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Assessment of gamma radiation exposure of beach sands in highly touristic areas associated with plutonic rocks of the Atticocycladic zone (Greece)

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ABSTRACT

This study aims to evaluate the activity concentrations of ^{238}U, ^{226}Ra, ^{232}Th, ^{228}Th and ^{40}K along beaches close to the plutonic rocks of the Atticocycladic zone that ranged from 15 to 628, 12-2292, 16-10,143, 14-9953 and 191-1192 Bq/kg respectively. A sample from island of Mykonos contained the highest ^{232}Th content measured in sediments of Greece. The heavy magnetic fraction and the heavy non-magnetic fraction as well as the total heavy fraction, were correlated with the concentrations of the measured radionuclides in the bulk samples. The heavy fractions seem to control the activity concentrations of ^{238}U and ^{232}Th of all the samples, showing some local differences in the main ^{238}U and ^{232}Th mineral carrier. Similar correlations have been found between ^{238}U, ^{232}Th content and rare earth elements concentrations. The measured radionuclides in the beach sands were normalized to the respective values measured in the granitic rocks, which at least in most cases are their most probable parental rocks, so as to provide data upon their enrichment or depletion. Since the Greek beaches are among the most popular worldwide the annual effective dose equivalent received due to sand exposure has been estimated and found to vary between 0.002 and 0.379 mSv y^{-1} for tourists and from 0.018 to 3.164 mSv y^{-1} for local people working on the beach. The values corresponding to ordinary sand samples are orders of magnitude lower than the limit of 1 mSv y^{-1}, only in the case of heavy minerals-rich sands the dose could reach or exceed the recommended maximum limit.

1. Introduction

Beach sands are composed mainly of quartz, feldspar and other minerals resistant to wave abrasion. They are the products of a combination of weathering, fragmentation, and degradation process (Pettijohn et al., 1987). Beach placer or “black sand” deposits around the world are known for their economic concentrations of heavy minerals such as monazite, zircon, ilmenite, rutile, garnet, allanite and sillimanite. They often contain high amounts of Rare Earth Elements (REE) like U and especially Th (Alam et al., 1999; Freitas and Alencar, 2004).

The study of the distribution of natural radionuclides (^{238}U, ^{232}Th, their daughter products and ^{40}K) allows the understanding of the radiological implication of these elements due to the gamma-ray exposure of the body and irradiation of lung tissue from inhalation of radon and its daughters. Therefore, the assessment of gamma radiation dose from natural sources is of particular importance as natural radiation is the largest contributor to the external dose of the world population (UNSCEAR, 1993; 2000). Various studies on natural radioactivity levels of sands have been carried out worldwide, with particular attention directed at locations with high background levels of radiation, such as India and Brazil or countries with extended sand landscapes. Exposure dose rates of the public have been also assessed indicating that these dose rates vary depending upon the concentration of the natural radionuclides present in sands and bed-rocks, which in turn depend upon the local geology of each region (e.g. Alam et al., 1999; Freitas and Alencar, 2004, De Meijer et al., 1988; 2001, Mohanty

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et al., 2004; Veiga et al., 2006; Vassas et al., 2006; Harb, 2008; Shetty et al., 2011; Nada et al., 2012; Margineanua et al., 2014; Örgün et al., 2007).

The coastline of Greece is one of the largest worldwide and many of its beaches are highly touristic such as the beaches of the Aegean islands which are among the most famous summer destinations of the world. Heavy minerals-rich beach sands (black sands) which are usually associated with high levels of natural radioactivity have been reported in Greece and more especially in Touzla area (Filippidis et al., 1997) and in N. Peramos near Kavala (Pergamalis et al., 2001) as well as across the beaches of Kavala, Sithonia Chalkidiki, Maronia and Samothraki (Papadopoulos et al. 2014a,b; 2015a, b), being adjacent to nearby plutons – granitic rocks. The granitic rocks present, are well known for their elevated natural radioactivity levels compared to other natural stones. Therefore, any data providing information about the radioactive dose estimations to the people would be very important for radiological protection.

This study is focused on the beach sands that are placed adjacent to the plutonic rocks of the Atticocycladic zone, which are their most probable parental rock, or at least they provide weathering material. Any existing data on the natural radioactivity of these rocks are used. The main goal of this work is to assess the activity concentrations of the natural radionuclides on the beach sands close to the plutonic rocks of the Atticocycladic zone. The activity concentrations of ^{238}U, ^{226}Ra, ^{232}Th, ^{228}Th and ^{40}K were measured using gamma spectroscopy method. Radionuclide concentrations is correlated to varying mineral fractions total heavy, heavy magnetic and heavy non-magnetic fractions as well as to the REE (Rare Earth Elements) content. The evaluation of the enrichment or depletion of the natural radionuclides in beach sands relative to the granitic rocks is also attempted. Moreover, the absorbed gamma dose rate and the annual effective dose equivalent received by the population due to their exposure on gamma radiation of the beach sands are also presented.

2. Materials and methods

2.1. Geological setting of the granitic plutons

Granitic rocks compared to other types of rocks, contain higher amount of U and Th following the general concept that the more felsic rock types are the most U and Th enriched (Papadopoulos et al., 2014c). This is directly expressed in the mineralogical composition of these rocks which are generally rich in minerals such as zircon, apatite, titanite, monazite xenotime etc. All the above mentioned minerals are U and Th- enriched and they are classified as heavy minerals being the weathering products of the local granitic rocks. Therefore, in environments where the physical and mechanical conditions are favorable, for the formation of beach placer deposits, it is very likely that the beach sands contain high U and Th concentrations.

The geology of the Atticocycladic Zone is characterized by numerous granitic plutons of various compositions. More specifically, the granitic plutons placed in Serifos, Mykonos, Tinos, Paros, Naxos, Delos, Rinia and Ikaria islands. The petrography, geochemistry, petrogenesis and age of the granites of this zone have been extensively studied (Altherr et al., 1982; 1988; Buick, 1991; Pe-Piper et al., 1997; Pe-Piper, 2000; Altherr and Siebel, 2002; Pe-Piper and Piper, 2002; Pe-Piper et al., 2002; Skarpelis et al., 2008; Iglseder et al., 2009; Stouraiti et al., 2010). The mineralogical composition and rock-types of the granitic plutons of the Atticocycladic zone are given on Table 1 and the sampling locations are illustrated in Fig. 1.

2.2. Collection and pre-treatment of the samples

Representative sediment samples obtained from 28 sites (separated each other by around 500 m) were collected from beaches, close to the plutonic rocks of the Atticocycladic zone (Fig. 1), using sampling intervals relative to the length of each beach. Several samples collected, were collected from specific horizons of black or green color of 1–4 cm, heavily enriched in heavy minerals (Fig. 2) at the locations of samples MYK14 (Mykonos), SN2A, SN3, SN6 (Naxos) and SER2, SER3 (Serifos). All the above mentioned samples contain >10% wt heavy minerals.

For each sand sample analyzed, three sub-samples of equal mass (≈500 g) were obtained from a depth of 20 cm. The sub-samples, corresponded to 3 different points, forming an equilateral triangle (with dimensions of ≈1.4 m) corresponding to an area of approximately 1 m^2. The three sub-samples were homogenized by mixing in situ and this sand mixture, weighing approximately 1.5 kg, was considered as representative.

The samples were cleaned with warm water and dried in the laboratory. Any coarse wastes (sea shells, etc.) were removed during sieving. The 8, 4, 2, 1, 0.5, 0.125 and 0.063 mm sieves were used to obtain the grain-size distribution of the samples. For the mineral separations, the 0.125–0.5 mm grain-size fraction was used, after the determination of the average grain size of the heavy minerals under the binocular microscope. After magnetite removal using a hand magnet, heavy liquid (tetrabromoethane, 2.967 g/cm^3) and a Frantz isodynamic separator were employed to determine the wt % heavy fraction and the heavy magnetic and non-magnetic fractions of the whole sample. The heavy magnetic fraction (<0.8 amp at forward and side slope of 15° and 25°, respectively) contains allanite, amphibole, mica, clinopyroxene, magnetite and hematite while the heavy non-magnetic fraction (>0.8 amp at same settings) contains monazite, zircon, titanite and apatite. All of them were identified under the binocular microscope. Sample preparation and mineral separations were performed at the laboratories of the Department of Mineralogy-Petrology-Economic Geology, School of Geology; Aristotle University of Thessaloniki.

2.3. X-ray diffraction spectroscopy

Ten samples were submitted for mineral identification and semi-quantitative analysis at ACTLABS, Ontario, Canada. A portion of each pulverized sample was loaded into a standard holder. The quantities of the crystalline mineral phases were determined using the Rietveld method. The Rietveld method is based on the calculation of the full diffraction pattern from crystal structure information. The X-ray diffraction analysis was performed on a Panalytical X'Pert Pro diffractometer, equipped with a Cu X-ray source and an X'Celerator detector, operating at the following conditions: 40 kV and 40 mA; range 5–70 deg 2θ; step size 0.017 deg 2θ; time per step 50.165 s; fixed divergence slit, angle 0.5°; sample rotation 1 rev/sec.

2.4. REE chemical analyses

The REE and other trace elements content of the whole-rock samples was determined by ICP-MS at Activation Laboratories (ACTLABS, Ontario, Canada) following a lithium borate fusion and dilute acid digestion. Their concentrations are given in Annex A1.

2.5. Gamma-ray spectroscopy

The samples after oven-dried at 60 °C to constant weight, were measured using two high-resolution gamma ray spectrometry systems. The first one consisted of an HPGe coaxial detector with