Discovery of highly radioactive granite in the Bergen Region

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We report the discovery of the most radioactive granite ever found in Norway, namely the Løvstakken granite, located ~5 km southwest of Bergen. A preliminary gamma-spectrometry survey carried out in the Bergen Region, in autumn 2009, showed that the Løvstakken granite contained unusually high amounts of uranium and thorium. This finding was later confirmed by a more complete regional survey during the summer of 2010. We visited 281 sites and made 502 radiometric measurements in the Bergen Region and adjacent areas. Based on 87 measurements on the Løvstakken granite, we found that it contains ~18 ppm U, ~58 ppm Th and ~6% K on average (median values). Natural radioactivity is not harmful by itself, but the high uranium levels of the Løvstakken granite (i.e., up to ~69 ppm) cause concern in terms of radon hazard. In addition, geothermal gradients in the continental crust are strongly dependent on the amount of radioactive (i.e., heat-producing) elements it hosts. Our study indicates that the Løvstakken granite produces ~8 $\mu\text{W}/\text{m}^3$ of heat. Such high heat-generation values may result in anomalously high temperatures in the subsurface of the Bergen Region, that in turn may render the use of geothermal energy economically interesting.

Keywords: geothermal, heat-generation, radon hazard, gamma-spectrometry

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Introduction

On planet Earth, the highest concentrations in natural radioactive elements (i.e., U, Th, K and their respective unstable daughter elements) are found in continental crust. Their relative distributions are dictated mainly by lithological composition (Kukkonen & Lahtinen, 2001; Slagstad, 2008), metamorphic grade (Rybach & Čermák, 1982) and the age of the rocks hosting them (Rybach & Čermák, 1982; Kukkonen & Lahtinen, 2001). The study of natural radioactivity of rocks informs us about a wide range of geological processes such as magmatism, tectonics, sedimentation, erosion and weathering. Because a significant proportion of continental surface heat flow results from radioactive decay in the crust (i.e., typically ~40%; Pollack & Chapman, 1977), the study of natural

radioactive elements is primordial for the understanding and modelling of the Earth's thermal regime (e.g., Pascal et al., 2007; Rudlang, 2011; Maystrenko et al., 2014). Finally, uranium itself represents an economic interest but also produces radon through radioactive decay that, in turn, can be potentially hazardous in areas where natural concentrations of the former element are anomalously high (Smethurst et al., 2008).

Previous studies of natural radioactive elements in Norway have been motivated by geochemical mapping (Heier & Adams, 1965; Raade, 1973; Killeen & Heier, 1975; Slagstad, 2008) or mitigation of radon hazard (Smethurst et al., 2008). The main outcome of these investigations is that Norwegian basement rocks present, in general, low to moderate concentrations in radioactive

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elements. Exceptions to this rule are some Precambrian granitoids (e.g., Iddefjord Granite; Slagstad, 2008), Permian magmatic rocks and Cambrian alum shales of the Oslo Region (Slagstad, 2008; Smethurst et al., 2008). These particular rocks are the primary sources for radon hazard in Norway (Smethurst et al., 2008) and produce anomalously high surface heat flows (Slagstad et al., 2009; Pascal et al., 2010a, b). The Bergen Region has been overlooked until now, although it hosts the second most populated city of Norway. The present study was initiated in the framework of a confidential geothermal project (Pascal et al., 2010b), whose final results were released recently. By coincidence, the first author started with the gamma-spectrometry measurements, in October 2009, when anomalously high levels of radon were reported in some of the public buildings in Bergen (Løvø, 2009; Pascal, 2010). In this paper we present this very first radiometric study of the Bergen Region and surrounding areas, with particular focus on the Løvestakken granite, and discuss the implications of our findings in terms of radon hazard and geothermal exploration.

Geological setting

The gamma-spectrometry measurements were conducted in the Bergen Arc System (BAS) and the adjacent autochthonous Precambrian basement and Caledonian allochthons (Fig. 1). The BAS involves a series of Caledonian nappes, organised in an arcuate pattern, surrounding the city of Bergen (Kolderup & Kolderup, 1940). The system was emplaced during the final stages of the Caledonian Orogeny and rests in a synformal depression of the autochthonous basement (Kvale, 1960; Sturt & Thon, 1978; Ragnhildstveit & Helliksen, 1997). The BAS is divided into four main units from west to east: the Minor Bergen Arc, the Blåmannen Nappe, the Lindås Nappe and the Major Bergen Arc (Fossen & Dunlap, 2006). The Minor and Major Bergen arcs involve mainly Lower Palaeozoic metasedimentary and meta-igneous rocks and subordinate slices of Precambrian basement (Fossen, 1986, 1989). Proterozoic basement rocks form the Blåmannen and Lindås nappes which show evidence for both Precambrian and Caledonian deformation. In detail, the Blåmannen Nappe involves mainly granitic gneisses and subordinate quartzites (Fossen, 1988), whereas the Lindås Nappe contains abundant mangerites, amphibolitic gneisses and anorthosites in addition to gneisses with variable compositions (Austrheim & Griffin, 1985).

Measurements in the autochthonous Precambrian basement were carried out mainly in the Øygarden Gneiss Complex, just west of Bergen, and the Western Gneiss Region (Fig. 1). The Øygarden Gneiss Complex is dominated by gneisses (granitic, migmatitic, augen and amphibolitic) which derive from various Precambrian

(in places Caledonian) intrusions later deformed during the Sveconorwegian and Caledonian orogenies (Sturt et al., 1975; Fossen & Rykkeli, 1990). In particular, the Løvestakken granite forms a large part of the Laksevåg peninsula and is also found on Bjørøy and the southern parts of the island of Sotra (Fig. 1). The Løvestakken granite is a granitic gneiss, including augen gneisses, migmatites and banded gneisses, where the augen character becomes more pronounced to the east, towards the contact with the Minor Bergen Arc (Ragnhildstveit & Helliksen, 1997). Radiometric datings suggest emplacement ages between 1.2 and 1.0 Ga for the granite (Weiss, 1977). The Løvestakken granite is interpreted to be the substratum of the Bergen arcs. According to this interpretation the Kikedalen Complex, a granitic gneiss cropping out southeast of the Major Bergen Arc (Fig. 1), would be its counterpart (Ragnhildstveit & Helliksen, 1997). Two Caledonian batholiths crop out in the south of the studied area (Fig. 1), the Krossnes Granite (Fossen & Ingdahl, 1987) and the Sunnhordland Batholith (Andersen & Jansen, 1987). The Krossnes Granite, 430 ± 6 Ma old (Fossen & Austrheim, 1988), is dominated by a coarse-grained rock of mainly granitic composition and presents intrusive contacts with the Major Bergen Arc. The Sunnhordland Batholith is of similar age but involves a variety of rocks ranging in composition from gabbro to granite and was detached from its roots during Caledonian collision (Andersen & Jansen, 1987).

Gamma-spectrometry

We used the Exploranium GR-256 (Exploranium G.S. Limited), a hand-held spectrometer, in order to calculate the relative concentrations in heat-producing radioactive elements (i.e., uranium, thorium and potassium) and derive heat generation rates from the different rock units exposed at the surface in the study area. The Exploranium GR-256 can be used for ground, vehicle and small airborne radiometric surveys but also for laboratory data analysis and core logging. The instrument is supplied with a 21 cubic inch detector.

The Exploranium GR-256 involves 256 channels equally spread over the entire gamma-ray spectrum of interest and allows the study of all discrete phenomena. It was the first spectrometer to internally store conversion/correction constants and to display data in conventional counts/time period or directly in U, Th and K concentrations. Previous instruments were limited to typically 4 windows. The GR-256 allows selection of 8 windows which may be located anywhere in the spectrum with any channel width. More detailed information can be found in the GR-256 user manual (Anonymous, 1989). The spectrometer was calibrated using NGUs calibration pads in the spring of 2009. The calibration method is described in Heincke et al. (2009).

Figure 1. Simplified geological map of the Bergen Arc System and adjacent rock units (courtesy Haakon Fossen, University of Bergen). Abbreviations: B – Bergen, CN – Caledonian nappes (Bergen Arc System excluded), KC – Kikidalen Complex, KG – Krossnes Granite, SB – Sunnhordland Batholith, WGR – Western Gneiss Region, ØGC – Øygarden Gneiss Complex. The four main nappes of the Bergen Arc System are (1) the Minor Bergen Arc, (2) the Blåmannen Nappe, (3) the Lindås Nappe and (4) the Major Bergen Arc.

Measurements were taken on preferentially fresh and regular rock faces and measurement time was set to 120 seconds. This duration was selected in order to measure concentrations with reasonable accuracy which, in turn, depends on the total number of counts. As much as possible, measurements were repeated at least twice for each location. In particular, where a large discrepancy was found between two measurements, a third one was systematically conducted. Concentrations of radioactive elements were calculated using the stripping ratios determined during the course of the calibration rounds (see Electronic Supplement 1) and not the correction factors built in the spectrometer, the latter resulting in systematic underestimations by 2–3 ppm for U and Th and 5% for K.

Heat generation rates (A in $\mu\text{W}/\text{m}^3$) were finally calculated using Rybach's formula (Rybach, 1988):

$$A = \rho * (9.52 C_U + 2.56 C_{Th} + 3.48 C_K) * 10^{-5} \quad (1)$$

where ρ is rock density, C_U and C_{Th} represent U and Th concentrations in ppm, respectively, and C_K represents K concentration in wt.%. In the present study, rock density is assumed to be equal to $2700 \text{ kg}/\text{m}^3$.

We estimated the uncertainties associated with the derived heat generation rates using standard procedures for calculating the accuracy of gamma-spectrometry measurements (i.e., error equal to square-root of number of counts; IAEA, 2003) and assuming an error of $\pm 100 \text{ kg}/\text{m}^3$ for rock density. Our analysis suggests that errors are below 10%, remain between 10 and 15% and reach up to 30% for heat generation rates higher than $1 \mu\text{W}/\text{m}^3$, comprised between 0.5 and $1 \mu\text{W}/\text{m}^3$ and equal to $0.1 \mu\text{W}/\text{m}^3$, respectively.

Natural radioactivity in the Bergen Region

Altogether, 502 gamma-spectrometry measurements were conducted and 281 sites were visited during the course of two surveys, in the autumn 2009 and summer 2010, respectively. The results show, in general, a correlation between rock radioactive content, or conversely heat generation, and tectono-stratigraphic unit (Fig. 2). As expected, the Major Bergen Arc (unit (4) in Fig. 2), which involves abundant mafic rocks, is extremely depleted in the three radioactive elements.

Variable but on average low amounts of potassium and extremely low concentrations in uranium and thorium characterise the Lindås Nappe (unit (3) in Fig. 2), in agreement with its lithology dominated by amphibolitic

gneisses, mangerites and anorthosites (Austrheim & Griffin, 1985). The Blåmannen Nappe (unit (2) in Fig. 2), dominated by slices of Precambrian granitic basement, shows 'normal' (i.e., with respect to similar

Figure 2. Results of the gamma-spectrometry study in the Bergen Region: (A) potassium, (B) thorium and (C) uranium concentrations; (D) calculated heat generations. Acronyms and symbols as in Fig. 1.

rocks measured elsewhere in Norway; Slagstad, 2008) levels in radioactive elements. Similar levels appear to be associated with the Minor Bergen Arc (unit (1) in Fig. 2). However, fresh rock exposures of this latter unit are seldom and measurements were only possible at four locations.

Outside the Bergen Arc System, the surveyed Caledonian nappes to the east and southeast involve contrasting lithologies (Fig. 1) and show variable but, in general, low to moderate concentrations in radioactive elements, although some local peaks, in particular in K, were recorded (Fig. 2). The studied area belonging to the Western Gneiss Region contains mainly granitic gneisses but frequent changes in rock composition are to be found there and are reflected in our results. On average, the rocks in this latter region are relatively enriched in potassium and to some extent in thorium but contain 'normal' amounts of uranium.

The Øygarden Complex involves a mixture of Precambrian plutons of variable composition overprinted by a more or less pronounced gneissic foliation. On the

Øygarden Archipelago, potassium levels range from extremely low to very high but in general uranium and thorium levels remain low to moderate. The highest concentrations in all radioactive elements are undoubtedly associated with the Løvestakken granite, cropping out in the southeast of Sotra, on Bjørøy island and on the Laksevåg Peninsula, just southwest of the city of Bergen. At various localities, thorium and uranium concentrations exceed 40 and 20 ppm, respectively (Fig. 2B, C), and peaks of up to 94 ppm Th and up to 69 ppm U were measured locally (see Electronic Supplement 1). The Kikedalen Complex (Fig. 1), interpreted as a counterpart of the Løvestakken granite (Ragnhildstveit & Helliksen, 1997), also shows relatively high concentrations in radioactive elements. Admittedly, this latter conclusion relies on only four measured locations (Fig. 2). The Caledonian Krossnes Granite appears to be the second most radioactive rock unit of the Bergen Region, according to our results from three surveyed localities. The measurement sites for the Sunnhordland Batholith expose mainly granodiorites and monzogranites but the results indicate low to moderate amounts of radioactive elements.

Figure 3. Results of the gamma-spectrometry study presented according to lithology: (A) potassium, (B) thorium and (C) uranium concentrations; (D) calculated heat generations. Dots, diamonds and upper and lower limits represent average, median, minimum and maximum values respectively (see also Table 1). Abbreviation: N – number of measurements.

Table 1. Measured potassium, thorium and uranium concentrations and calculated heat generations as a function of lithology (281 sites, 502 measurements).

Lithology	N sites	N meas.	K (wt. %)					Th (ppm)					U (ppm)					Heat generation ($\mu\text{W}/\text{m}^3$)				
			Av	Med	Std	Min	Max	Av	Med	Std	Min	Max	Av	Med	Std	Min	Max	Av	Med	Std	Min	Max
Anorthosite	16	19	1.47	1.24	0.99	0.62	4.65	2.09	1.57	1.98	0.66	9.27	0.98	0.64	1.23	0.10	5.61	0.53	0.37	0.52	0.19	2.52
Amphibolite/ Amphib. gneiss	52	76	2.95	2.81	1.22	0.38	6.77	6.54	4.06	6.54	0.72	32.78	2.39	1.41	2.35	0.39	15.43	1.34	0.93	0.95	0.24	5.27
Diorite/ Dioritic gneiss	7	9	1.12	1.18	0.79	0.09	2.66	4.44	2.06	5.46	0.28	13.94	1.37	0.91	1.21	0.31	4.26	0.76	0.53	0.73	0.11	2.30
Eclogite	2	3	1.66	1.85	1.23	0.35	2.79	5.20	6.71	3.25	1.47	7.42	4.71	6.38	3.58	0.59	7.14	1.73	2.42	1.25	0.29	2.47
Gabbro/ Metagabbro	12	18	2.28	1.96	2.08	0.27	7.37	5.93	3.38	6.14	0.79	21.29	2.81	2.41	2.56	0.22	9.31	1.35	1.03	1.23	0.15	4.52
Gneiss (other)	44	84	3.90	3.86	1.55	0.67	7.29	14.29	11.05	14.12	0.91	74.17	4.92	4.13	4.20	0.33	20.00	2.62	2.41	1.91	0.28	9.78
Granite/ Granitic gneiss	79	145	4.88	4.90	1.17	1.69	7.56	19.78	16.07	14.28	0.88	71.61	6.28	4.95	5.20	0.36	28.48	3.44	2.78	2.11	0.56	11.18
Løvstakken Granite	32	87	6.17	6.33	1.03	2.69	9.08	51.04	57.58	21.56	11.93	93.98	19.17	17.98	11.81	3.18	68.57	9.04	8.37	3.79	2.83	23.82
Mangerite	2	3	6.52	6.60	0.14	6.36	6.61	2.75	2.33	0.78	2.27	3.64	0.92	0.72	0.37	0.70	1.35	1.04	0.96	0.14	0.96	1.20
Monzonite	2	3	1.32	1.25	0.16	1.20	1.49	1.26	1.04	0.53	0.88	1.87	0.75	0.66	0.30	0.51	1.08	0.40	0.36	0.13	0.31	0.55
Meta-basalt	4	4	0.37	0.37	0.10	0.25	0.50	1.26	1.25	0.29	1.00	1.52	0.52	0.49	0.25	0.26	0.84	0.26	0.25	0.09	0.16	0.37
Quartzite	2	2	2.28	2.28	2.76	0.32	4.23	7.24	7.24	6.21	2.85	11.63	3.11	3.11	3.57	0.58	5.64	1.51	1.51	1.61	0.38	2.65
Schist	27	49	2.89	3.22	1.35	0.23	5.76	12.24	12.81	5.18	1.19	23.34	4.68	4.14	2.23	0.55	9.62	2.32	2.40	0.98	0.38	4.53

In agreement with previous works (e.g., Kappelmeyer & Hanel, 1974; Rybach, 1988), the measured mafic rocks are more depleted in radioactive elements, especially in U and Th, than the felsic ones (Fig. 3). For example, taken altogether, anorthosites, amphibolites, gabbros and metabasalts yield median values ranging from 0.37 to 2.81 wt.% K, from 1.25 to 4.06 ppm Th and from 0.49 to 2.41 ppm U (Fig. 3; Table 1).

In contrast, the measured granites and granitic gneisses, excluding the Løvstakken granite, delivered median values of 4.90 wt.% K, 16.07 ppm Th and 4.95 ppm U. The measured intermediate rocks in the Bergen Region (i.e., diorite, mangerite and monzonite) are, in general, markedly depleted in radioactive elements. This latter observation relies, however, on a limited number of measurements on this type of rocks (Fig. 3A). Schists and undifferentiated gneisses are expected to show variable compositions and consequently variable radioactive contents. Our results, despite relative dispersion (Fig. 3), indicate similar median concentrations in K (~3–4 wt.%), Th (~11–13 ppm) and U (~4 ppm) for the two types of rocks. It is interesting to note that these latter concentrations imply relatively high heat generations (i.e., ~2.4 $\mu\text{W}/\text{m}^3$; Table 1) compared to the average values derived from similar rocks elsewhere in southern Norway (i.e., 1–2 $\mu\text{W}/\text{m}^3$; Slagstad, 2008). It is noteworthy that the three measurements taken on eclogites at two separated sites resulted in unexpectedly high concentrations in radioactive elements (Rybach, 1988). We suspect that lithologies with higher radioactive contents were present at the second measurement site and influenced the total number of counts recorded there (see Electronic Supplement 1).

With ~6 wt.% K, ~58 ppm Th and ~18 ppm U (Table 1), the Løvstakken granite is by far the most radioactive rock of the surveyed area (Figs. 2 & 3) and, consequently, the most heat-producing one (Table 1). By comparison, the Iddefjord/Bohus Granite, extending from Southeast Norway to Sweden, which until now has been considered to be the most radioactive pluton in Norway (Slagstad, 2008), yields values of ~4 wt.% K, ~45 ppm Th and ~9 ppm U (average values derived from geochemical analyses on 69 samples; Landström et al., 1980). To note the significant scatter affecting our data most probably reflects variable rock-face freshness from site to site and/or internal variations in the composition of

Table 2. U and Th concentrations determined by means of XRF fluorescence analysis of one sample of the Løvstakken granite.

Sample ID	Coordinates (UTM 32V, WGS84)	U (ppm)	Th (ppm)
Løv_1	0293954E 6694602N	16.2 ± 10%	55.9 ± 5%

the Løvstakken granite. In order to confirm our results, we analysed one sample of the granite by means of X-ray fluorescence at the Geological Survey of Norway. The sample was collected by the first author along an exceptionally fresh rock face, opened in the course of the extension of the ring road of Bergen during the summer 2009. Thorium and uranium concentrations (i.e., ~56 ppm Th and ~16 ppm U; Table 2) were found to be very close to the ones derived from the gamma spectrometry survey (Table 1).

Further implications

The Løvstakken granite, with its high contents of U, Th and K and an average heat generation of ~8 $\mu\text{W}/\text{m}^3$, represents one of the most radioactive rocks of Norway.

If we exclude some thin pegmatitic or granitic dykes, only Cambrian organic-rich alum shales, preserved mainly in the Oslo Graben, are known to contain higher amounts of uranium (~100 ppm U) and to produce more heat (~30 $\mu\text{W}/\text{m}^3$; Slagstad et al., 2009). Nevertheless, the fortuitous discovery of high natural radioactivity associated with the Løvstakken granite triggers societal issues for the second most populated area of Norway. The anomalously high uranium concentrations in the bedrock represent a concern in terms of radon hazard. Radon gas, as a daughter product of uranium, is the primary source for hazardous exposure to natural radiations, especially inside buildings (UNSCEAR, 2000). In the case of sufficient bedrock permeability, radon gas may travel from its origin inside the rock, enter buildings through their respective basements and finally accumulate indoors.

We interpolated our data points (Fig. 2C) in order to create a uranium concentration map of the study area (Fig. 4A). The contours were built by averaging values on 1 x 1 km cells using a near-neighbour algorithm with a 20 km search radius and then filtering wavelengths shorter than 3 km. The obtained map may be used as a proxy for radon hazard. However, bearing in mind that high uranium concentrations in bedrock do not automatically imply radon gas release to the surface (i.e., in the case of

Figure 4. Maps depicting (A) uranium concentrations and (B) heat generations obtained after interpolation of the results given in Fig. 2C and D, respectively. Acronyms and symbols as in Fig. 1. White dots represent measurements points. Interpolation was carried out using the near-neighbour algorithm of the GMT software suite (see text for details).

poor permeability), this type of map must be used with caution (Smethurst et al., 2008).

As expected, our map suggests that radon hazard potential might be maximal where the Løvestakken granite crops out on Bjørøy and southeast Sotra (bright green colours; Fig. 4A) and, in particular, on the Laksevåg Peninsula (yellow to white colours). The Kikedalen and Krossnes areas might also present high radon hazard potential. Admittedly, this statement is made on the basis of a rather limited number of measurements. The dark blue to violet zones (Fig. 4A) represent the ones where radon hazard potential would be minimal and encompass ~70–80% of the total studied area. However, geological heterogeneities can here be determinant at the local scale. The present study serves to identify the priority areas that need to be properly checked for radon hazard. Only accurate measurement of radon concentrations indoors can be used as ultimate data for hazard analysis.

Using the same procedure as mentioned above, we created a heat generation map of the studied area (Fig. 4B). The anomalously high amounts of heat produced by the Løvestakken granite (i.e., $>4\text{--}5\text{ }\mu\text{W}/\text{m}^3$) are a prominent feature of the map, which also indicates high heat generation for the granitic rocks of the Kikedalen Complex. The Krossnes Granite appears to be a significant heat source as well. In contrast, the Lindås Nappe and the Major Bergen Arc are characterised by extremely low heat generation levels (i.e., $<1\text{ }\mu\text{W}/\text{m}^3$; Fig. 4B). By comparison, average heat generation values for basement rocks of Norway are $\sim 1\text{--}2\text{ }\mu\text{W}/\text{m}^3$ (Slagstad, 2008).

Heat flow and temperatures underground are strongly dependent on the amount of heat produced inside the rocks. Our results suggest that the Løvestakken granite might be a target for extraction of geothermal energy and its location inside a densely populated area enhances its economic interest. Furthermore, the current geological interpretation of the Bergen area proposes that the granite extends eastwards at depth before cropping out again in Kikedalen (Ragnhildstveit & Helliksen, 1997). If correct, this latter hypothesis implies that, in most of the Bergen area, the deep underground would be warmer than usually recorded onshore Norway (Slagstad et al., 2009; Pascal, 2015).

Based on numerical modelling results, Rudlang (2011) suggested temperature gradients and heat flows respectively $>10^\circ\text{C}/\text{km}$ and $>20\text{ }\mu\text{W}/\text{m}^2$ higher than normally expected. A similar and recent study by Maystrenko et al. (2015a) supports this earlier finding. However, these numerical models assume that the Løvestakken granite still hosts significant amounts of radioactive elements at depth. It is traditionally assumed that radioactivity decreases exponentially with depth in plutons (Lachenbruch, 1968) but constraining the exact shape of the exponential function is, in general,

problematic and leads to a broad collection of possible geotherms (e.g., Pascal et al., 2007). The deepest borehole drilled in the studied area is indeed located on the Løvestakken granite but hardly reaches $\sim 500\text{ m}$ depth below surface level (Maystrenko et al., 2015b). It penetrated a typical shallow depth range where recent ground surface temperature changes and fluid advection severely affect pristine geothermal gradients (Kukkonen et al., 2011). Furthermore, the modelling study of Maystrenko et al. (2015a) suggests relatively high permeabilities and fluid flow reaching significant depths in the Bergen area. Tentative corrections carried out by Maystrenko et al. (2015a, b) point to high heat flow (i.e., $72\text{ }\mu\text{W}/\text{m}^2$ compared to typical Norwegian values of $\sim 50\text{--}60\text{ }\mu\text{W}/\text{m}^2$; Slagstad et al., 2009; Pascal, 2015), but this latter result still needs to be validated by deeper borehole data.

Conclusions

The very first gamma-spectrometry survey of the Bergen Region and adjacent areas was conducted during the autumn of 2009 and the summer 2010. We visited 281 sites and made 502 radiometric measurements. Our results show that the Lindås Nappe and the Major Bergen Arc, containing abundant mafic rocks, are very depleted in natural radioactive elements. The Løvestakken granite and to some extent the Kikedalen Complex and the Krossnes Granite are anomalously radioactive. In particular, the Løvestakken granite contains $\sim 18\text{ ppm U}$, $\sim 58\text{ ppm Th}$ and $\sim 6\%$ K (median values) and is the most radioactive granite ever measured in Norway. The high uranium levels of the Løvestakken granite (i.e., up to $\sim 69\text{ ppm}$) cause concern in terms of radon hazard. In addition, our study indicates that the granite produces on average $\sim 8\text{ }\mu\text{W}/\text{m}^3$ of heat. Such high heat-generation values may result in anomalously high temperatures in the subsurface of the Bergen Region, making the use of geothermal energy potentially interesting.

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