recorded as 60 to 90 cps in the central part of the study area (probable karst), while the background radiation was 100-150 cps (Ali, 2004; Ali and Al- Sheikh, 2009) in the surrounding area and the Ubaid Formation, which hosts the bauxite karsts. An isorad map of the total radioactivity measurements at the surface of the studied area was plotted (Figure 5). Since the surface radiometric measurements reflect the radioactivity of the top few meters of the soil (not more than three meters), the map in Figure 5 obviously exhibits the radioactivity on the surface of karst as depleted level in comparison with the background radiation of the areas surrounding the karst (Ubaid Formation). The continuous chemical washing of the sediments at the surface of the karst caused leaching alkalis and some elements downward (Millot, 1970). The humid climate that was prevalent during Jurassic time participated in activation of chemical weathering; dissolution and washing of overburden moved Uranium, thorium, potassium and rubidium with alkalis downward producing an overburden depleted with radioelements, especially uranium and thorium, whereas the buried sediments filled the karst enriched with radioelements due to adsorption of those radionuclides (U and Th) by clay minerals and bauxite deposits.

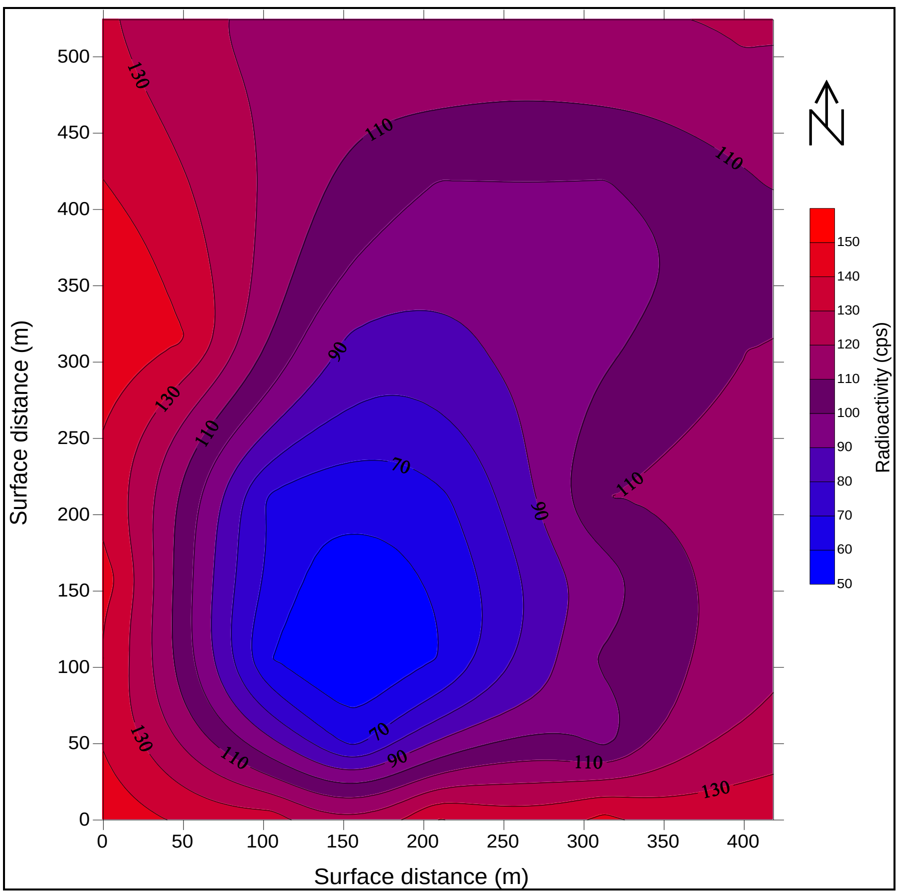

Figure 5. Isorad map plotted from data in Table 1, displaying the depletion of radioactivity at the overburden of karst (the blue color), and illustrates the estimated boundary of the karst by contour line of 90 cps.

This mechanism led to accumulating the radioactive materials within clay beds, flint and bauxite at a depth of more than 5m which can't be detected by the portable gamma ray spectrometer (Eisenbud and Gesell, 1997), while the washed overburden remained with radioactivity less than the background radiation in comparison with the surrounded area.

Table 1. Total radioactivity in the studied area.

Measurement point no.	Radioactivity total count (cps)	Measurement point no.	Radioactivity total count (cps)
1	147	22	110
2	135	23	115
3	141	24	140
4	143	25	88
5	138	26	94
6	139	27	98
7	65	28	110
8	97	29	146
9	125	30	100
10	140	31	96
11	60	32	105
12	60	33	130
13	102	34	118
14	118	35	100
15	145	36	100
16	57	37	110
17	96	38	123
18	115	39	117
19	138	40	120
20	68	41	118
21	68	42	119
Range	57 - 147		

According to the scale of Figure 5 the surface diameter of the karst is estimated to be about 150 to 200 m. These results were supported by results of the gamma spectral analysis which have been done on the surface soil samples and the core samples collected from well penetrating the karst (Table 2). The results showed, that the radioactivity of ^{238}U and ^{232}Th in the surface soil is as low as 0.5 Bq/kg and 3 Bq/kg respectively at the surface of the karst, while the average radioactivity of ^{238}U, ^{232}Th and ^{40}K in soil surface and rock samples of the Ubaid formation outside the karst were 33 Bq/kg, 26 Bq/kg and 359 Bq/kg respectively. On the other hand, the radioactivity of ^{238}U and ^{232}Th in bauxite and flint clay at depth more than 5 m of the karst center is higher, and reaches up to 240 Bq/kg and 160 Bq/kg respectively.

This case is interpreted as that the source rock including radioelements were washed and leached from the high lands of the older formations such as the Gaara Fotmation (Permocarboniferous) which have a relatively high concentration of radioelements (Ali, 2004; Ali and Al- Sheikh, 2009). Then, these were accumulated in the low lands at the first stage and filled the karsts. The continuous washing and leaching of the surface soil introduced karsts with overburden depleting in radioelements. The leached elements were accumulated within the clay and bauxitic beds at depth of more than 5 m. It is believed that the Ga'ara Formation outcroping to the west of the study area is the main source rocks that has supplied radioactive elements to younger formations (Ali, 2004; Ali and Al- Sheikh, 2009). The regional background radiation of the area, represented by the Ubaid Formation and other lower Jurassic formations, is between 100 and 150 cps. The radioactivity concentration of the different lithologies within the karst are illustrated in Figure 6. Soil has a finite capacity to adsorb potassium (Chrestopher *et al*. 2007). Concentration of ^{40}K in the surface soil was higher than of its concentration in the others beds of the test well, but it was lower than its concentration in the soil and rock samples collected from the Ubaid Formation which was found to be 359Bq/kg in average (Table 2). On the other hand, ^{238}U and ^{232}Th have low radioactivity in the surface soil, while they have higher radioactivity in the deeper beds (red clay, sandy clay, flint and sand) within the karst (Figure 3).

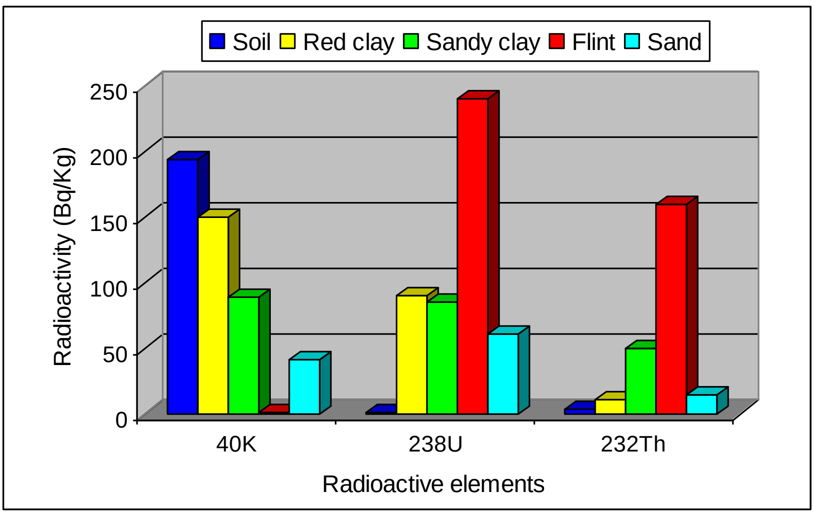

Figure 6. Radioactivity concentration of selected core samples from the test well within the studied karst.

Table 2. Total radioactivity (cps) and radioactivity of ^{238}U, ^{232}Th and ^{40}K in selected samples of the test well penetrating the karst and the average(av.) radioactivity in samples selected from the Ubaid formation(host rock).

Sample type	Depth (m)	Total Radioactivity (cps)	Radioactivity (Bq/Kg)		
			^{40}K	^{238}U	^{232}Th
Soil	0 - 5.0	80	194	0.5	3
Red clay	5.0 - 20.0	130	150	90	11
Sandy clay	20.0 - 23.5	130	89	85	50
Flint	23.5 - 25.0	115	0.5	240	160
Sand	25.0 - 26.6	90	41	61	14
Formation Ubaid	Surface	116 (av.)	359 (av.)	33(av.)	26(av.)

The radioelements U-238 and Th-232 were leached from the overburden (soil) leaving it poor with radioactivity. Thereafter these elements are accumulated in the clay beds and flint so they have relatively high concentrations as shown in the histogram (Table 2) and (Figure 6).

7. Conclusion

From the results obtained from this study, it can be concluded that the ground radiometric survey coupled with gamma ray spectroanalysis technique can be considered as an effective technique in preliminary studies to detect mineral deposits especially those deposits containing radioelements. This study confirms that the detailed ground radioactivity measurements technique is one of the important methods and a successful technique for providing useful information in the investigation of clay and bauxite deposits. Accordingly, also this technique has enough capability in determining the surface boundary of the bauxites karst and its dimensions.

8. References

ABBADY, A.G.E and El-ARABI, A.M., 2006. Naturally occurring radioactive material from the aluminium industry, a case study: the Egyptian Aluminium Company, Nag Hammady, *Egypt, J. Radiol. Prot.,* **26 (1):** 415-422.

Al-ATIA, M.J., 1993. Study of possibility of using the radiometric methods for bauxite deposits exploration in Western Desert of Iraq. Inter. Rep. no. 2211 A, Geosurv. Baghdad, Iraq.

AL-BASSAM, K. and MUSTAFA. M., 1989. Report about bauxite ore site in Al-Zubayra Saudi Arabia. Internal report No. 1795, G, Geosurv., Baghdad, Iraq.

ALI, K.K. and Al- SHEIKH, Z., 2009. Natural radioactivity of the southeast limb of Gaara depression – West of Iraq. *"Proceeding of the 3rd scientific conference of College of Science"*, University of Baghdad, 24-26 March 2009, Baghdad, Iraq.

ALI, K.K., 2004. Radiogeological study of Western Desert-Iraq with special emphasis on radioecology. Ph.D. Thesis, Baghdad University.

Al-MUBARAK, M., 1983. Regional mapping of the southern and western desert of Iraq. Unpublished report. Geoserv., Baghdad. Iraq.

Al-RUBAII, D.A.H., 1997. Geochemistry and mineralogy of the Karst bauxite rocks in the western desert of Iraq. M.Sc. unbuplished thesis. University of Baghdad, College of Science. 117p.

B'ARDOSSY, G., 1995. Carboniferous to Jurassic bauxite deposits as paleoclimatic and paleogeographic indicators. Can. Soc. Petroleum Geologists, Mem. **17:** 283-93.

B'ARDOSSY, G. and ALEVA, G.J.J., 1990. *Lateritic bauxites Developments in Economic Geology*. Elsevier, Amsterdam.

BUCCIANTI, A., APOLLARO, C., BLOISE, A., DE ROSA, R., FALCONE, G., SCARCIGLIA, F., TALLARICO, A., and VECCHIO, G., 2009. Natural radioactivity levels (K, Th, U and Rn) in the Cecita Lake area (Sila Massif, Calabria, Southern Italy): An attempt to discover correlations with soil features on a statistical base. *Geoderma*. **152 (1-2):** 145-156.

BUDAY, T. and HACK, J. 1980. On the geological survey of the Western part of the Western Desert of Iraq. Geol. Survey Iraq. Internal Report. Baghdad, Iraq.

CHARBONNEAU, B.W., 1987. Gamma spectrometric and magnetic anomalies associated with Cu-U mineralization, Faber Lake Volcanic Belt, District of Mackenzie, NWT, in Current Research, Part C, *Geological Survey of Canada*. Paper 88-1C :255-258.

CHRESTOPHER, A.B. CLAUDE, E.B. and ROUSE, D.B., 2007. Potassium adsorption by bottom soils in ponds for inland culture of marin shrimp in Alabama. *Journal of the World Aquaculture Society.* **38 (1):** 85-91.

CONSTELLO, J.T. and NORQAUY, I.P., 1967. Logging the prairie evaporates formation in Saskatchewan, in Miming and underground geophysics/1967, *Economic. Geology*. **26:** 492-496.

DARNLEY, A.G., 1991. The development of airborne gamma-ray spectrometry: Case study in technological Innovation and Acceptance, *Nuclear Geophysics*. **5 (4):** 377-402.

DARNLEY, A.G. and FORD, K.L., 1987. Regional airborne gamma-ray surveys: *a review. In: Exploration '87* (*ed. G.D.Garland*), 229-240. *Third Decennial International Conference on Geophysical and Geochemical*

Exploration for Minerals and Groundwater. Special Volume 3*. Geological Survey of Canada, Ontario, Canada..*

DARNLEY, A.G., and GRASTY, R.L., 1971. Mapping from the air by gamma-ray spectrometry, *Geochemical exploration*, special volume. **11:** 485-500.

EISENBUD, M. and GESELL, T., 1997. *Environmental Radioactivity*, 4th edition, Academic press, USA.

GANDHI, S.S., PRASAD, N. and CHARBONNEAU, B.W., 1996. Geological and geophysical signatures of a large polymetallic exploration target at Lou Lake, Southern Great Bear Magmatic Zone, NWT; *in Current Research*, 96-1E, Geological Survey of Canada, 147-158.

HOWELL, L.G., and FROSCH, A., 1939. Gamma-ray well logging: *Geophysics*, **4:**106-114.

IAEA , 2003, Guidelines for radioelement mapping using gamma ray spectrometry data, IAEA-TECDOC-1363.

JASSIM, S.Z. and GOFF G.C., 2006. *Geology of Iraq*. Dloin, Prague and Moravian Museum, Brno. Czech Republic.

KELLOGG, W.C., 1975. Observations and interpretation of radioactive patterns over some California oil fields, *Mining Magazine*, **47:** 26-28.

KOTEL'NIKOV, G.N. and GRIGOR'EV, V.V., 1972. The application of radiometric methods in the mapping of discontinuous structures (faults) and in searching for rare-metal deposits. Translated from Atomnaya Énergiya**. 33 (6):** 989-990.

LUNDBERG, H., ROULSTON, K.I., PRINGLE, R.W. and BROWNELL, G.W., 1952. Oil exploration with scintillation counters: *Oil in Canada*, **4:** 40-46.

MCCAFFERTY, A.E. and VAN GOSEN, B.S., 2009. Airborne gamma-ray and magnetic anomaly signatures of serpentinite in relation to soil geochemistry, northern California. *Applied Geochemistry*. **24 (8):**1524-1537.

MEYER, F.M. 2004. Availability of bauxite reserves. *Natural Resources Researches*.**13 (3):** 161-172**.**

MILLOT, G. 1970. *Geology of Clay*. Chapman and Hall, London.

MUSTAFA, M. HUSSAIN, D.A., and JIBRAAIL, A.S., 1991. Exploration results about bauxite in north of Hussayniat, Western Desert, part 1, inter. Rep., 45p., Geosurv., Baghdad, Iraq.

PLUNKERT, P, A, 2001. *Bauxite and Alumina*. U.S. Geol. Survey, Minerals Year book, Metals and Minerals, USA. http://minerals.er.usgs.gov/minerals/pubs/commodity/bauxite/bauxmyb01.pdf

RABIE, S.I., AMMAR, A.A. and GOUD, M.A., 2000. Application of factor analysis as an aid to geological mapping, using aerospectrometric data, wadi Atalla area, Central Eastern Desert, Egypt: *Proceedings of the fourth Arab conference on the peaceful uses of atomic energy*, Tunis, **3:**19-45.

SAMAMA, J., 1984. Uranium in lateritic terrain in surficial uranium deposits. *IAEA*, TECDOC. 322, 53-59.

SHIVES, R.B.K., 1996. Application of airborne multiparameter geophysical data (Gamma-ray, Magnetometer, VLF-EM) to mapping and exploration in the Rusty Lake and Snow Lake areas; in EXTECH 1: A multidisciplinary approach to massive sulphide research in the Rusty Lake-Snow Lake Greenstone Belts, Manitoba, Ed. By G.F. Bonham-Carter, A.G. Galley and G.E.M. Hall, *Geological Survey of Canada Bulletin*, **426:** 277-279.

SWEETING, M.N., 1972. Karst land forms. Macmillon, London.

TIXER, M.J. and ALGER, R.P., 1970. Log evaluation of nonmetallic mineral deposits: *Geophysics*, **35:** 124-142.

VALETON, I., 1972. *Bauxites, Vol. 1:* Developments in Soil Science, Elsevier, New York.

VAN WIJNGAARDEN, M., VENEMA, L.B., DE MEIJER, R.J., ZWOLSMAN, J.J.G., VAN, O.B. and GIESKE, B., 2002. Radiometric sand-mud characterization in the Rhine–Meuse estuary Part A. *Geomorphology*. **43:** 87-101.

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