

RADIOACTIVITY OF GRANITIC ROCKS FROM NORTHERN GREECE

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Abstract

Forty-nine samples from several plutons in northern Greece have been studied for their activity concentrations of ⁴⁰K, ²²⁶Ra and ²³²Th by using gamma-ray spectroscopy. The activities of ⁴⁰K, ²²⁶Ra and ²³²Th of the majority of the samples exceed the average level of these radionuclides in soil and building materials. Samples of basic composition have very low concentrations of radionuclides while intermediate and acid rocks are more enriched in ⁴⁰K, ²²⁶Ra and ²³²Th and their decay products. In order to assess the radiological impact from the investigated rocks, absorbed gamma dose rate (D_a), annual effective dose (H_E), activity index (AI) and gamma-ray index (I_γ) were estimated. The activity concentrations and hazard indices were compared to those of plutonic rock samples from all over the world, as well as other building materials. The average of hazard indices of Greek granites is below 'world' average in all cases. Moreover, it is still below the criteria of UNSCEAR (2000). Therefore, at least from radiological point of view and for the investigated rocks, the use of granites from northern Greece as building materials is recommended.

Key words: granite, natural radioactivity, radiation, dose assessment, northern Greece.

1. Introduction

In igneous petrology, granite is a prevailing rock-type describing acid plutonic rocks having a particular mineralogy and geochemistry. However, in dimension stone market the term granite includes a variety of igneous and metamorphic rock-types, used as building materials. In recent years, use of granite as a decor material in buildings (indoors and outdoors) and monuments has globally increased, due to its durability and appearance. In this paper, the term "granite" is used for the plutonic rocks under study including granitic and monzonitic as well as gabbroic rocks.

Radioisotopes that are found in the environment can be classified as naturally occurring radionuclides that are components of the earth's crust since its formation (e.g. ²³⁸U, ²³⁵U, ²³²Th and ⁴⁰K and their decay products), cosmogenic radioisotopes (radioisotopes that are produced by the interaction between cosmic radiation and the atmosphere (e.g. ¹⁴C, ¹⁰Be, ⁴⁴Ti and ²²Na) and finally artificially produced radionuclides that are produced in nuclear reactors (e.g. ⁹⁰Sr and ¹³⁷Cs). Natural radionuclides can be found in soil, rocks, water, air, food, building materials, etc.

The study of natural radioactivity present in rocks and ornament stones, such as granite, is an im-



Fig. 1: Sketch map of northern Greece, presenting the location of plutons from which the granite samples were obtained.

portant subject in environmental radiological protection (Anjos et al., 2005) as it provides the possibility to assess any associated health hazard. This contribution aims at investigating the natural radioactivity level of selected granites from north Greece in order to assess their radiation dose exposure and give information about the potential use of them as building materials.

2. Materials and methods

The samples studied were taken from Pelagonian zone (Varnountas and Kastoria plutons), Circum Rhodope Zone (Sithonia and Maronia plutons), Serbomacedonian Massif (Mouries pluton) and Rhodope Massif (Vrontou, Elatia, Granitis, Panorama, Xanthi, Philippi, and Leptokaria-Kirki plutons) (Fig. 1). The mineralogy of the selected samples is presented in Table 1, while the rock-type along with the location of plutons from which the samples were obtained, is presented in Table 2. The petrographic classification was based on the QAP tertiary diagram (I.U.G.S., 1973).

Details on the petrography and geochemistry of the above plutonic rocks can be found in Christofides et al., 1998 and references therein, Koroneos, 1991; Grigoriadou et al., 2003; D' Amico et al., 1990 and Christofides et al., 1999.

The activity concentration of natural radionuclides was measured by gamma-ray spectrometry for 20 granite samples. Additionally, 29 samples from the same area were used from the literature (Karavasili et al., 2005).

In particular, the content of ^{226}Ra , ^{232}Th and ^{40}K of each sample was measured, as these occur in relatively high levels in the majority of the building materials and they represent the main external source of irradiation to the human body.

All samples were crushed into grains less than 400 μm in diameter, oven-dried at 60 °C to constant weight, well blended and measured using two different high-resolution gamma ray spectrometry systems. The first one consisted of a high purity (HP) Ge coaxial detector with 42% efficiency and 2.0 keV resolution at 1.33 MeV gamma-ray photons, shielded by 4'' Pb, 1 mm Cd and 1 mm Cu and the second one consisted of a low energy (LE) Ge planar detector with 0.7 KeV resolution at 122 keV gamma-ray photons, shielded by 1.3'' Pb, 1mm Cd and 1 mm Cu. The efficiency calibration of

Table 1. Mineralogy (modal composition) of selected samples

sample	Qz	Kf	Pl	Hb	Bi	Mu	Px	Oth	Tot
MP-6	1.2	20.2	50.5	8.8	12.7	0.0	1.1	5.5	100.0
MP-77	14.4	37.0	28.2	16.4	0.1	0.0	0.0	3.9	100.0
XMZ-501	4.1	39.4	28.2	0.2	11.3	0.0	16.0	0.8	100.0
MP-3	6.6	31.0	35.9	11.0	12.4	0.0	0.0	3.1	100.0
MP-38	2.3	31.0	40.6	0.7	9.5	0.0	15.0	0.9	100.0
MP-53	1.8	20.6	28.4	14.7	7.5	0.0	21.5	5.5	100.0
STH-162	35.4	22.9	24.3	0.0	9.4	7.8	0.0	0.2	100.0
MP-90	17.1	33.3	31.6	7.8	3.6	0.0	2.1	4.5	100.0
X-270	17.8	20.0	42.2	7.0	8.3	0.0	0.0	2.2	100.0
MP-501*	37.4	45.9	8.5	5.5	1.7	0.0	0.0	0.9	100.0
P-5**	23.5	42.5	24.6	7.5	0.0	0.1	0.0	1.8	100.0
I-3**	43.7	23.9	24.4	4.4	0.0	0.0	0.0	2.6	100.0
STH-5*	44.0	14.7	34.1	3.9	3.1	0.0	0.0	0.2	100.0
STH-13*	30.4	23.8	41.4	2.3	1.3	0.0	0.0	0.8	100.0
STH-118	38.0	7.1	45.6	9.0	0.0	0.0	0.0	0.3	100.0
STH-450	30.0	12.2	35.5	11.3	0.0	6.7	0.0	4.3	100.0
D-8b***	16.4	0.8	60.4	15.6	0.0	0.0	0.0	6.8	100.0
D-15***	26.2	35.6	32.2	2.0	1.2	0.0	0.0	2.8	100.0
DSK-17***	18.8	0.0	56.5	22.0	0.0	0.2	0.0	2.5	100.0
A-13***	28.7	24.7	37.0	0.0	3.0	0.0	0.0	6.6	100.0
G-2***	34.8	44.7	18.1	2.0	0.0	0.0	0.0	0.4	100.0
YD-12*	11.2	22.3	45.5	7.8	0.0	8.8	0.0	4.3	100.0

(Qz: Quartz, Kf: K-feldspars, Pl: Plagioclase, Hb: Hornblende, Bi: Biotite, Mu: Muscovite, Px: Pyroxenes, Oth: Others, Tot: Total)

* (Karavasili, 2004), ** (Koroneos, 1991), *** (Soldatos, 1985).

the gamma-ray spectrometry systems was performed with the radionuclide specific efficiency method in order to avoid any uncertainty in gamma ray intensities, as well as the influence of coincidence summation and self-absorption effects of the emitting gamma-ray photons. A set of high quality certified reference materials (IAEA, RG-sets) was used, with densities similar to the building materials measured after pulverization. Cylindrical geometry (\varnothing : 55 mm, h = 20 mm) was used assuming that the radioactivity is homogeneously distributed in the measuring samples. The measurement duration was up to 200.000 s and was carried out in the Laboratory of Atomic and Nuclear Physics, Department of Physics, Aristotle University of Thessaloniki.

3. Results and discussion

The specific activities of ^{40}K , ^{226}Ra and ^{232}Th measured in the granite samples are presented in Table 2. The specific activity of ^{40}K has a much wider range (64-1632 $\text{Bq}\cdot\text{kg}^{-1}$) than those of ^{226}Ra and ^{232}Th , which are respectively 1,4-315,4 and 2-372,2 $\text{Bq}\cdot\text{kg}^{-1}$. The average values of ^{40}K , ^{226}Ra and ^{232}Th are 929,3, 77,3 and 91,4 $\text{Bq}\cdot\text{kg}^{-1}$, respectively.

The worldwide average and range (within brackets) of natural radioactivity background levels in soil are 400 (140-850), 35 (17-60) and 30 (11-64) Bq·kg⁻¹, respectively for ⁴⁰K, ²²⁶Ra and ²³²Th (UNSCEAR, 2000). As it was expected, the average activity mass concentrations of the radionuclides measured in the granites from northern Greece are above the average activity levels given in the above UNSCEAR, 2000 report for soil (Pavlidou et al., 2006; Karavasili et al., 2005; Stoulos et al., 2003).

According to UNSCEAR (1993), the world average of natural radioactivity levels of ⁴⁰K, ²²⁶Ra and ²³²Th in building materials is 500, 50 and 50 Bq·kg⁻¹, respectively. Taking into account the measured levels of natural radioactivity in Greek building materials by this study as well as by other Greek researchers (Siotis and Wrixon, 1984, Papastefanou et al., 1984; Pakou et al., 1994; Savidou et al., 1995; Petropoulos et al., 2002) and considering that most of Greek dwellings were constructed mainly by clay bricks and concrete in weight proportion 40–60%, the specific activities of natural radionuclides in building materials that appeared in a typical Greek room are the following: ⁴⁰K, 550 Bq·kg⁻¹; U-series, 35 Bq·kg⁻¹ and Th-series, 32 Bq·kg⁻¹ (Stoulos et al., 2003). This means that granites contain a much higher amount of radionuclides presumably caused by the presence of U- and Th-rich minerals in them. For example, tetravalent Th and U may be isomorphously substituting in the Ca position in allanite, sphene and apatite. Ce-rich monazite rivals zircon in common rocks as a ubiquitous and important carrier of Th. To a much lesser extent U, was also found in monazite, apparently also in isomorphic substitution. The situation is reversed in xenotime, where U was generally more abundant than Th. Uraninite and thorianite are two other minerals found in common rocks that are believed to contain Th and U as essential components in regular crystal structural positions (Adams et al., 1959). According to Faure (1986), U- and Th-rich minerals can be found in acid igneous rocks than in basic rocks. This can be explained by the incompatibility of both U and Th during partial melting and fractional crystallization processes (Kd<1), leading thus in the remaining of U and Th in the melt and their incorporation in minerals of acid rocks.

Activity concentrations of ⁴⁰K, ²²⁶Ra and ²³²Th in granite samples from various countries of the world, including Greece, have been compiled from literature and are presented in Table 3 for comparison. The ‘world’ weighted average calculated from the above measurements has also been used for comparison. The activity concentrations of these radionuclides vary over a wide range. Their average activity concentration in Greek granite samples is below the ‘world’ average in all cases. The minimum and maximum ⁴⁰K were found in the granite from Wadi Karim and Gable El Aradiya in Egypt, respectively. The granite of Gable Gattar II in Egypt contains the maximum and that of Africa has the minimum ²²⁶Ra. The maximum ²³²Th was found in the Pakistani granite and the minimum in the granite of Gable El Aradiya in Egypt.

In order to assess the radiological impact of granites used as building materials, the model of a rectangular parallelepipedon house building 3 m X 3 m X 3m, with infinite thin walls and no doors and windows (standard room model) was commonly considered (UNSCEAR, 1993)

A variety of radiation hazard indices representing different methods to assess the collective effect of mass concentrations of ⁴⁰K, ²²⁶Ra and ²³²Th was used:

1) Absorbed gamma dose rate (D_a). The measured activity concentrations of ²³⁸U (²²⁶Ra), ²³²Th and ⁴⁰K is converted into doses (nGy·h⁻¹·Bq⁻¹·kg⁻¹) (where Gy=Gray and Bq=Becquerel) by applying the factors 0.462, 0.604 and 0.0417 for U (²²⁶Ra), Th and K, respectively (UNSCEAR, 1993). These factors were used to calculate the total absorbed gamma dose rate in air at 1 m above the ground level using the following equation:

$$D_a \text{ (nGy·h}^{-1}\text{)} = 0.462C_U + 0.604C_{Th} + 0.0417C_K$$

Table 2. Activity concentrations of ^{40}K , ^{226}Ra and ^{232}Th in $\text{Bq}\cdot\text{kg}^{-1}$ along with their total uncertainties of the studied samples.

Sample	Location	Rock-type	^{226}Ra	^{232}Th	^{40}K
GAE-1	Xanthi	gabbro	15.6±0	18.2±0	291.0±5
GAE-9	Xanthi	gabbro	42.7±1	50.7±1	685.0±9
GAE-11	Xanthi	gabbro	5.3±0	6.5±1	175.0±4
SB-55*	Vrondou	gabbro	1.4±0	2.0±0	68.0±4
NG-5*	Xanthi	gabbro	2.5±0	6.5±0	64.0±3
MP-6	Maronia	hb-bi monzogabbro	65.9±1	71.8±1	810.0±10
MZ-500*	Xanthi	bi-px-qz-monzodiorite	170.0±2	189.0±3	1304.0±22
MP-5	Varnountas	hb-bi-qz-monzonite	61.4±1	79.5±1	1027.0±12
KR-9*	Varnountas	hb-bi-qz-monzonite	50.0±1	78.0±1	956.0±14
SB-41*	Vrondou	hb-qz-monzonite	109.0±1	113.0±2	1110.0±14
YD-12*	Philippi	bi-hb-qz-monzodiorite	28.0±1	39.0±1	709.0±10
L-23*	Leptokaria-Kirki	bi-px-hb-qz-monzonite	64.0±1	59.0±1	882.0±13
MP-77	Maronia	hb-qz-monzonite	123.4±1	124.9±2	1146.0±13
P-6*	Panorama	qz-monzonite	122.0±1	143.0±2	1177.0±16
XMZ-501	Xanthi	bi-px-qz-monzonite	169.2±1	188.2±2	1172.0±14
MP-3	Maronia	hb-bi-qz-monzonite	106.7±1	110.0±1	954.0±12
MP-38	Maronia	bi-px-monzonite	146.2±1	148.5±2	924.0±11
MP-53	Maronia	bi-hb-px-monzonite	51.4±1	50.0±1	663.0±10
MR-11*	Maronia	hb-bi-px-monzonite	97.0±1	99.0±1	1051.0±14
SB-36*	Vrondou	hb-syenite	136.0±1	152.0±2	1466.0±17
DSK-17*	Elatia	bi-tonalite	41.0±1	80.0 ±1	524.0±10
D-8b*	Elatia	bi-tonalite	44.0±1	82.0 ±1	748.0±10
STH-162	Sithonia	two mica granite	45.2±1	28.8 ±1	751.0±10
STH-170	Sithonia	two mica granite	29.0±1	29.4 ±1	603.0±10
STH-5*	Sithonia	granodiorite	38.0±1	43.0 ±1	693.0±9
STH-118*	Sithonia	bi-granodiorite	69.0±1	80.0 ±1	777.0±10
STH-450*	Sithonia	hb-bi-granodiorite	56.0±1	77.0 ±1	754.0±14
D-5*	Elatia	bi-granodiorite	41.0±1	77.0 ±	546.0±11
MP-501*	Mouries	bi-granite	73.0±1	95.0 ±1	1386.0±15
P-5	Varnountas	bi-granite	44.0±1	88.1 ±1	1104.0±13
SB-50*	Vrondou	hb-granite	69.0±1	70.0 ±1	717.0±12
L-4*	Vrondou	hb-granite	54.0±1	75.0 ±1	919.0±12
TS-10*	Vrondou	hb-granite	90.0±1	138.0±2	1460.0±16
G-6*	Granitis	hb-bi-granite	106.0±1	100.0±1	1060.0±13
MP-90	Maronia	hb-granite	315.4±1	372.2±4	1420.0±16
STH-6*	Sithonia	granite	68.0±1	64.0±1	689.0±11
B-7*	Vrondou	granite	88.0±1	123.0±2	993.0±13
D-15*	Elatia	granite	46.0±1	130.0±2	1448.0±19
A-13*	Elatia	granite	231.0±1	49.0±1	1232.0±16

Table 2. Continued

Sample	Location	Rock-type	²²⁶ Ra	²³² Th	⁴⁰ K
G-2*	Granitis	granite	141.0±1	195.0±3	1632.0±21
PR-27*	Panorama	granite	56.0±1	66.0±1	987.0±14
PE-11	Kastoria	granite	44.7±1	50.2±1	973.0±12
TH-5	Kastoria	granite	70.0±1	68.6±1	1099.0±13
X-270	Xanthi	bi-hb-granite	79.6±1	73.1±1	915.0±11
T-10	Varnountas	granitic gneiss	73.2±1	100.1±1	970.0±12
H-9*	Elatia	alkaligranite	33.0±1	124.0±2	1111.0±14
STH-13*	Sithonia	leucogranite	16.4±1	18.0±1	892.0±11
L-13	Varnountas	leucogranite	58.7±1	115.6±2	1113.0±13
I-3	Varnountas	leucogranite	97.3±1	104.9±1	1386.0±15
Average			77.3±1	91.4±1	929.3±12

(qz: quartz, px: pyroxene, bi: biotite, hb: hornblende), * (Karavasili, 2004)

Table 3. Average values of activity concentrations of ⁴⁰K, ²²⁶Ra and ²³²Th in Bq·kg⁻¹ of granite samples from different countries of the world.

Country/origin	No. of samples	⁴⁰ K	²²⁶ Ra	²³² Th	Reference
Austria	1	1340	40	253	(Chen & Lin 1996)
Belgium	1	1129	68	77	(Tzortzis et al., 2003)
Brazil	14	1297	82	168	(Tzortzis et al., 2003)
Brazil	1	1819	91	152	(Chen & Lin 1996)
China	8	1256	95	158	(Chen & Lin 1996)
Egypt/Wadi Karim	10	4819	56	54	(El-Arabi, 2007)
Egypt/Um Taghir	39	3918	558	359	(El-Arabi, 2007)
Egypt/Gable Gattar II	10	1140	6018	113	(El-Shershaby, 2002)
Egypt/Gable El Majai	10	681	198	30	(Arafa, 2004)
Egypt/Gable El Misikat	9	705	1184	40	(Arafa, 2004)
Egypt/Gable El Aradiya	10	480	126	25	(Arafa, 2004)
Egypt/Homert Waggat North	10	1590	489	109	(Arafa, 2004)
Egypt/Homert Waggat South	10	2302	787	163	(Arafa, 2004)
Finland	3	1223	94	163	(Chen & Lin
Greece	49	929	77	91	(Karavasili et al., 2005 & Present work)
Holland	1	1540	162	490	(Tzortzis et al., 2003)
India	4	1082	119	172	(Chen & Lin 1996)
Italy	4	1206	64	91	(Menager et al., 1993)
Malaysia	1	1019	86	134	(Chen & Lin 1996)

Table 3. Continued

Country/origin	No. of samples	⁴⁰ K	²²⁶ Ra	²³² Th	Reference
Portugal	1	1490	117	105	(Chen & Lin 1996)
S. Africa	1	1151	92	153	(Chen & Lin 1996)
Spain	1	1289	80	123	(Chen & Lin 1996)
Sweedeen	2	1226	107	110	(Chen & Lin 1996)
Turkey/Kaymaz	7	1266	306	248	(Orgun & Altinsoy, 2005)
Turkey/Sivrihisar	7	1058	67	153	(Orgun & Altinsoy, 2005)
Pakistan/Ambela	20	1203	659	598	(Asghar et al., 2008)
	Maximum	4819	6018	598	
	Minimum	480	23	25	
	Weighted				
	Average	1749	567	194	

where C_U , C_{Th} and C_K are the activity concentrations ($Bq \cdot kg^{-1}$) of U, Th and K in the samples. The limiting value of this index is $80 \text{ nGy} \cdot h^{-1}$ (EC, 1999).

2) Annual effective dose (H_E). The effective dose rate indoors in $mSv \cdot y^{-1}$ (Sv =Sievert), is calculated by the following formula:

$$H_E = 10^{-6} \times D \times T \times F$$

where D is the calculated dose rate in $nGy \cdot h^{-1}$, T is the indoor occupancy time, which implies that 20% of time is spent outdoors, and is equal to 7000 h, and F is the doses conversion factor equal to $0.7 \text{ Sv} \cdot y^{-1}$. H_E should be $< 1 \text{ mSv} \cdot y^{-1}$ (UNSCEAR 1993, 2000).

3) Activity index (AI). Several authors have proposed formulae to estimate this index. In this study it is calculated on the basis of former USSR and W. Germany criterion (Chen & Lin, 1996):

$$AI = C_{Ra} / 370 + C_{Th} / 259 + C_K / 4810$$

AI should be less than 1 mSv.

4) Gamma-ray index (I_γ). European Commission (EC, 1999) has proposed this index which is calculated by the formula:

$$I_\gamma = C_{Ra} / 300 \text{ Bq} \cdot \text{kg}^{-1} + C_{Th} / 200 \text{ Bq} \cdot \text{kg}^{-1} + C_K / 3000 \text{ Bq} \cdot \text{kg}^{-1}$$

and is correlated with the annual dose rate due to gamma radiation. Materials having $I_\gamma < 2$ would increase the annual effective dose by 0.3 mSv, while for $2 < I_\gamma < 6$, the gamma-ray index corresponds to an increase in effective dose by $1 \text{ mSv} \cdot y^{-1}$. Building materials used superficially rather than in bulk amounts (tiles, boards, etc.) should be exempted from all restrictions concerning radioactivity, if the excess of gamma radiation originating from them increases the annual effective dose of a member of public by 0,3 mSv at the most. On the other hand, dose rates higher than $1 \text{ mSv} \cdot y^{-1}$ are allowed only in exceptional cases, where materials are locally used. Finally, samples with $I_\gamma > 6$ cannot be recommended for use in buildings (EC, 1999).

Table 4. Absorbed gamma dose rate (D_a), annual effective dose (H_E), activity index (A_I) and gamma-ray index (I_γ) for the granites examined.

sample	D_a (nGy·h ⁻¹)	HE (mSv·y ⁻¹)	AI (Bq·kg ⁻¹)	I_γ
GAE-1	31.20	0.15	0.18	0.2
GAE-9	80.19	0.39	0.46	0.6
GAE-11	13.18	0.06	0.07	0.1
SB-55*	4.58	0.02	0.02	0.0
NG-5*	7.85	0.04	0.05	0.1
MP-6	110.95	0.54	0.64	0.9
MZ-500*	243.25	1.19	1.42	1.9
MP-5	122.41	0.60	0.70	1.0
KR-9*	110.60	0.54	0.63	0.9
SB-41*	169.09	0.83	0.98	1.3
YD-12*	65.93	0.32	0.37	0.5
L-23*	100.28	0.49	0.57	0.8
MP-77	182.58	0.89	1.05	1.4
P-6*	192.81	0.94	1.12	1.5
XMZ-501	245.64	1.20	1.44	1.9
MP-3	157.53	0.77	0.91	1.2
MP-38	200.35	0.98	1.17	1.6
MP-53	81.73	0.40	0.47	0.6
MR-11*	146.79	0.72	0.84	1.1
SB-36*	218.71	1.07	1.26	1.7
DSK-17*	88.57	0.43	0.52	0.7
D-8b*	102.34	0.50	0.59	0.8
STH-162	70.43	0.35	0.39	0.5
STH-170	58.08	0.28	0.33	0.5
STH-5*	73.00	0.36	0.41	0.6
STH-118*	113.82	0.56	0.66	0.9
STH-450*	104.38	0.51	0.60	0.8
D-5*	88.85	0.44	0.52	0.7
MP-501	150.22	0.74	0.85	1.2
P-5	122.62	0.60	0.70	1.0
SB-50*	104.48	0.51	0.60	0.8
L-4*	108.42	0.53	0.62	0.9
TS-10*	192.27	0.94	1.10	1.5
G-6*	155.67	0.76	0.90	1.2
MP-90	438.12	2.15	2.59	3.4
STH-6*	97.88	0.48	0.56	0.8
B-7*	165.16	0.81	0.96	1.3
D-15*	163.39	0.80	0.93	1.3
A-13*	188.02	0.92	1.07	1.4
G-2*	259.03	1.27	1.50	2.0
PR-27*	105.93	0.52	0.60	0.8
H-9*	139.71	0.68	0.80	1.1
STH-13*	56.33	0.28	0.30	0.4
L-13	147.59	0.72	0.85	1.2
I-3*	171.01	0.84	0.98	1.3
T-10	135.33	0.66	0.78	1.1

Table 4. Continued

sample	D_a (nGy·h ⁻¹)	HE (mSv·y ⁻¹)	AI (Bq·kg ⁻¹)	I_γ
PE-11	92.16	0.45	0.52	0.7
TH-5	119.01	0.58	0.67	0.9
X-270	122.61	0.60	0.70	1.0
Lim. Values	80	1	1	6

Table 5. Comparison of radiological parameters based upon data available for granite samples from different countries of the world (Asghar et al., 2008).

Country/origin	D_a (nGy·h ⁻¹)	HE (mSv·y ⁻¹)	AI (Bq·kg ⁻¹)	I_γ
Africa	70	0.5	0.4	0.6
Austria	227	0.8	1.4	1.8
Belgium	125	1.2	0.7	1.0
Brazil	193	1.2	1.1	1.5
Brazil	210	1.4	1.2	1.7
China	192	1.2	1.1	1.5
Egypt/Wadi Karim	259	1.7	1.4	2.1
Egypt/Um Taghir	638	0.5	3.7	5.0
Egypt/Gable Gattar II	2896	17.8	16.9	21.0
Egypt/Gable El Majai	138	0.5	0.8	1.0
Egypt/Gable El Misikat	601	3.7	3.5	4.4
Egypt/Gable El Aradiya	93	0.6	0.5	0.7
Egypt/Homert Waggat North	358	2.3	2.1	2.7
Egypt/Homert Waggat South	558	3.5	3.2	4.2
Finland	193	1.2	1.1	1.5
Greece*	131	0.6	0.8	1.0
Holland	435	2.8	2.6	3.5
India	204	1.3	1.2	1.6
Italy	135	0.9	0.8	1.1
Malaysia	163	1.0	1.0	1.3
Portugal	180	1.2	1.0	1.4
S. Africa	183	1.2	1.1	1.5
Spain	165	1.1	1.0	1.3
Sweedden	166	1.1	1.0	1.3
Turkey/Kaymaz	344	2.2	2.0	2.7
Turkey/Sivrihisar	167	1.1	1.0	1.3
Pakistan/Ambela	716	4.5	4.3	5.6
Limits	80	1	1	6
Average	455	2.2	2.7	3.4
Maximum	2896	17.8	16.9	21.0
Minimum	70	0.5	0.4	0.6

*present study/

The D_a , H_E , AI and I_γ values obtained for the samples of the present study along with their limiting values are presented in Table 4.

The radiological parameters of the basic samples studied (GAE-1, GAE-9, GAE-11, SB-55, NG-5 and MP-6) seem to be below the international dose limiting values. On the other hand, the radiological parameters for two granite samples (MP-90 and G-2 from Maronia and Granitis, respectively) appear to be above limits in all cases except for I_γ .

From the worldwide activity concentration data given in Table 3, hazard indices, as defined above, have been calculated and are given in Table 5.

Among the 27 countries/locations selected for comparison, granite of 7 countries (including Greece) fulfill the criterion of $H_E < 1$ to be used as building materials. Moreover, the average H_E of Greek samples is very close to the minimum H_E found. However, since granites are usually used in small quantities in house buildings, they do not induce an activity level exceeding the $1 \text{ mSv}\cdot\text{y}^{-1}$ dose limit (Pavlidou et al., 2006). As far as the AI is concerned, the average value of the samples studied is half than the 'world' average as it was calculated in this report. Finally, considering the values of gamma-ray index granites from Greece have the fourth lowest value. Only one of the selected countries/locations does not fulfil the criterion of $I_\gamma < 6$, and consequently, its use as building material is not recommended. This is the case of Gable Gattar II granite in Egypt, where there is U mineralization with high economic potential (El-Shershaby, 2002).

As the research on the natural radioactivity of the greek granites is in progress it must be noted here that the present results are considered as preliminary.

4. Conclusions

Twenty granite samples from northern Greece have been measured for their natural radioactivity in order to assess the radiological impact in case they are used as building materials, while 29 more samples were obtained from a previous study. The activities of ^{40}K , ^{226}Ra and ^{232}Th of the majority of the samples exceed the average level of these radionuclides in soil and building materials. That is because granites contain U and Th-rich minerals in them. Samples of basic composition have very low concentrations of radionuclides, which reflect to the values of their hazard indices that are below limits. On the other hand, intermediate and acid rocks are more enriched in ^{40}K , ^{226}Ra and ^{232}Th and their decay products. Four hazard indices were calculated in order to assess the health risk of using the above samples as building materials. The average of hazard indices of Greek granites is below 'world' average in all cases. Moreover, it is still below the criteria of UNSCEAR (2000). Therefore, at least from radiological point of view and for the investigated rocks, the use of granites from northern Greece as building materials is recommended.

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