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Technical note

Evaluation of heat generation by radioactive decay of sedimentary rocks in Eastern Desert and Nile Valley, Egypt

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ABSTRACT

Radioactive heat-production (RHP) data of sedimentary outcrops in Gebel Anz (Eastern Desert) and Gebel Sarai (Nile Valley) are presented. A total of 103 rock samples were investigated, covering all major rock types of the areas. RHP were derived from uranium, thorium and potassium concentrations measured from gamma-radiation originating from the decay of ^{214}Bi (^{238}U series), ^{208}Tl (^{232}Th series) and the primary decay of ^{40}K, obtained with a NaI (Tl) detector. The heat-production rate of Gebel Anz ranges from 0.94 (Nubai Sandstone) to 5.22 $\mu W\,m^{-3}$ (Duwi Formation). In Gebel Sarai it varies from 0.82 (Esna Shale) to 7 $\mu W\,m^{-3}$ (Duwi Formation). The contribution due to U is about 62%, from Th is 34% and 4% from K in Gebel Anz. The corresponding values in Gebel Sarai are 69.6%, 26.9% and 3.5%, respectively. These data can be used to discuss the effects of the lateral variation of the RHP rate on the heat flux and the temperature fields in the upper crust.

1. Introduction

During radioactive decay mass is converted to energy. This energy is set free as the kinetic energy of the involved particles and nuclei (emitted α- and β-particles, recoil nuclei) and as the energy of the accompanying γ-radiation. Except for the energy carried away by the neutrino the whole decay is converted to heat. All naturally radioactive isotopes generate heat to a certain extent. It can be shown, however, that the only significant contributions arise from the decay series of U^{238}, U^{235} and Th^{232}, and from the isotope K^{40}. In geophysical studies, the heat produced by radioactive decay in rocks is of fundamental importance in understanding the thermal history of the Earth and interpreting the continental heat-flux data (Hurley and Fairbairn,1953; Rybach, 1976).

Radioactive elements found in the crust and mantle form the basis for several major applications in geophysics and geochemistry. The heat produced by naturally radioactive elements in rocks is a key factor in geothermal studies, especially in the interpretation of continental heat-flow density data. Combined determinations of heat-flow density and of radioactive heat production rate yield basic information about the temperature field and the structure of the Earth's crust and are indispensable to understanding the interrelations between heat-flow density and geology (Rybach, 1988).

Radiogenic heat production (RHP) represents a significant fraction of surface heat flow, both on cratons and in sedimentary basins. RHP within continental crust – especially the upper crust – is high. RHP at any depth within the crust can be estimated as a function of crustal age. Mantle RHP, in contrast, is always low, contributing at most 1–2 mW/m^2 to total heat flow (Waples, 2002). On the average, heat flow at the earth's surface amounts to about 65 $mW\,m^{-2}$ and the heat flow from the mantle – in continental areas – is around 20 $mW\,m^{-2}$; the difference is due to radioactive heat generation in crustal rocks. In this regard, K^{40}, U^{238}, U^{235} and ^{232}Th are the most important radioactive nuclides. These heat sources contribute significantly to the heat flowing out from the Earth, since they are abundant, their heat production is sufficiently large and they have been effective during a time comparable with the age of the Earth (Verdoya et al., 1998; Chiozzi et al., 2000; Kukkonen and Lathinen, 2001).

Surface exposures of rocks forming the crust and upper mantle are a possible source of information for estimating the distribution of the heat-producing elements and thus the variation with depth of the radiogenic heat production rate (e.g. Nicolaysen et al., 1981; Ashwall et al., 1987; Jaupart et al., 1998; Verdoya et al., 1998; Paolo et al., 2002). Several analytical techniques can be used to determine the concentrations of the heat-producing elements, but gamma-ray spectrometry is the only one that enables simultaneous determination of U, Th and K, and its accuracy is generally sufficient in most ordinary crystal rocks.

The vertical distribution of radioactive heat production in the crust is an important factor for estimating temperatures at depth. In island arcs, Furukawa and Uyeda (1989) found for rocks in the Hidaka region, northern Japan that the heat generation in the

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granitic rocks decreases with depth in a similar way to that in the exponential model (Lachenbruch, 1970), which has been widely accepted for stable continental areas. Mukai et al. (1999) recently carried out measurements on samples from Kohistan and the northeast Japan arcs and demonstrated that the heat production is extremely low in the lower crust. The radioactive heat production is fairly well known for a large set of igneous, metamorphic and sedimentary rocks (Pint and Jaupart, 1987), but information is still relatively poor for Egyptian rocks (Abbady et al., 2006).

This paper presents results of radioactive heat production (RHP) measurements on sedimentary rock outcrops in the Eastern Desert and Nile Valley, Upper Egypt. These data can be used to discuss the effects of the lateral variation of the RHP rate on the heat flux and the temperature fields in the upper crust.

2. Experimental procedure

One hundred and three samples from Gebel Anz (Eastern Desert) and Gebel Sarai (Nile Valley) have been collected and prepared for measuring by gamma spectroscopic analysis. Both G. Anz (longitudes 34°5′ and latitudes 26°55′) and G. Sarai (longitudes 32°50′ and latitudes 26°55′) consist of the following sedimentary rocks layers: 1—Thebes Formation, 2—Esna Shale, 3—Tarawan Chalk, 4—Dakhia Shale, 5—Duwi Formation, 6—Qusier Shale and 7—Nubian Sandstone (Mousa, 1988).

In order to calculate heat production from the sample under investigation the uranium, thorium and potassium concentrations must be determined. The spectrometer consists of a Na (Tl) detector connected with a 1024 microcomputer multichanel analyzer. The detector has the following characteristics: peak efficiency: 1.2×10^{-2} at 1332 keV, crystal dimensions 3×3 in and resolution: 7.5% for 662 keV. The samples are collected in their natural form and ground to a fine powder, dried and sealed in cylindrical polyethylene containers of 5.5 cm diameter and 1.3 cm height (Abbady, 1994).

The ^{238}U activities for samples were estimated from ^{214}Pb (242.2, 295.2, 351.9 keV) and ^{214}Bi (609.3, 1120.3 keV). The gamma-ray energies of ^{212}Pb (238.6 keV), ^{228}Ac (338.4, 911 keV) and ^{208}Tl (583.2 keV) were used to measure the concentration of ^{232}Th, while the ^{40}K activity was determined from the 1460.7 keV emission. The sample was sealed and the measurements were made one month later to assure secular equilibrium between the ^{226}Ra and its daughters (ICRP, 1983; Manazul et al., 1999). The activity concentrations of the natural radionuclides in the measured samples were computed using the following relation (Noorddin, 1999; Abbady, 2002):

$$A_S(\mathrm{Bq\,kg^{-1}}) = C_a/\varepsilon P_r M_s \tag{1}$$

where C_a is the net gamma counting rate (counts per second), ε the detector efficiency of the specific γ-ray, P_r the absolute transition probability of gamma-decay and M_s the mass of the sample (kg).

The contents m in (ppm) of U, Th and K in the samples is determined from their measured activity values by applying the equation (Knoll, 1989):

$$m(\mathrm{ppm}) = AMt_{1/2}/N_{Av}\ln 2 \tag{2}$$

where A is activity in (Bq/g), M the molecular weight (g/mol), N_{Av} avogadro's number (6.02×10^{23}) and $t_{1/2}$ is half-live in seconds.

The radioactive heat generation of a given rock A (in μW m^3) can be calculated by taking into account the heat generation constant (amount of heat released per gram U, Th and K per unit time) and from the uranium, thorium and potassium concentrations C_u, C_{Th} and C_k present in rock (Rybach, 1976; Bucker and Rybach, 1996):

$$A = \rho(9.52C_u + 2.56C_{Th} + 3.48C_k)10^{-5} \tag{3}$$

where ρ is the density of the rock (in kgm^{-3}); C_u and C_{Th} are in weight ppm; C_k are in weight %.

3. Results and discussion

Radioactive heat generation is a scalar petrophysical property independent of *in situ* temperature and pressure. It is usually expressed in terms of heat generated per unit volume and time (e.g. in μW m^{-3}). The heat generated by the decay of naturally radioactive elements in the earth's crust contributes a substantial portion to terrestrial heat flow.

Mean concentrations of U, Th and K from Na (Tl) analysis and the calculated heat generation in Sedimentary rock layers from Gebel Anz and Gebel Sarai are shown in Figs. 1 and 2. The lowest values of U (3.5 ppm), K (0.54%) and Th (9.1 ppm) were observed in Nubian Sandstone and Thebes Formation from G. Anz. With respect to shale samples the lowest values of Th (4.9 ppm) and U (5.5 ppm) were observed in Dakhla Shale and Tarawan Chalk from G. Sarai but for K (1.03%) the value is observed in Esna Shale from G. Anz. The highest mean values of U (63.6 ppm), K (1.9%) and Th (56.6) were found in Duwi Formation (phosphorite beds) in G. Sarai and G. Anz.

Representative averages of radioactive heat production in Thebes Formation, Esna Shale, Tarawan Chalk, Dakhia Shale, Qusier Shale, Nubian Sandstone and Duwi Formation are 1.02, 1.4, 1.6, 1.3, 2.1, 0.94 and 5.2 μW m^{-3} for G. Anz, respectively. The corresponding values in G. Serai are 1.22, 0.82, 0.97, 0.92, 1.55, 1.8 and 7 μW m^{-3}, respectively.

It is evident from Eq. 3 that heat generation in a given rock is governed by the amounts of uranium, thorium and potassium present, which vary greatly with rock type but exhibit certain regularities due to the similar geochemical behavior of U, Th and K during the processes which determine the distribution of the natural radioelements (magmatic differentiation, sedimentation, metamorphism). Uranium and thorium do not exhibit similar behavior as they do in igneous rocks, mainly because U is more readily oxydized ($U^{4+}\rightarrow U^{6+}$) in aqueous solutions. Consequently, Th/U ratios show considerable variation which reflects pH–E_h conditions during sedimentation: one finds high ratios (Th/U > 6) in continental formations deposited in an oxydizing milieu but low ratios (Th/U < 2) in sediments of a reducing marine environment (Cermak et al., 1982a, b).

The ratios of heat production due to U (HP_U/HP_{Total}), Th (HP_{Th}/HP_{Total}), K (HP_K/HP_{Total}) and total heat production for all studied samples are listed in Tables 1 and 2 U and Th contribute in most sedimentary rocks a comparable amount whereas K contributes an always smaller amount to total heat production, in proportions of about 62%:34%:4% in all samples from G. Anz. The corresponding values in G. Sarai were 69.6%, 26.9% and 3.5%, respectively. U, Th and K abundances as well as heat generation values for sedimentary rocks compared with other published data are given in Table 3.

Radiogenic heat from any noncrystalline basement that may be present also contributes to total heat flow. RHP from metamorphic rocks is similar to or slightly lower than that from their precursor Lithospheric RHP today is than in the distant past, as a result of radioactive decay. In modeling, RHP can be varied through time by considering the half lives of uranium, thorium,