Atlas of the elemental composition and radionuclides for strategic regions in Egypt by neutron activation analysis

Report of summer student programme

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Summary

During this program, many scientific skills were trained such as;

- Employing neutron activation analysis as instrument to investigate samples
- Scientific skills and laboratory experience concerning sample preparation
- Spectra analysis by using Genie-2000 program
- Calculation of mass fractions of the elements by using CalConc software

The report contains scientific details and some analyses and data that were conducted during the training period. The main aim of the project is to perform elemental composition and estimate the abundance of naturally occurring radioactive materials (NORM) in the strategic regions in Egypt. There are many strategic regions that can be studied and the project will focus on the most strategic sites as following.

- Sukari and Hamash gold mines
- Qena and Safaga
- South of Marsa Alam
- Halayib Triangle
- Phosphate mines (Abu tartor and Um Ara)

the present work helps to establish an study the distribution patterns of trace elements and the natural radioactivity for the national strategic regions. Not only but also aims at the evaluation of the ecological situation and assessment of the radiological hazards in the sites under study.

The created atlas will help for mining of the strategic nuclear materials for peaceful uses. It gives sustainable outcomes for various benefits in scientific research, global development, energy, industry, and nuclear materials. The project supports Egypt's economic vision 2030 and helps for solving some great issues regarding energy and mining national projects.

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Abstract

The present work was conducted to outline the atlas of elemental composition and radionuclides for rock samples concerning strategic regions such as some selected gold mines in Egypt namely, Sukari and Hamash mines. Sukari and Hamash granitoid pluton are situated in the Central Eastern Desert (CED) of Egypt and is considered one of the best examples of the gold-bearing granites in the Arabian Nubian Shield. A total of 19 and 20 investigated samples were collected from Sukari and Hamash, respectively. Sampling strategy were collected according to the International Atomic Energy Agency TECDOC-1415. The investigated samples were subjected to neutron activation analysis at the reactor IBR-2 Frank Laboratory of Neutron Physics FLNP – Joint Institute for Nuclear Research JINR. A total of 32 and 26 elements were determined in Sukari and Hamash, respectively. In addition, the concentrations of the determined elements in mg/kg were calculated using a developed software (CalConc) at FLNP – JINR. The quality of the measurements was weighted using certified reference materials. The basic descriptive statistics was performed, and the obtained concentrations were found to be considerably high for rare earth elements, uranium, and thorium in both gold mines. The obtained data are considered as a baseline data for characterizing the gold mines in terms of the elemental content and radioactivity scheme of area under study.

Content

Chapter 1

Introduction

Neutron activation analysis (NAA) is a nuclear process used for determining the concentrations of elements in a vast number of materials. NAA relies on excitation by neutrons so that the treated sample emits gamma-rays. It allows the precise identification and quantification of the elements, above all of the trace elements in the sample. NAA has applications in chemistry but also in other research fields, such as geology, archeology, medicine, environmental monitoring and even in the forensic science (Bierlein 2000; El Gaby 1977). Neutron Activation Analysis is very sensitive and is therefore used to analyze for minor elements, which are present in very low concentrations (Fu, X 2013; Goldfarb 2005). The method is especially useful for trace element analysis, e.g., in high-purity substances, and is therefore important in semiconductor techniques. It can also be used to detect trace element in water, biological material, and minerals. In archaeology, NAA can give useful information about the origin of the findings according to the so-called “fingerprint” of the individual element composition in their raw materials. It is usually used as an important reference for other analysis methods (Goldfarb 2005; Gordon 1968).

NAA can detect up to 74 elements depending on the experimental procedure, with minimum detection limits ranging from 10^{-7} to 10^{-15}g/g, depending on the elements and matrix materials. Some nuclei can capture a number of neutrons and remain relatively stable, not undergoing transmutation or decay for many months or even years. Different nuclei have different cross sections and half-lives, and the intensities of the emitted gamma-rays can also vary – therefore the detection limits are quite variable. Rare earth elements (REE) have very high thermal neutron cross sections and NAA is usually the first choice for the determination of REEs in a trace elements analysis (Stosch 2016; Zhao 2007; Goldfarb 2005; Gordon 1968).

The method is based on neutron activation and therefore requires a source of neutrons. The sample is bombarded with neutrons, causing the elements to form radioactive isotopes. The radioactive emissions and radioactive decay paths for each element are well known. Using this information, it is possible to study spectra of the emissions of the radioactive sample and determine the concentrations of the elements within it. A particular advantage of this technique is that it does not destroy the sample, and thus has been used for analysis of works of art and historical artifacts (Goldfarb 2005; Gordon 1968). (NAA) is one of the most powerful techniques for simultaneous multi-elements analysis. This technique has been studied and applied to analyze major, minor, and trace elements in the Frank Laboratory of neutron physics at the joint institute for Nuclear Research. NAA techniques can give accurate results in the following:

- Determination of the concentrations of rare-earth, uranium, thorium, and other elements in Geological samples according to the requirement of clients particularly the geologists, who want to find out the mineral resources.
- The evaluation of the contents of trace elements in basement rock samples.
- Analytical of standard reference material, toxic elements, and natural radionuclides in sediment soil to evaluate the ratio of toxicity and contamination with heavy elements.

1. Neutron activation analysis

Amongst the various elemental analysis techniques, neutron activation analysis (NAA) is still the reference method (referee method). It is a sensitive and accurate analytical method that identifies and quantifies elements in a sample through analysis of characteristic gamma rays emitted during radioactive decay after being irradiated by neutrons and converted into radioactive nuclei (Pavlov 2014). NAA procedure consists of three main consecutive steps: (i) activation via irradiation with

reactor neutrons, (ii) measurement of the gamma-radiation after one or more decay times, and (iii) interpretation of the resulting gamma-ray spectra in terms of elements and concentrations15 (Pavlov 2014; Goldfarb 2005; Gordon 1968).

The NAA technique can be categorized according to whether gamma rays are measured during neutron irradiation (PGNAA also called PGAA) or at some time after the end of the irradiation after radioactive decay(s) (DGNAA or just NAA). The PGAA technique is generally performed by using a beam of neutrons extracted through a reactor beam port. Fluxes on samples irradiated in beams are in the order of one million times lower than on samples inside a reactor but detectors can be placed very close to the sample compensating for much of the loss in sensitivity due to flux. The PGAA technique is most applicable to elements with extremely high neutron capture cross-sections (B, Cd, Sm, and Gd); elements which decay too rapidly to be measured by DGAA; elements that produce only stable isotopes (e.g., light elements); or elements with weak decay gamma-ray intensities. 2D, 3D-analysis of (main) elements distribution in the samples can be performed by PGAA. DGNAA (sometimes called conventional NAA) is useful for the vast majority of elements that produce radioactive nuclides.

The technique is flexible with respect to time such that the sensitivity for a long-lived radionuclide that suffers from an interference by a shorter-lived radionuclide can be improved by waiting for the short-lived radionuclide to decay or quite the contrary, the sensitivity for short-lived isotopes can be improved by reducing the time irradiation to minimize the interference of long-lived isotopes. This selectivity is a key advantage of DGNAA over other analytical methods. With the use of automated sample handling (e.g., using rabbit system), gamma-ray measurement with solid-state detectors, and computerized data processing it is generally possible to simultaneously measure more than thirty elements in most sample types without chemical processing. The application of purely instrumental procedures is

commonly called instrumental neutron activation analysis (INAA) and is one of NAA's most important advantages over other analytical techniques, especially in the multi-element analysis (Pavlov 2014; Goldfarb 2005; Gordon 1968). If chemical separations are done to samples after irradiation to remove interferences or to concentrate the radioisotope of interest, the technique is called radiochemical neutron activation analysis (RNAA). The latter technique is performed infrequently due to its high labor cost.

2.1. Advantages and limitations of NAA

In common with most analytical techniques, neutron activation analysis has advantages and limitations relative to other methods.

2.1.1. Advantages:

1. Sensitivity: The method has a very high sensitivity for many elements, in some instances to 10^{-10} g.
2. Matrix effects: The fact that nuclear reactions are involved results in the chemical or physical nature of the matrix being unimportant, (exceptions occur where a major matrix element has a high absorption cross-section). Thus, samples and standards do not have to have similar bulk compositions.
3. Contamination: As the only operations performed on environmental samples before irradiation are usually collection and preparation, there is no reagent blank and the possibility of contamination from apparatus or reagents is greatly reduced or eliminated.
4. Multi-element technique: For many applications, the method is non-destructive and multi-element. For example, as many as 28 elements may be determined in air particulates (80). Even where radiochemical separations are necessary, groups of elements can often be separated rather than individual elements.

5. Isotopic ratios: Where an element possesses several stable isotopes, isotopic ratios may be measured in certain cases by activation analysis.
6. Non-destructive technique: Materials can be activated in any physical state, viz. solid, liquid, or gaseous. There is no fundamental necessity to convert solid material into a solution before activation.

2.1.2. Limitations:

1. Not all elements possess suitable radioactive nuclides; either formation cross-sections are low, or half-lives are very long or very short, resulting in poor sensitivity.
2. In INAA methods for environmental samples, decay periods of up to one month may be necessary to allow the determination of some long-lived nuclides. Hence, the method will have a time lag for some results.
3. Not all laboratories have access to a nuclear reactor.

3. Types of NAA

There are two types of NAA:

3.1. **Nondestructive NAA**, i.e. The resulting radioactive sample is kept intact. Nevertheless, there will be changes at the nucleus level. Nondestructive NAA contains the following types:

- Instrumental Neutron Activation Analysis Activation INAA
- Epithermal Neutron Activation Analysis Activation ENAA
- Fast Neutron Activation Analysis Activation FNAA
- Cyclic Neutron Activation Analysis Activation CNAA
- In Vivo - Neutron Activation Analysis Activation In-vivo NAA

3.2. Destructive NAA

The destructive NAA the radioactive sample is decomposed or in other wards chemically processed after irradiation. This kind includes only radiochemical or destructive neutron activation analysis RNAA or DNNA

4. Activation

The activation with neutrons is the first stage in an NAA procedure. Its purpose is to convert some of the stable nuclei into radioactive nuclei emitting radiation that can be used for analytical purposes. Insight into the reactions that may take place during activation facilitates the identification of the relation between the observed radioactive nucleus, its target nucleus, and associated element. Insight into the reaction rates is of importance for the quantitative analysis and a priori estimates of the feasibility of an analysis (Stosch 2016; Zhao 2007; Goldfarb 2005; Gordon 1968). Each atomic nucleus can capture a neutron during irradiation.

A nuclear reaction results, in which often the nuclear mass changes; immediately after the capture ('promptly') excess energy in the form of photons and/or particles will be emitted. The newly formed nucleus may be unstable. When unstable, already during an activation it starts to decay to a stable state by the emission of radiation through one or more of the following processes: β^--decay, β^+-decay, electron capture, α-decay, or internal transition decay. In most cases, γ and X-radiation will be emitted too. The capture of a neutron by an atomic nucleus and the resulting reaction may be illustrated, in the case of a cobalt target nucleus as ^{59}Co (n, γ) ^{60}Co[15].

The most common reaction occurring in NAA is the (n, γ) reaction, but also reactions such as (n, p), (n, α.), (n, n') and (n,2n) are important. Some nuclei, like ^{235}U, are fissionable by neutron capture and the reaction is denoted as (n, f) yielding fission products and fast neutrons. The cross-section and the neutron flux are neutron energy dependent (Goldfarb 2005; Gordon 1968).

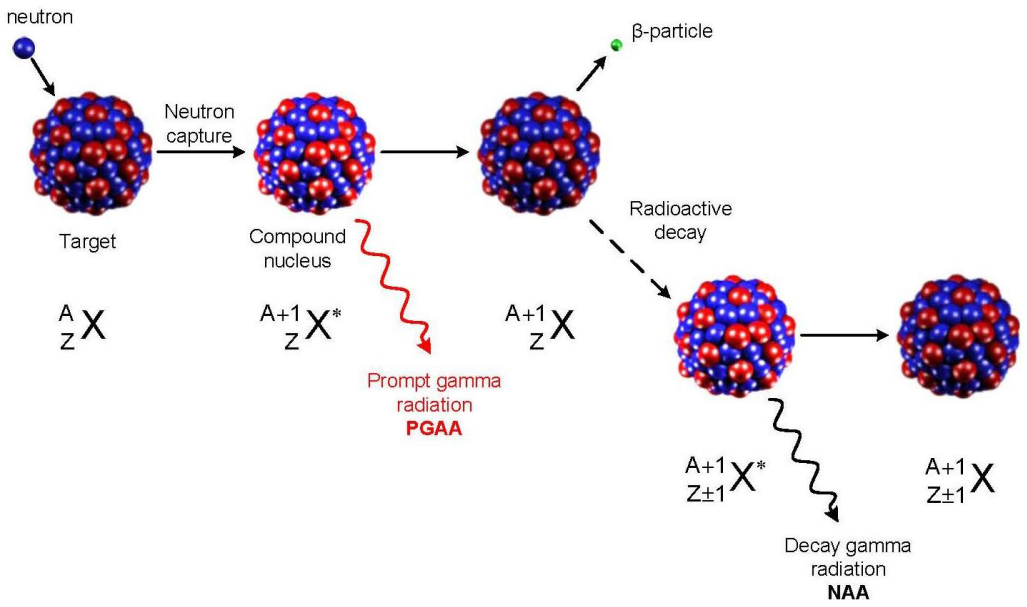

Fig (1): Neutron capture by a target nucleus followed by emission of gamma-rays

Reactions of the (n, γ) and (n, f) type have the highest cross-section (typically in the order of 0. 1 - 100 barn) for thermal neutrons whereas the other reactions ((n, p), (n, α), (n, n'), (n,2n)) mainly occur with fast neutrons at cross-sections 2 or 3 orders of magnitude lower. In several cases, nuclear reactions result in the conversion of a stable nucleus into another stable nucleus.

In the majority of NAA procedures, thermal neutrons are used for activation. Sometimes activation with epithermal reactor neutrons is preferred to enhance the activation of elements with a high ratio of resonance neutron cross-section over thermal neutron cross-section relative to the activation of elements with a lower such a ratio.

5. Radioactivity

radioactivity, property exhibited by certain types of matter of emitting energy and subatomic particles spontaneously. It is, in essence, an attribute of individual atomic nuclei. An unstable nucleus will decompose spontaneously, or decay, into a more stable configuration but will do so only in a few specific ways by emitting certain

particles or certain forms of electromagnetic energy. Radioactive decay is a property of several naturally occurring elements as well as of artificially produced isotopes of the elements.

The rate at which a radioactive element decays is expressed in terms of its half-life, i.e., the time required for one-half of any given quantity of the isotope to decay. Half-lives range from more than 1024 years for some nuclei to less than 10−23 second. The product of a radioactive decay process—called the daughter of the parent isotope—may itself be unstable, in which case it, too, will decay. The process continues until a stable nuclide has been formed (EPA 1994, NCRP 2015).

Chapter 2

Experimental technique

1. Gamma Detection system setup:

The measurement of Gamma-radiation in NAA as a spectroscopic method. The differences with other spectroscopic methods for elemental analysis in:

1. In activation analysis, the Gamma-radiation originates from the atomic nucleus, not from election shells. So, its energy in order of MeV.
2. The radiation is measured not during the excitation, as the nuclear reaction, but at a given time after the end of activation (short-lived – long-lived 1 – long-lived 2, depending on the decay time).
3. The method is isotope-characteristic, in contrast to other methods in which the total of all isotopes of the element is assessed. Because isotopic abundance is well-known fraction of every element (with only a few also well-known exceptions), determination of isotope implicitly means determination of elements.

Gamma-radiation detectors are based on the principle that, upon interaction with matter, the energy quantum of a photon is converted into a product that can be detected by physical or electronic means (Koval 2019).

The radionuclide activity concentrations in JINR are measured using a High-Purity Germanium Detector (HPGD). The gamma spectrometry system consists of an N-type HPGD (CANBERRA), mounted in a cylindrical lead shield (100 mm thick) and cooled in liquid nitrogen, and coupled to a computer based Multi-Channel Analyzer (MCA).

The relative efficiency of the detector was 40 %, with an energy resolution of 2 keV at a gamma ray energy of 1332 keV of ^{60}Co. LABSOCS efficiency calibration

software, mathematical efficiency calibration software and software program (Genie 2000) were used to calculate the activity concentrations of the samples, taking care to subtract the natural background level (Koval 2019; Stosch 2016).

Some problems appear during the analysis. One of them is, there are more than one reaction induced by neutrons producing Al^{28} & Mg^{27}: ^{27}Al (n, γ)^{28}Al; ^{28}Si (n, p)^{28}Al, ^{31}P (n, α)^{28}Al & ^{26}Mg (n, γ)^{27}Mg; and ^{27}Al (n, p) ^{27}Mg. Which leads to less accuracy and errors in determination of concentrations of the corresponding elements. Another problem is the high background from Compton effect, which can be overcome by measurements are sometimes carried out after an appropriate delay time which is beneficial if the main interfering radionuclides have relatively short half-lives (Stosch 2016; Zhao 2007; Goldfarb 2005; Gordon 1968).

Another problem in IBR-2 is the limitation to detect (Cu, Cd, Pb & some light elements $Z < 10$) which are permanently installed in the reactor irradiation channel or placed into transport containers. So, they can detect by another technique like atomic absorption spectrometry (AAS).

The data in Table 1 are for the elements determined from short-lived products of (n, γ) reactions with half-lives below 15 h, and the data in Table 2 are for the elements determined from long-lived products of those reactions. These tables present radionuclides and their associated γ lines most often used to determine the corresponding element and fractions of decays where each γ ray is emitted in coincidence with the one or more than one γ ray.

2. Sampling strategy

The investigated rock samples of 200 gm for each station were collected from Sukari and Hamash gold mines area shown as an overview in Fig. 2 and details on the geological maps in Fig. 3 and 4.

The mentioned maps have shown that 39 samples were obtained from Sukari and Hamash gold mines and their surrounding areas SGMA, and HGMA respectively, CED, Egypt.

The first investigated area, SGMA included 19 samples which were collected by different locations according to geological maps and type of rocks. The sampling procedures followed recommended protocol from the Geological Survey and Mining Authority of Egypt, and TECDOC-1415 guidelines of sampling for environmental contaminants, International Atomic Energy Agency IAEA. Besides other investigated areas, HGMA included 20 samples which were collected as the same methodology as SGMA.

2.1. Sukari area setting

SGMA is situated within the Precambrian rocks of the CED, and it is occupied by mafic-ultramafic ophiolitic rocks, island arc-related volcaniclastic metasediments-plutonic assemblages, Syn- to late tectonic granites, orogenic strike-slip faults, and syn-orogenic intrusions.

Also, it is worth noting that all these rocks are cut later by dolerite, diorite, and felsic dykes (Abd El-Wahed et al., 2016; Helmy et al., 2004).

2.2. Hamash area setting

As shown in Fig. 4 and 5, the HGMA's dominant geological formations are metasedimentary mudstones. Also, contains other formation such chlorite-quartz-epidote schists, phyllites, and actinolite-epidote schists at the contact between basement igneous rocks and Nubian Rock formations.

Tectonic contacts appear between serpentinite and metasediments. A metagabbro-diorite complex forms a NW-SE trending body with a leach territory to the south of the HGMA.

With a length of 12.5 km. These rocks are similar to the Dokhan volcanic and have chemical properties that are consistent with a calc-alkaline continental arc setting (El Gaby & El Aref, 1977) A semi-circular body (4.5 x 3.2 km) of coarse-grained pink granite and granodiorite at the Hamash gold mine contains large inclusions of metagabbro. In the Hamash area, five locations with copper (and gold) mineralization are known as Um Hagalig, Um Tundub, Hamash North, and both west and east of Ara, the main gold mine of Hamash as shown in Fig. 5.

Metamudstones, phyllites, chlorite-quartz-epidote schists, and actinolite-epidote schists dominate the HGMA, and particularly both of Serpentinite and talc-carbonate rocks which enclosed in metasediments (Helmy & Kaindl, 1999; Helmy et al., 2004; Hilmy & Osman, 1989)

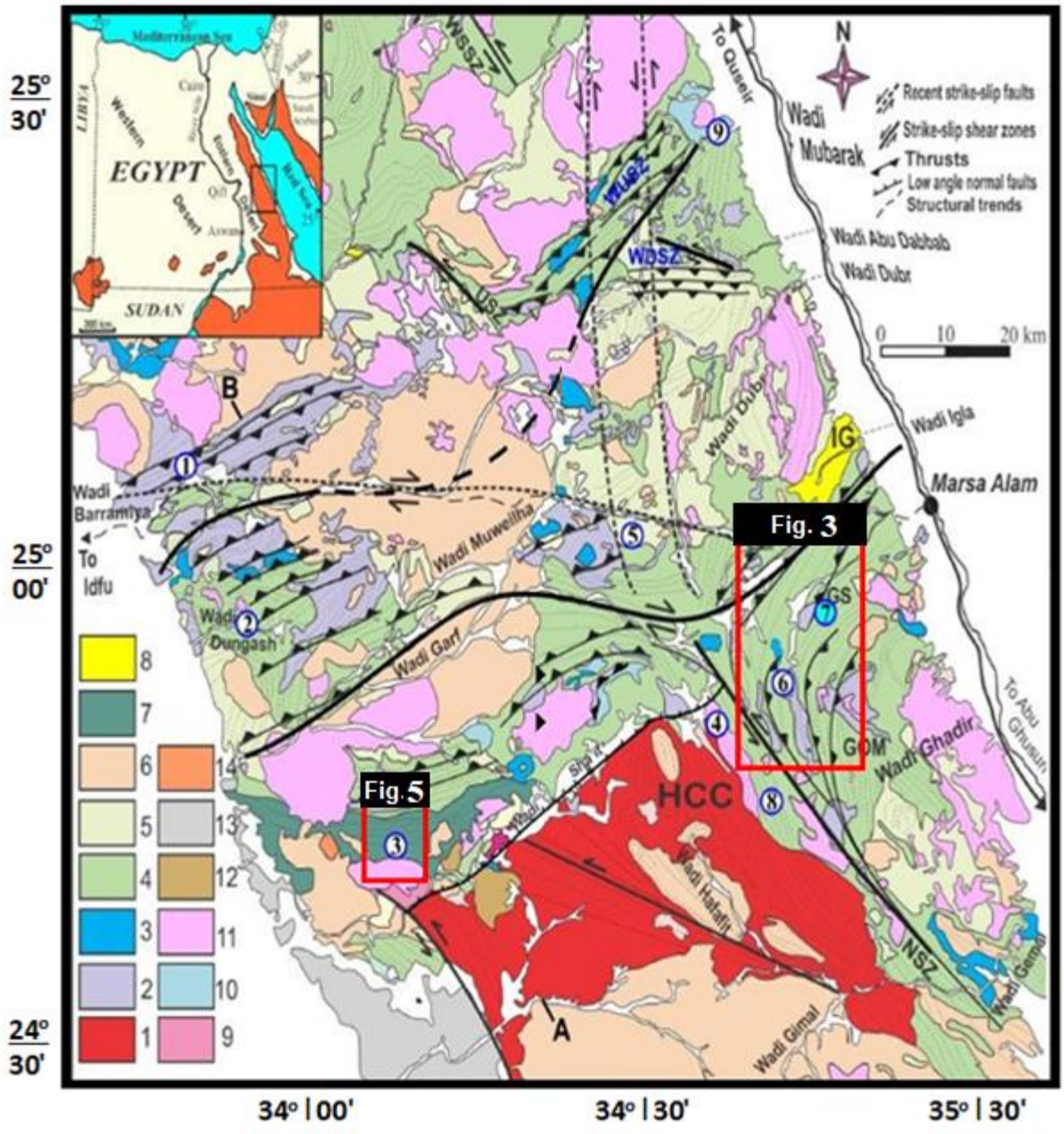

Fig. (2): Geological map of the southern part of the Central Eastern Desert show distribution of gold mines in Egypt (Abd El-Wahed, 2014; Abd El-Wahed et al., 2016)

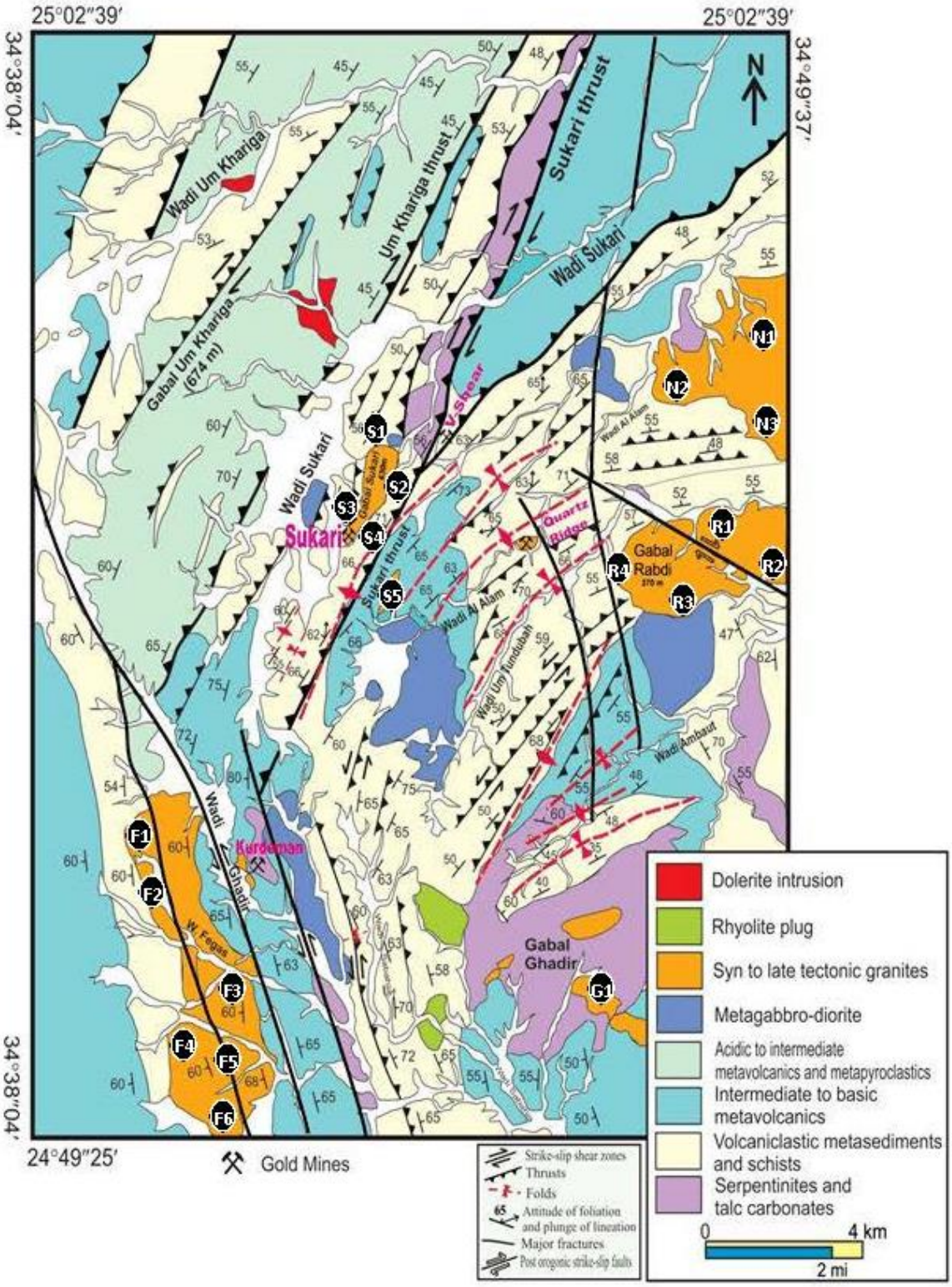

Fig. (3): The selected investigated location on the geological map of Sukari, SGMA, Egypt (Abd El-Wahed, 2014; Abd El-Wahed et al., 2016)

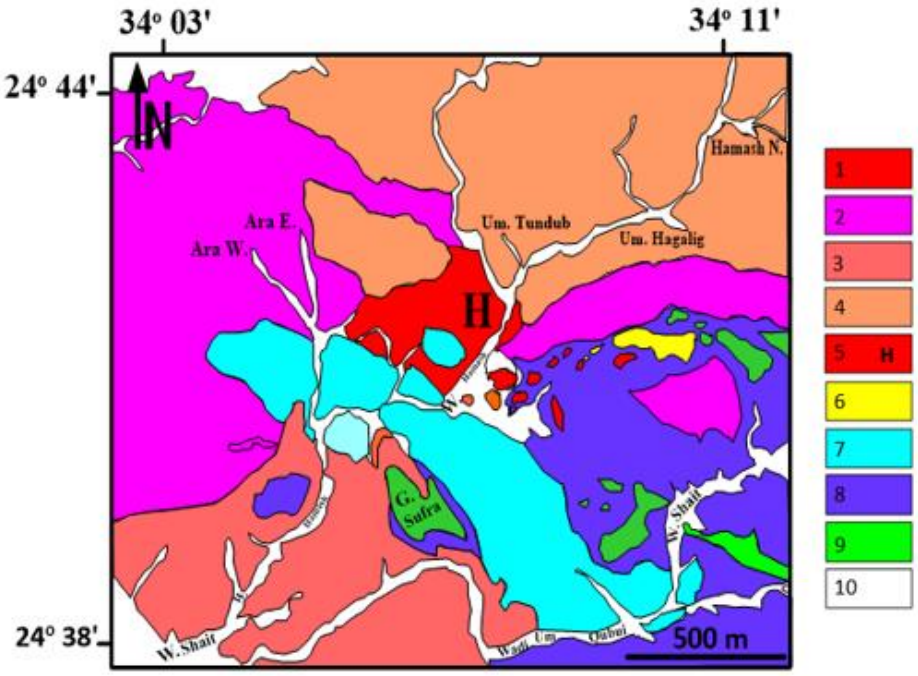

Fig. (4): The location and geological map of Hamash gold mines areas, Egypt (Helmy et al., 2004)

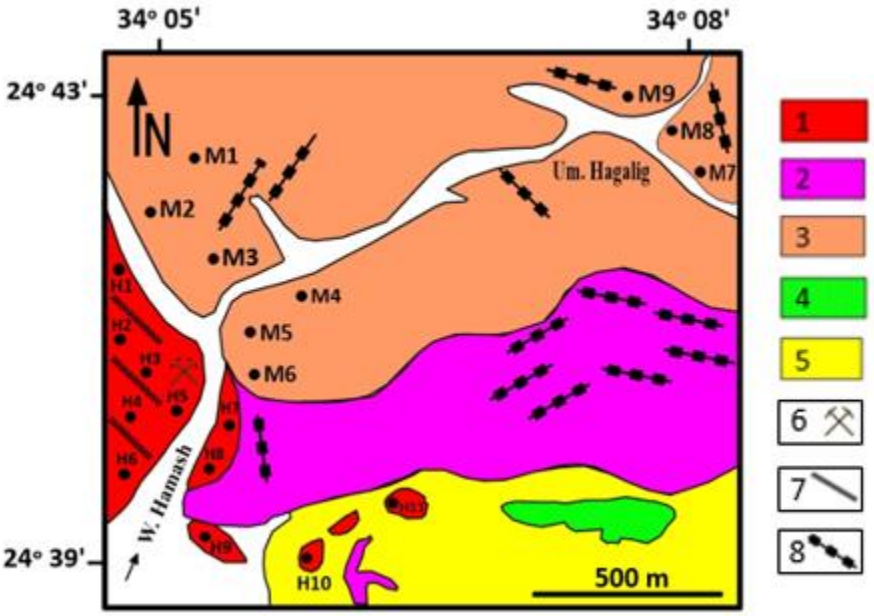

Fig. (5): The geological map of the samples collected from Hamash, HGMA, Egypt. (Mitwalli, Saleh, et al., 2019; Helmy & Kaindl, 1999)

1. Younger granites, 2. Older granites, 3. Metavolcanics, 4. Serpentinites, 5. Metasediments, 6. Hamash gold mine, 7. Au-Cu quartz veins, 8. Shear zones.

2.3. Sample preparation:

Neutron activation analysis of the samples obtained was carried out by relative and absolute methods (Atomizdat, Moscow, 1974). First, the samples are dried in electric oven for one hour, then it was necessary to grind to a fine powder. The grinding time was chosen—5–8 min, the rotation speed—600 rev/min. The resulting powder was carefully poured for temporary storage in labeled glass vials. The mass of each sample was approximately 0.1 gm. as shown in Fig (6 and 7).

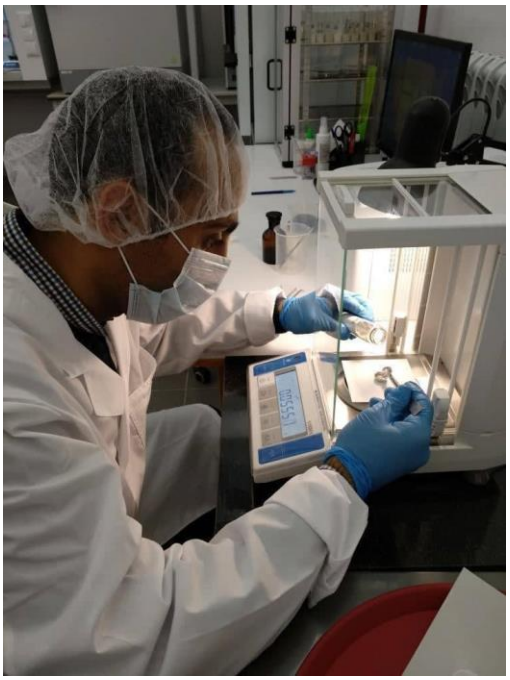

Fig. (6): weighting stage

Fig. (7): packaging stage

2.4. Packaging samples:

Standards with a similar mass were packed in the same way as the samples in aluminum capsules. In the experiment, the following standards were used, made at the National Institute of Standards and Technology, USA: 2710A—Montana I Soil, 1633C—Bituminous coal fly ash, 1635A—Trace elements in coal (subbitumimous), 2586—Trace elements in soil containing lead from paint, 2684C—Bituminous coal (nominal mass fraction 3% sulfur), 2431—Titanium base alloy, 87A—Silicon-aluminum alloy, 2782—Industrial sludge, 50C—Tungsten,

chromium, vanadium steel. Standards are needed to calculate the mass fractions of elements in the samples by the relative method of NAA.

In addition to the studied samples and standards, flux monitors were prepared for irradiation – zirconium samples, which were used to calculate thermal and resonance neutron fluxes. We need to know the fluxes to control the flux gradient and to quantify the content of elements by the absolute method of NAA. The masses of zirconium samples were from 0.12 to 0.15 g.

Capsules with samples and standards, as well as flux monitors, were packed with aluminum foil in 9 sets of cylindrical shape. In five sets, zirconium was placed on the first (towards the neutron flux) and the penultimate position, on the last one—zirconium in cadmium protection. The samples under investigation were placed between the zirconium samples, and standards in the middle of the sets. All nine sets were placed in a 3 by 3 matrix and packed in aluminum foil.

3.3. Irradiation samples

A facility for radiation studies at beam no. 3 of the IBR-2 reactor at the FLNP JINR was used to irradiate samples (Cheplakov et al 2014; Bulavin 2018). This facility has unique characteristics. It allows even large objects (180 × 180 mm) to be irradiated with neutrons and gamma quanta just a few tens of millimeters from the reactor core, which makes it possible in a short time to get a sufficiently large neutron fluence on the sample under study (~1018 n/cm^2) in wide energy range (25–10 MeV).

Capsules with samples and standards for irradiation was placed out in the head of the facility at a distance of 100 mm from the surface of the water retarder VZ-303 of the IBR-2 reactor. Irradiation was carried out for 2 days at an average reactor power of 1875 kW. Herewith, the thermal neutron flux density Φth was 7.2 × 10^{11} n/(cm^2 s), the resonance Φ_{res}1—1.2 × 10^{11} n/(cm^2 s).

3.4. Gamma acquisition

Five days after the end of the irradiation, samples and standards were repacked from aluminum capsules into clean plastic containers, and zirconium samples were removed from cadmium protection. Immediately after repacking, the first measurements of the spectra of induced activity were carried out for 1.5 h. The second measurements of the spectra started 22 days after the end of the irradiation. Spectra were measured within 4 hours. An automatic system for measuring the spectra of induced activity, developed and successfully used at FLNP JINR (Frontasyeva 2016; Pavlov 2014), was used for the data acquiring. The spectra were measured with a Canberra GC4018 HPGe detector with a resolution of 2.1 keV for 60Co gamma line with energy of 1332.5 keV.

3.5. Analysis spectra of NAA and calculations

Concerning spectra processing the Canberra Genie-2000 program was used. Since the end result of the work of the Genie-2000 program is the activities of the isotopes found in the studied samples as shown in Fig (11).

The calculations of concentration depended on program created at FLNP JINR (Dmitriev 2013) was used to calculate the mass fractions of the elements. When processing neutron flux monitors 2 lines of Zr-95: 724.2 keV (intensity 44.2%) and 756.7 keV (intensity 54%) were considered as shown in Fig. (12).

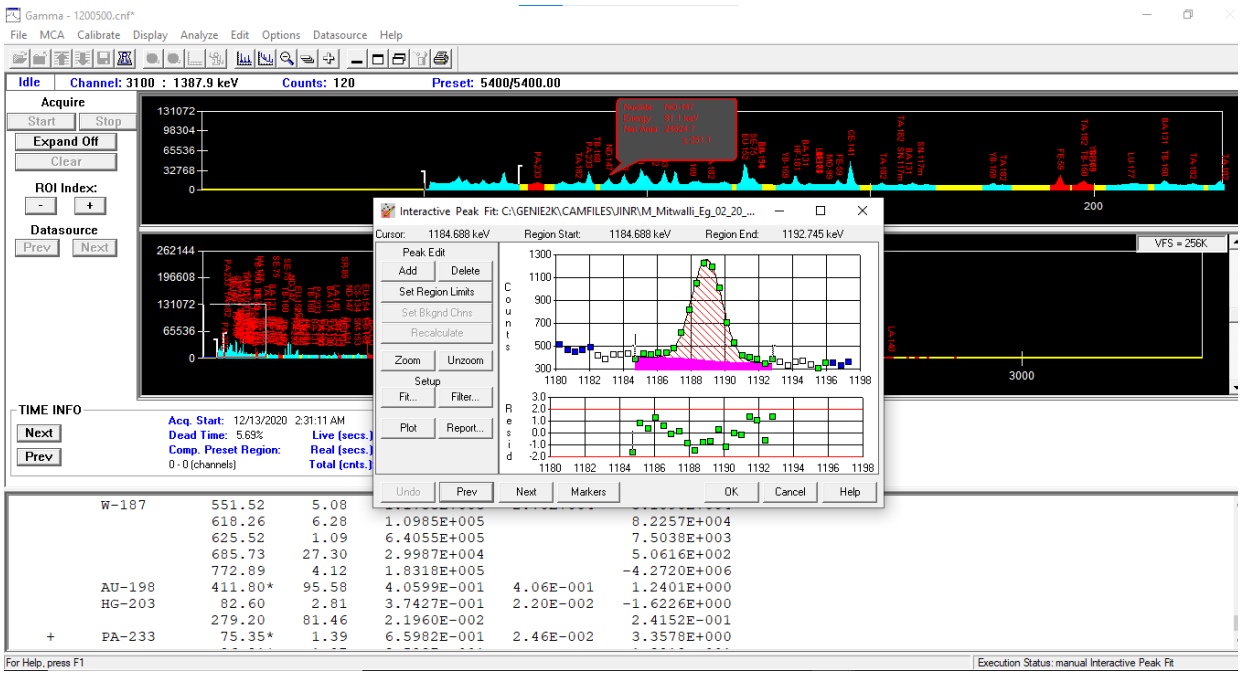

Fig (11): Genie-2000 software for analysis process of investigated spectrum.

Finally, the results must be processed by program CalcCONC to obtain the fractional mass of elements as shown in Fig. (31).

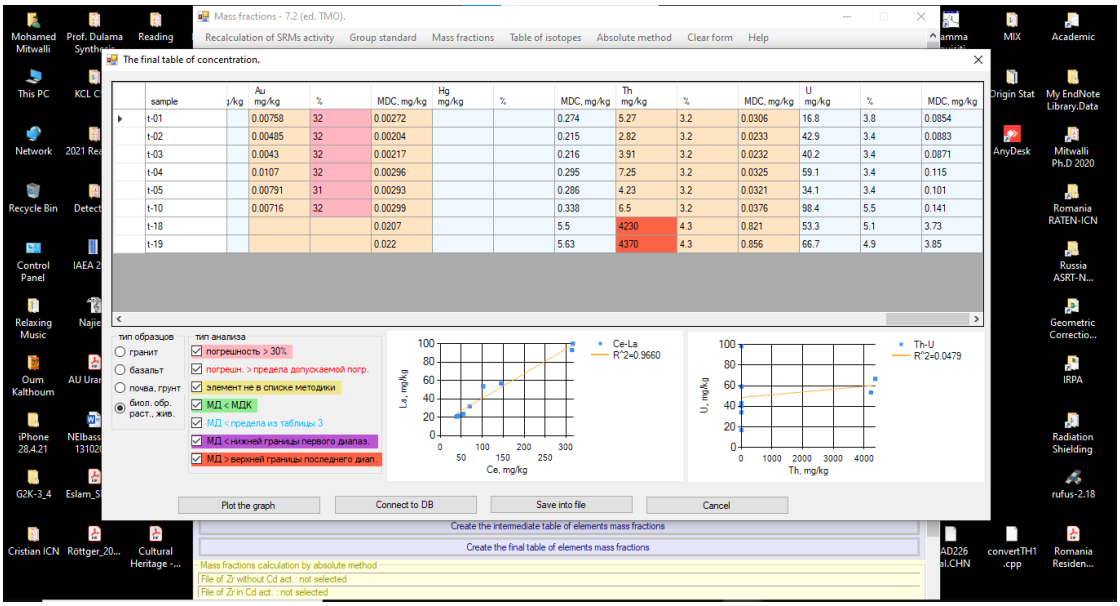

Fig. (12): The results with the concentrations for long-lived samples from Egypt.

Chapter 3

Result and Discussion

The obtained data of radioanalytical measurements are shown Fig. (13and 14) indicated a significant high concentration of equivalent uranium and thorium according to reports of (IAEA 2013, ICRP 2007, ICRP 1993; UNSCEAR 2000; NCRP 2015). Fig. (15 and 16) shown the comparison between the values of Clark ratio of Uranium/Thorium for both Sukari and Hamash Gold Mines which indicated also of high abundance of equivalent uranium and thorium respectively.

Concerning distribution pattern of both equivalent uranium and thorium, contour maps had established to track the activity concentration belonging coordination as shown in Fig. (17, 18, 19, and 20).

Regarding, rare elements have been assessed as well as high abundance particularly (Sc, La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu) (Stosch, 2016) compared to UCC and NASC (Taylor & McLennan, 1995; Zhao et al., 2007). The data set of investigated samples furnish elemental composition of both gold mines and proved that correlation relation and picking-up of a heavy element, perpetually uranium and thorium combined to gold mines.

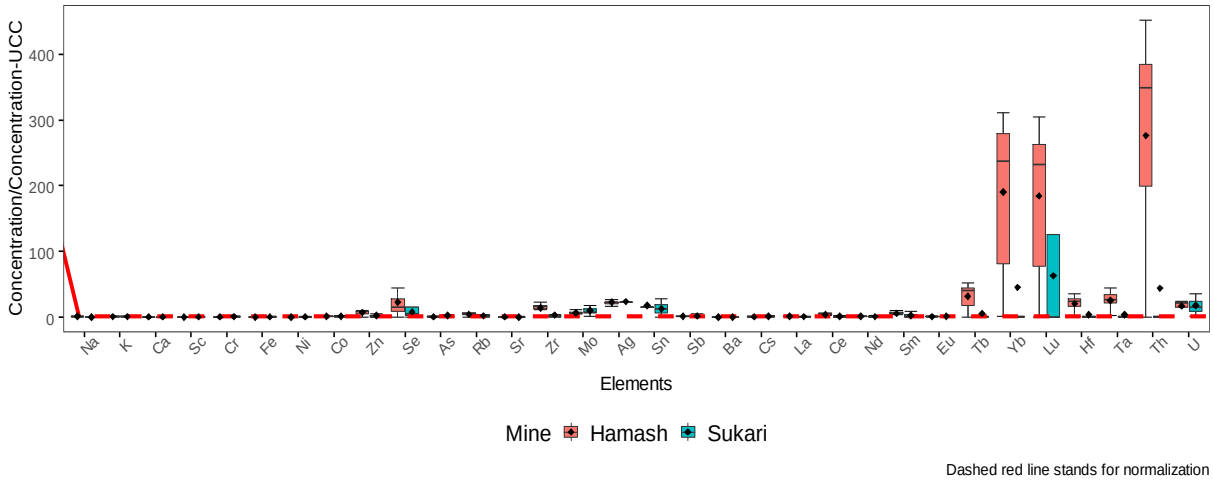

Fig. (13): Boxplot shows the normalized concentrations to Upper Continental Crust UCC.

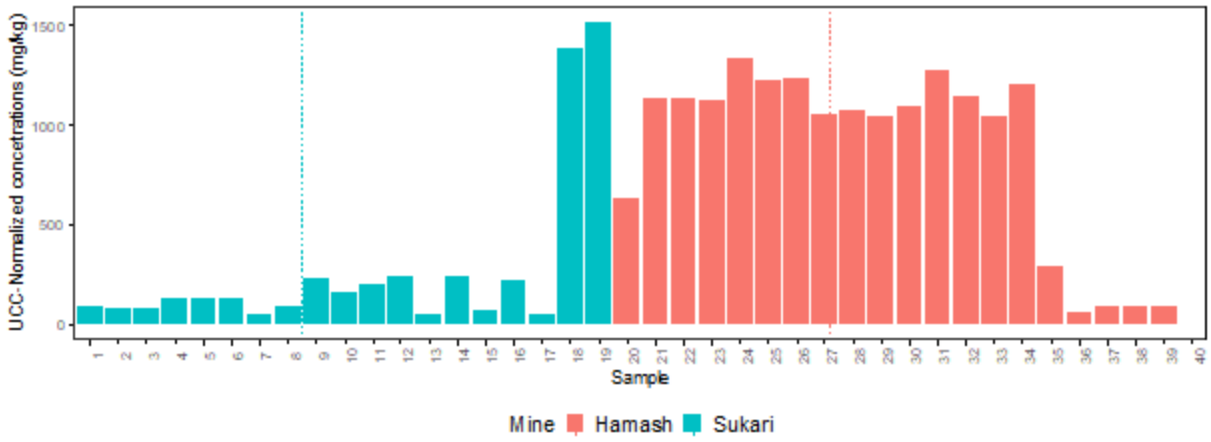

Fig. (14): Upper Continental Crust normalized the average value of all elements from each mine.

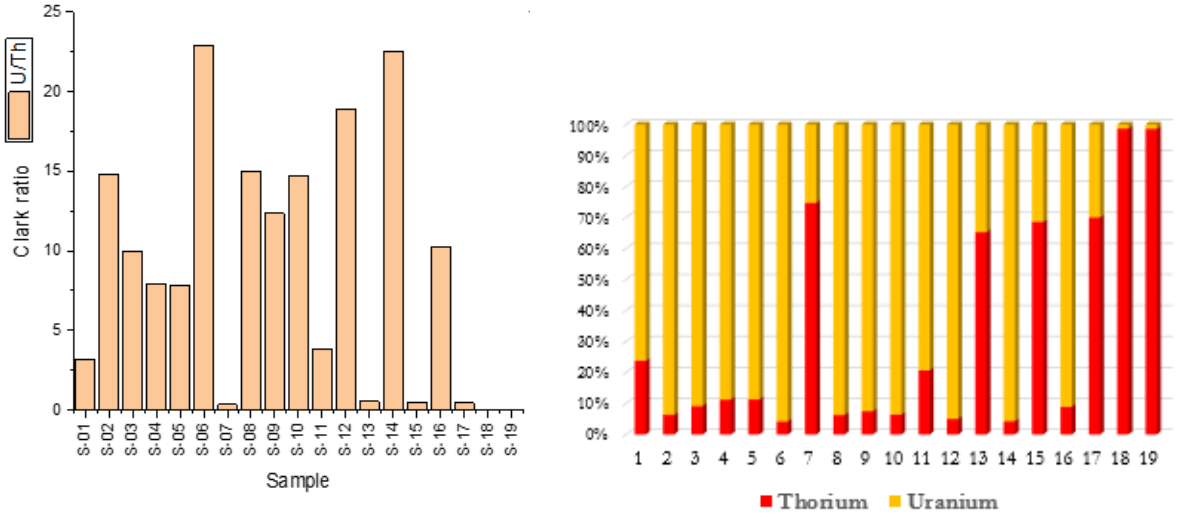

Fig. (15): The comparison between the values of Clark ratio of Uranium/Thorium Sukari Gold Mine (SGM)

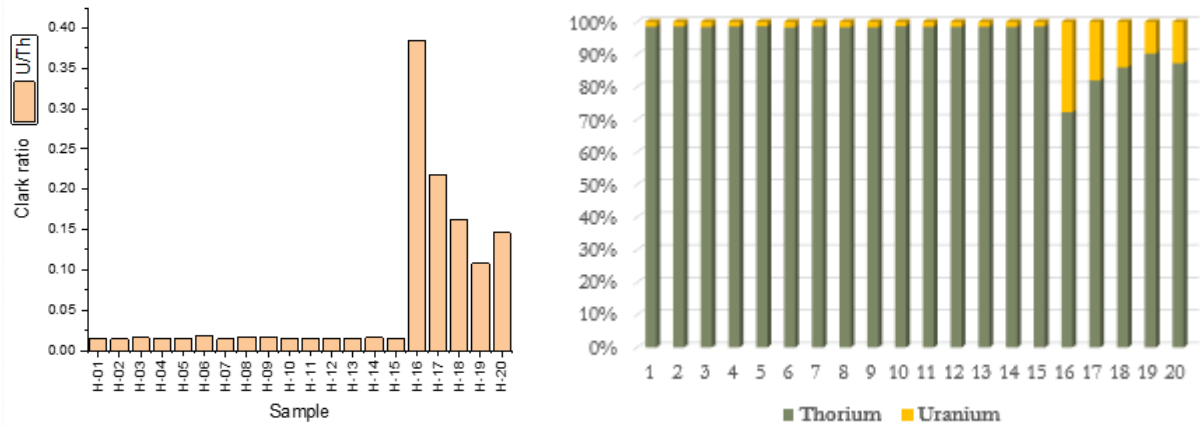

Fig. (16): The comparison between the values of Clark ratio of Uranium/Thorium Hamash Gold Mine (HGM)

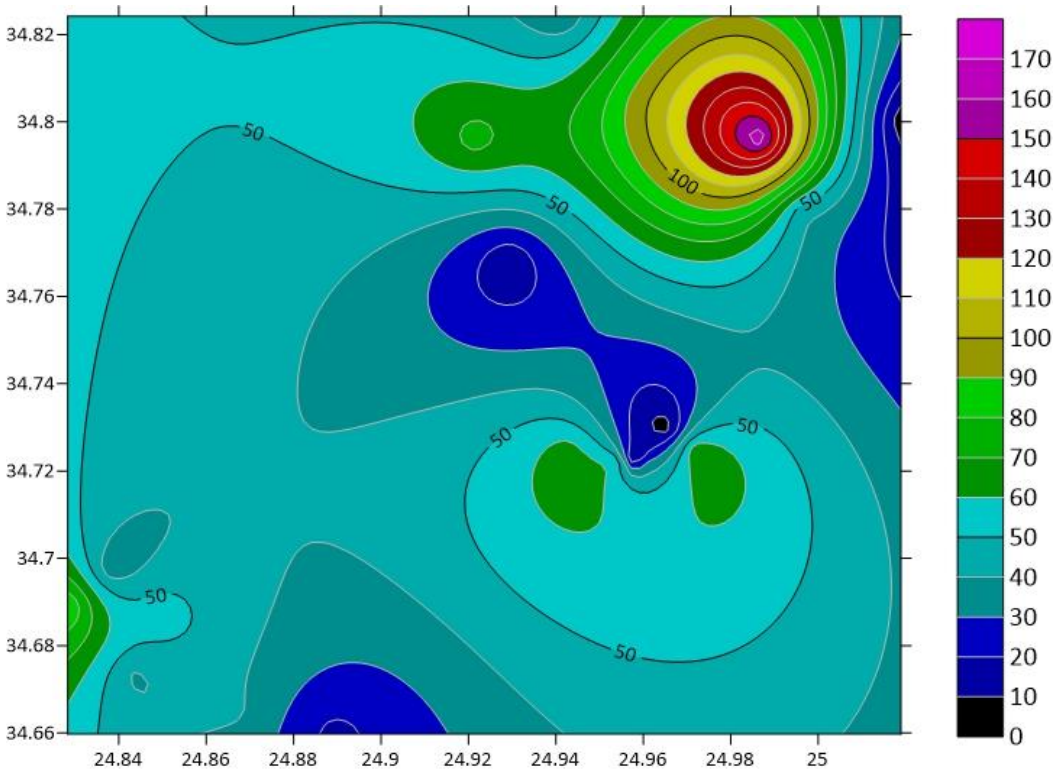

Fig. (17): Contour map of uranium distributions in Sukari Gold mine (SGM)

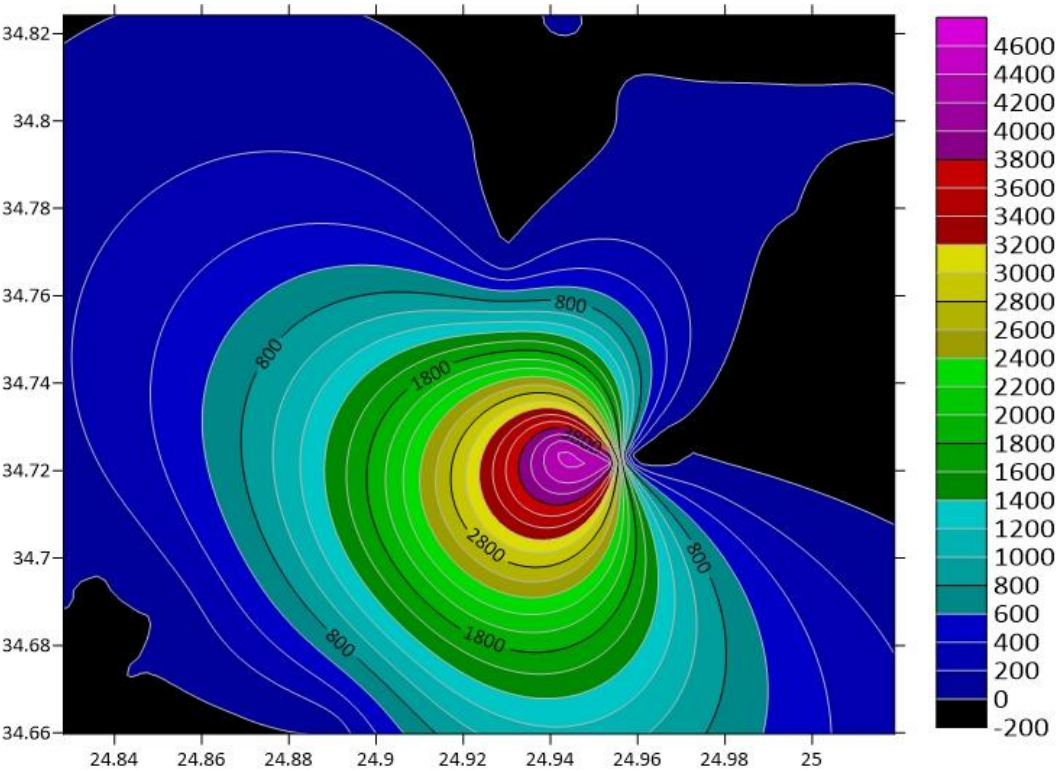

Fig. (18): Contour map of Thorium distributions in Sukari Gold mine (SGM)

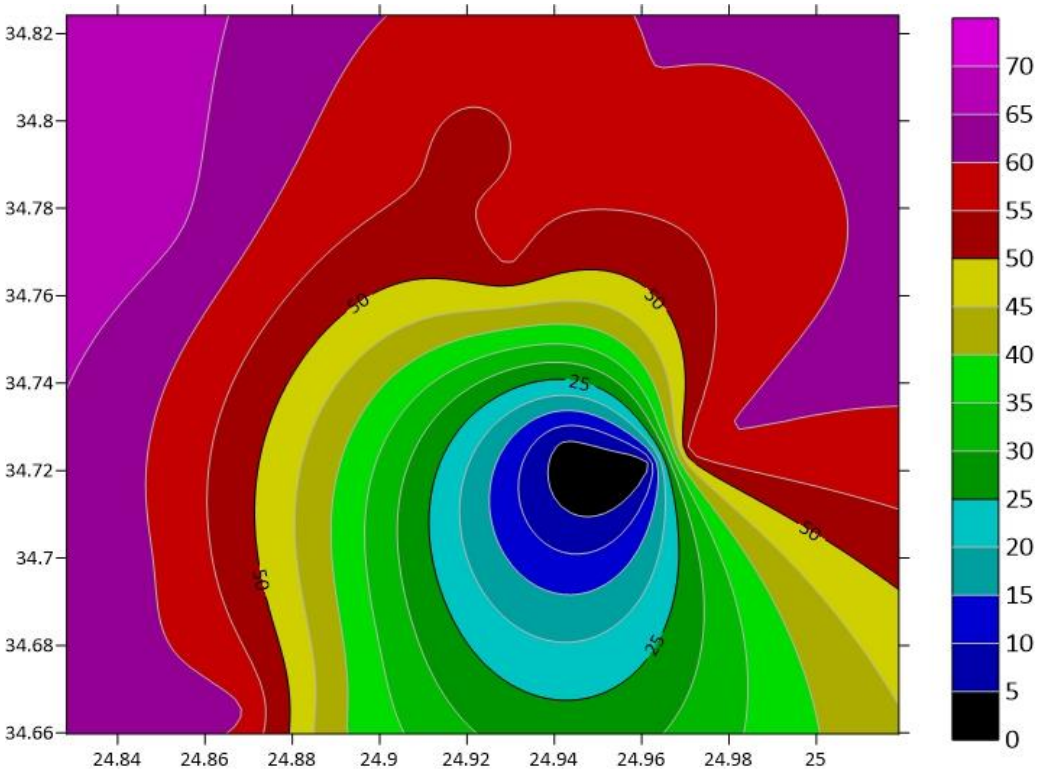

Fig. (19): Contour map of uranium distributions in Hamash Gold mine (HGM)

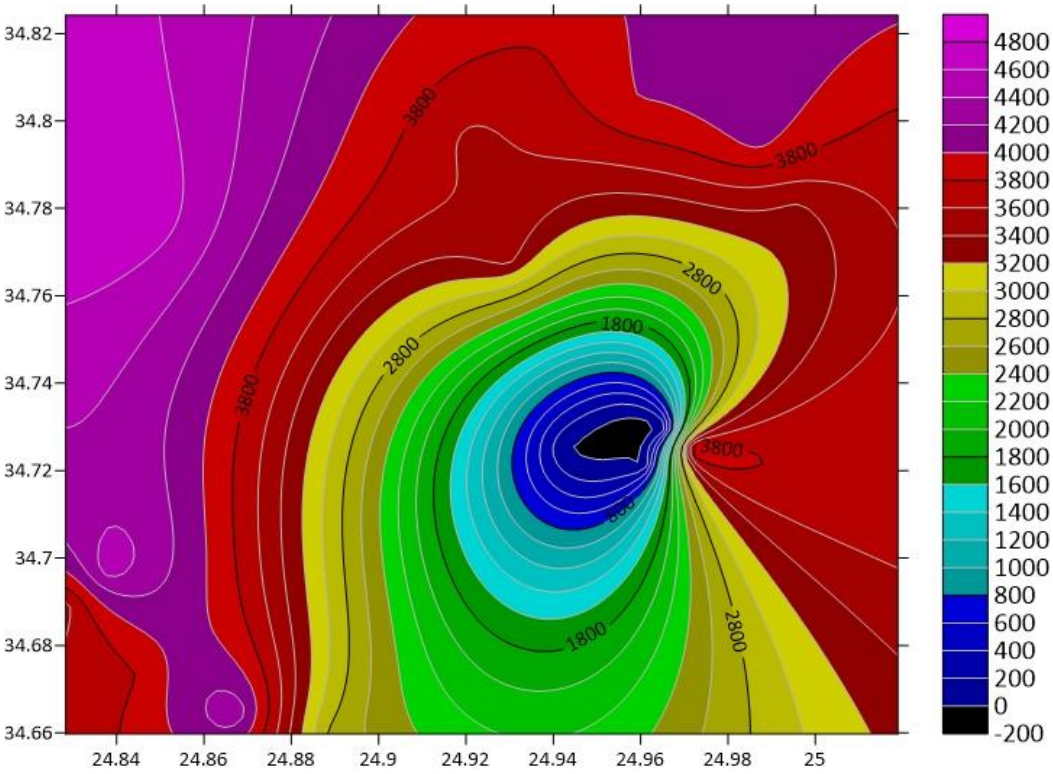

Fig. (20): Contour map of Thorium distributions in Hamash Gold mine (HGM)

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Report of summer student programme

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