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MAPPING OF GROUNDWATER RADON POTENTIAL

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Abstract

The domestic use of water with elevated radon concentration may represent a public health hazard, partly due to the release of radon to the indoor air, but also due to the radiation dose caused by radon and its progeny upon intake. While only a limited number of countries have implemented regulations with respect to radon in water, many more are considering doing so. The compulsory limits proposed by Swedish authorities are 100 Bq/l for public water, while water from private wells is not to exceed 1000 Bq/l. Furthermore, it is recommended that water with a radon content above 500 Bq/l should not be given to children under five years of age. In Sweden, the estimated number of wells with radon levels above 1000 Bq/l exceeds 10 000, with a considerable amount in excess of 10 000 Bq/l. The highest radon concentration in a well supplying drinking water encountered so far is 57 000 Bq/l. Radon levels exceeding 500 Bq/l are almost exclusively found in wells drilled into bedrock and in springs with intramontaneous water. Elevated ground water radon levels require that the water has passed through bedrock with elevated concentration of uranium, or through fractures with coatings of minerals containing enhanced concentrations of radium-226. Intramontaneous water from areas with uranium-bearing rock types (e.g. uranium-rich granites, pegmatites and vulcanites) often manifests elevated radon levels. The implementation of compulsory radon limits has led to a demand from Society regarding regional information on ground water radon risk. Routines for the establishment of risk maps focusing on water are currently under development. The backbone of the process is the access to high spatial resolution radiometric information together with bedrock and soil information on a detailed scale (1:50 000). This information is available from the Geological Survey of Sweden, which is routinely carrying out airborne measurements at an altitude of 30 m and a line spacing of 200 m. While some 60% of Sweden is covered up to now, 75% is expected to be covered within the next ten years. Moreover, an increasing part of Sweden is covered by digital geologic information on an appropriate scale. Other available databases utilized in the risk mapping process include radon measurements in wells, geochemical data from ground- and biogeochemical sampling, ground radiometric measurements on outcrops and soils, and the information gathered during the former Swedish programme for uranium resource evaluation.

1. INTRODUCTION

Radon in water may be a cause of cancer. Given the radon concentrations normally found in ground water, health risks are small. However, the radon dose may be important if ground water containing a high concentration of radon is consumed by infants and young children regularly as drinking water or if radon gas is released into an indoor environment. Elevated radon concentrations in ground water are most common in areas where the crystalline bedrock contains elevated concentrations of uranium. Geological, geophysical and geochemical data from uranium exploration and other surveys of natural radiation are used to indicate and delimit areas of varying risk of elevated radon concentration in ground water in Sweden. This information is utilised by local authorities in an effort to discover which wells may have unsuitably high radon concentrations.

2. RADON IN WATER — A HEALTH RISK

Radon in water may constitute a health risk, partly due to inhalation of the radon gas released from water and partly due to ingestion of the water. When water containing radon is used, 10-90% of the radon is released into the air. The release is greater the more the water is atomised, processed or heated. For example, showering causes the release of 50–70% of the radon in water [1]. If the release occurs indoors and the water radon concentration is elevated, the radon concentration in the indoor air could be high. How high depends upon the water's radon concentration, how much water is used and how the water is used. In Sweden, a very rough rule of thumb is used to estimate the concentration which a household is subjected to: residential radon concentration is 2×10^{-4} of the water radon concentration (e.g. if the concentration of radon in the water is 1000 Bq/l, then the concentration of radon in the indoor air of the home will be 200 Bq/m^3). In air, radon gas decays into its progeny which are inhaled along with air and whose radiation may cause lung cancer.

When water containing radon is ingested, a dose of radiation is imparted to the digestive system by the radon gas and its progeny. The greater portion of the radon is absorbed through the intestinal walls, transported throughout the body and, for the most part, released upon exhalation. The radon which decays in the body and the continued decay of radon's short- and long-lived progeny impart radiation to the various organs of the body. Because radon is quite soluble in fat, the radon progeny may concentrate in organs rich in fat. The greatest risk associated with the ingestion of water containing radon and radon progeny is considered to be that the radiation could cause stomach-colon cancer [2] and other organ cancers. Radon as a cause of leukaemia has also been discussed [3].

Earlier, it was calculated that the greatest radiation dose from radon in water would be derived from the contribution of radon to the air and that the ingestion of water containing radon would give a considerably lower radiation dose. That calculation is still accurate for adults. However, in recent years, it has been shown that young children, especially infants, receive a greater dose of radiation from ingesting water containing radon than do adults [4, 5]. This is because the ingestion of water is great in comparison to body weight and because young children drink more unprocessed water than do adults. Table I shows radiation doses calculated for Swedish adults, children and infants for various radon concentrations in water [6]. The calculation of the radiation dose received from indoor air assumed that an average household used 200 l of water per day. The calculation of the radiation dose due to ingestion of water is based upon the assumption that adults ingest 50 l of unheated or otherwise unprocessed water per year, children 75 l/y and infants 100 l/y [7]. In comparison, consider that the highest radiation dose allowed for persons exposed to radiation in the workplace is 50 millisievert per year (mSv/y) during one year and at most 20 mSv/y as an average for five consecutive years. Individuals within the most exposed group of the general public, but who

TABLE I. TYPICAL VALUES FOR EFFECTIVE RADIATION DOSES VIA INHALATION AND INGESTION OF RADON FROM HOUSEHOLD WATER FOR ADULTS, CHILDREN AND INFANTS CALCULATED FOR THE LIMITS PROPOSED BY THE SWEDISH NATIONAL FOOD ADMINISTRATION FOR RADON CONCENTRATIONS IN PUBLIC AND PRIVATE DRINKING WATER, 100 AND 1000 Bq/l, RESPECTIVELY. INDIVIDUAL DOSES MAY VARY GREATLY [6]

Radon in water (Bq/l)	**Inhalation** Approximate effective dose (mSv/y)	**Ingestion** Approximate effective dose (mSv/y)	**Rounded Sum** Approximate effective dose (mSv/y)
100	0.4	0.05	0.45
		(0.15)[a]	0.55
		(0.7)[b]	1.1
1000	4	0.5	4.5
		(1.5)[a]	5.5
		(7)[b]	11

[a] Children aged 10 years   [b] Infants aged 1 year

do not work with radiation, must not be exposed to a dose in excess of 5 mSv/y resulting from human activity involving radiation. This is according to the European Union suggestion for Directive on basic safety standards (BSS) for the protection of the health of workers and the general public against the dangers arising from ionising radiation [8].

Radiation doses from radon in water can be very high. In Sweden, households have been discovered in which the children daily ingest water with radon concentrations of 55 000 Bq/l. Every day approximately 60 000 Swedes (population of Sweden 8.8 million) consume water having radon concentrations higher than 1000 Bq/l.

Radon gas released from household water into the indoor air is calculated to cause approximately 50 cases of lung cancer per year. Ingestion of water containing radon is calculated to cause 13–20 cases of cancer per year [9].

After consultation with the Swedish Radiation Protection Institute and the Swedish National Board of Health & Welfare, the Swedish National Food Administration proposed limits for radon in drinking water in 1995 (Table II) [10]. These will be compulsory limits. None of Sweden's large public water works deliver water with radon concentrations above 100 Bq/m^3. On the other hand, Sweden has 20 000–30 000 drilled wells in which the water contains radon concentrations above 500 Bq/l, and approximately 10 000 drilled wells with more than 10 000 Bq/l. In total, there are approximately 200 000 drilled wells in Sweden which are utilised year round by permanent residents and 200 000–300 000 drilled wells which are utilised irregularly by non-permanent recreation residents. The latter will not be subject to the proposed limits for radon in water.

TABLE II. PROPOSED SWEDISH LIMITS FOR RADON CONCENTRATIONS IN DRINKING WATER

Concentration	Subject to limits	Comments
100 Bq/l	Public water supply	Compulsory limit. Concerns concentrations in water delivered by public water works.
500 Bq/l	Private water supply	Recommended limit. Concerns the maximum concentration in water given to children under 5 years of age.
1000 Bq/l	All drinking water	Unfit for human consumption.

Finland since 1993 has a compulsory limit of 300 Bq/l for public water supplies [11]; the Czech Republic has a compulsory limit of 50 Bq/l for public water supplies and a compulsory limit of 1000 Bq/l for all water supplied to dwellings [12].

3. RADON IN WATER — WHY AND WHERE

Radon in water is primarily a problem for water supplies which extract water from drill holes in rock or from springs flowing through areas with crystalline rocks, which have somewhat higher uranium concentrations than the average bedrock. Examples of rock types which often have enhanced uranium concentrations, >5 ppm U (approx. 60 Bq/kg), include the following: granites, syenites, pegmatites, acid volcanic rocks, and acid gneisses. Wells in areas with these rock types commonly contain intramontaneous ground water with radon concentrations of 50-500 Bq/l or considerably higher. Intramontaneous waters from sedimentary rocks such as limestone, sandstone, and shales, as well as igneous, volcanic intermediate and basic rocks usually have radon concentrations of 5–70 Bq/l, which is to be expected since these rock types generally have low uranium concentrations. Exceptions do exist, however rare. Well waters with elevated radon concentrations from wells in bedrock with low uranium concentrations are known. In such instances, the water has been in contact with uranium mineralizations, e.g. in sandstone and basic rocks, or the ground water has passed through sedimentary layers of bedrock with high uranium concentrations and then travelled long distances, e.g. artesian water in contact with underlying granites. In the latter case, the reason for the high radon concentration in the well water or spring is that uranium and radium have leached from the underlying bedrock, been transported by water and precipitated out along the path of transportation, but relatively near the well or spring.

Ground water in soil layers has considerably lower radon concentrations, as a rule, than does water occurring in cracks in the bedrock. Normal radon concentrations are 5–100 Bq/l in water from dug wells, which receive water from the surrounding soil layers. Factors which determine the radon concentration in the ground water of soil layers are as follows: radon concentration in the soil, the emanation coefficient of the soil (how much of the radon formed is released from the mineral grains into the water in the soil pores), and the soil porosity. Radon concentration in pore water in soil is governed by Formula 1:

$$A_{w\ max,\ pore} = A_e = ra \cdot e \cdot \delta \frac{1-p}{p} \quad (1)$$

where

$A_{wmax,\ pore}$	= radon concentration in the pore space water
A_{ra}	= activity of radium-226 (Bq/kg)[a]
e	= emanation coefficient (emitted radon / formed radon)
δ	= compact density (kg/m^3), normal rock material 2700 kg/m^3
p	= porosity (pore volume/total volume)

[a] 1 ppm uranium is equivalent to 12.3 Bq/kg Ra-226 assuming equilibrium in the decay series

Normal emanation, e, for soils is 0.2-0.4, and may for certain clays reach 0.6. Porosity, p, is normally 0.25–0.45. The radium concentration, A_{ra}, is 5–25 Bq/kg for silts, sands and soils with origins in rocks with low uranium concentrations, e.g. limestone. Soils originating from rocks with normal uranium concentrations have radium concentrations of 10–50 Bq/kg. These values correspond to radon concentrations of 5–50 Bq/l for ground water in soils with low uranium concentrations, and 10–100 Bq/l in soils with normal uranium concentrations.

In water from surface water reserves, the radon concentration is low, <2 Bq/l, mainly because the radon has had time to decay during the long holding period in the surface reserve, among other reasons.

Radon concentrations in intramontaneous water are normally considerably higher and often much higher than in ground water in soil layers. Water arising from uranium-rich rocks, e.g. uranium-rich granites and pegmatites, commonly have radon concentrations in excess of 500 Bq/l, with maximum concentrations of 20 000–60 000 Bq/l. This concentration is 2–100 times higher than the radon concentration of the surrounding bedrock, calculated per kg rock. One explanation for the elevated radon concentration in intramontaneous ground water is that 6-valence uranium is relatively easily dissolvable and is leached out of the rocks by the ground water. Dissolved uranium and its decay products precipitate onto the surface of fractures, partly because they react chemically with fracture minerals on the surfaces of the cracks, and partly because the decay products are sparingly soluble, thus precipitating out [13]. Landström and Tullborg [14] found that uranium concentrations in fracture coatings are often 3–20 times higher than in the surrounding rock. Consequently, a coating of radium-rich material builds up on the surfaces of cracks and fissures, from which radon emanates directly into the water in the crack. Figure 1 illustrates the process. Another possible reason for increased radon in ground water is that in any particular grain of uranium, the radon concentration is many times greater than that of the surrounding rock and water, thus it diffuses from the grain of uranium into the water phase. Since the rock porosity is very low, conditions exist for the water radon concentration to be 10–100 times greater than the rock matrix radon concentration (Formula 1).

4. RADON IN WATER IN SWEDEN

Radon in water is a relatively great problem in Sweden. As discussed earlier, many Swedes drink water containing high concentrations of radon, and approximately 40% of the population obtain their water from drilled wells. The reason for the pervading relatively high radon concentrations is that a major portion of the bedrock in Sweden is made up of Precambrian rocks, which consist mainly of granites, acid gneisses, and acid volcanics. In regions of gneiss, pegmatites and aplites are abundant. Table III presents normal concentration variations for radon, as well as radon concentrations for various types of water reserves and bedrock in Sweden. Figure 2 shows the distribution of water radon concentrations of some 1200 drilled wells in Southern and Central Sweden, and Fig. 3 areas with uranium-rich rock types. The wells were randomly selected for radon analysis during hydrogeological surveys carried out by the Geological Survey of Sweden and a national survey of water radon concentration performed by the Swedish Radiation Protection Institute [15]. It is evident from the map that there is a cluster of wells with enhanced radon concentrations in the central portion of the map, at Bergslagen, where the bedrock consists primarily of acid gneisses, granites, and acid vulcanites containing numerous pegmatites. Another area with numerous radon wells is the northeast coast of Sweden, with geology similar to that of Bergslagen. In Scania, Southern Sweden, where the bedrock mainly consists of non-metamorphic Cambrian-Tertiary sediments, the radon concentration in water is low. These conditions are also applicable to Southwest Sweden which primarily exhibits intermediate and acid gneisses, and intrusives low in uranium.

TABLE III. RADON AND RADIUM IN SWEDISH GROUND WATER. NORMAL AND MAXIMUM CONCENTRATIONS [13]

	Radon-222 (Bq/l)	Radium-226 (Bq/l)
Lake and sea water	<2	0.005–0.007
Wells dug in soil:		
normal in Sweden	10–300	0.001–0.09
in granite areas	40–400	
Wells bored in sedimentary rocks:		
Eocambrian -Tertiary	10–50	
Wells bored in crystalline Precambrian bedrock:		
normal bedrock	50–500	0.01–0.25
uranium-rich granites	300–4000, max. 57 000	
uranium-rich pegmatites	max. 30 000	max. 2.5
Uranium ores:		
Lilljuthatten, Stenfjällen	2000–100 000	max. 6
Pleutajokk, Arjeplog	18 000–55 000	0.1–0.17

Bohus granite is generally uranium-rich, 5–40 ppm U, and occurs in a large contiguous area along the northwest coast of Sweden, where wells with high radon concentrations are frequent. The Municipality of Sotenäs lies in that region and 60% of the drilled wells have radon concentrations in excess of 500 Bq/l and 30% in excess of 1000 Bq/l. Wells with much higher radon concentrations, >5000 Bq/l, are primarily located within uranium-rich granite regions. A campaign to measure radon in Sweden's drinking water is currently underway and several wells with more than 20 000 Bq/l have been discovered. So far, the well found with the highest radon concentration, 57 000 Bq/l, was drilled in Blomskogs granite, a uranium-rich granite.

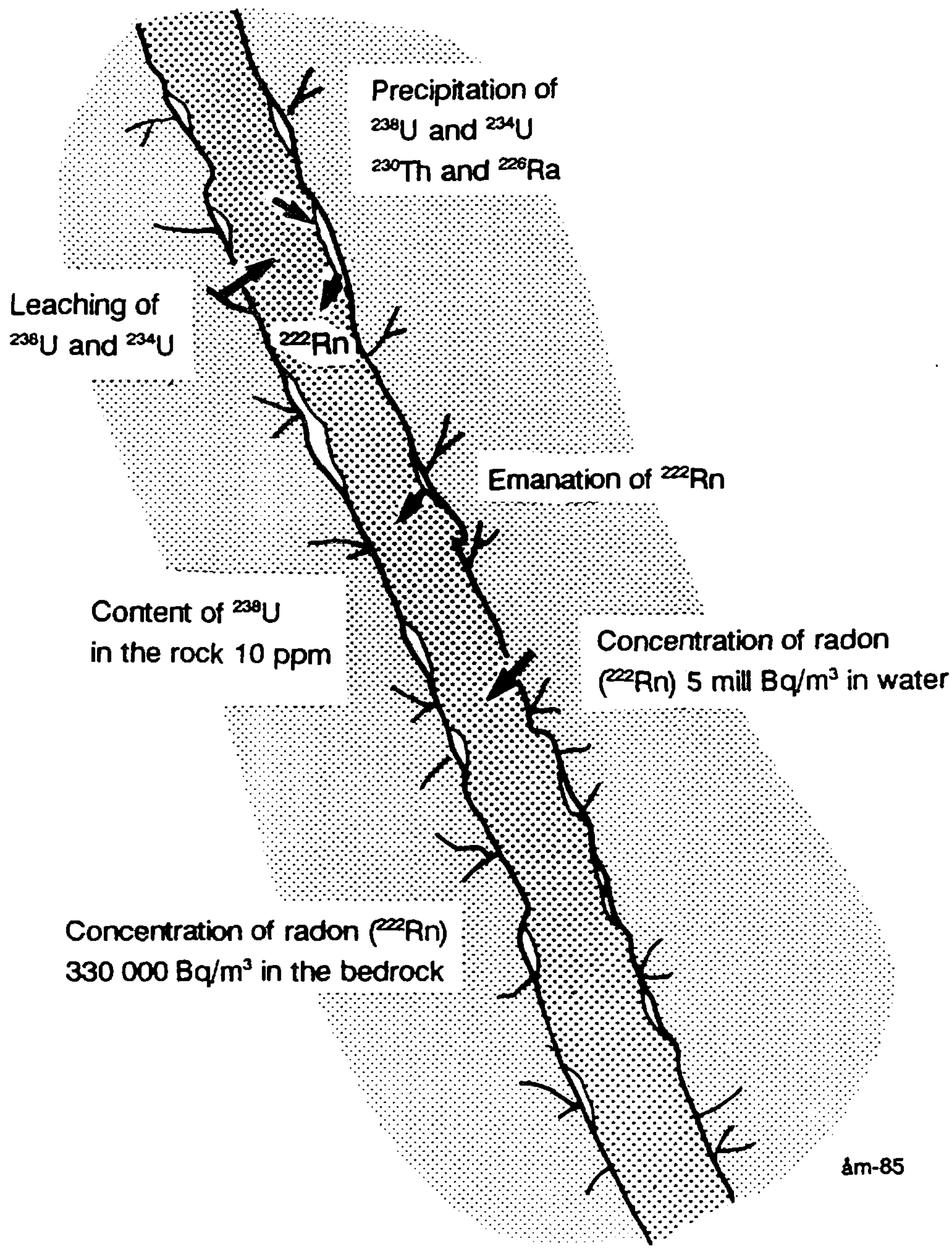

FIG. 1. Formation of radon gas in a water-filled crack [13].

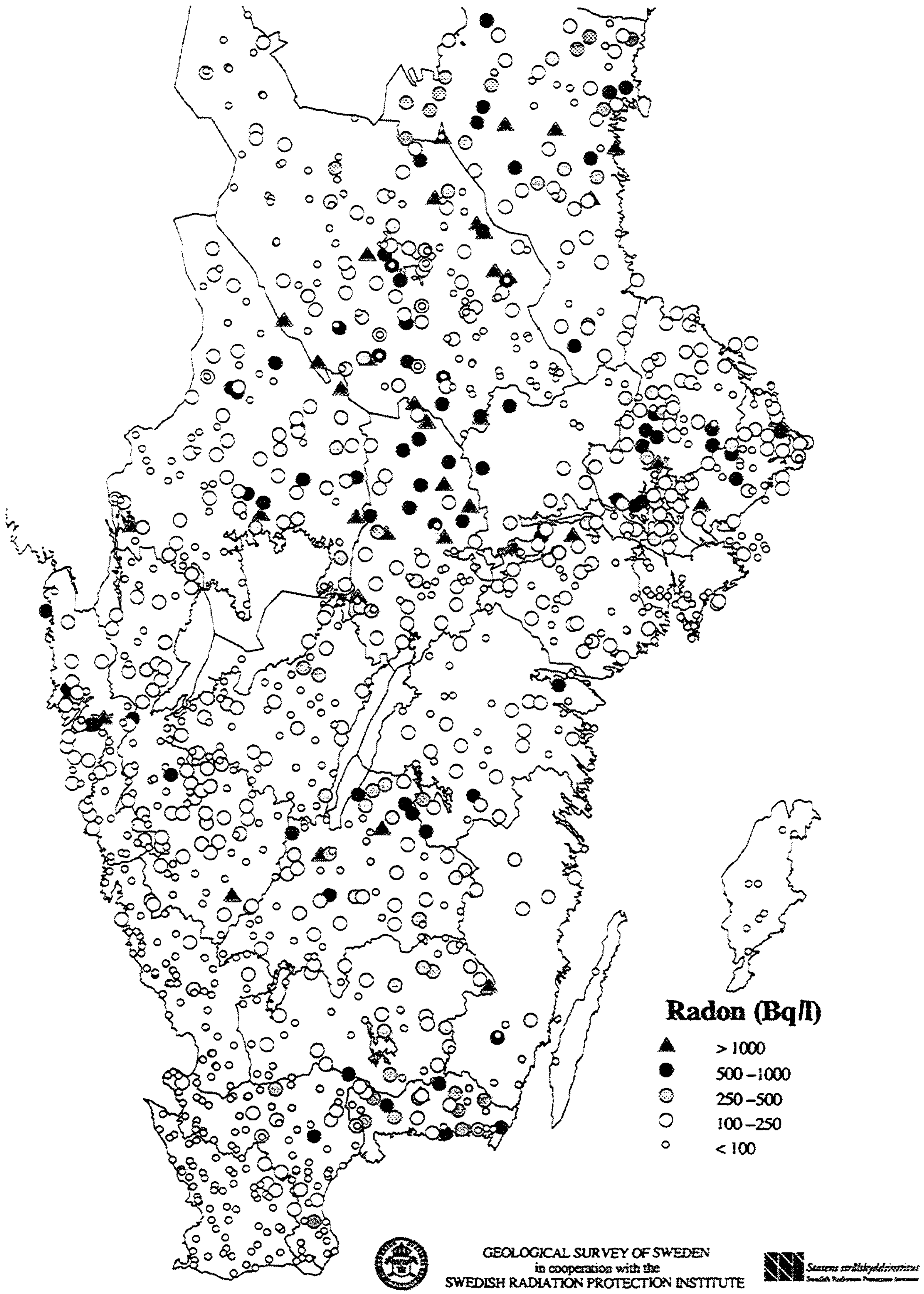

FIG. 2. Radon concentrations in randomly selected bedrock wells in Southern Sweden.

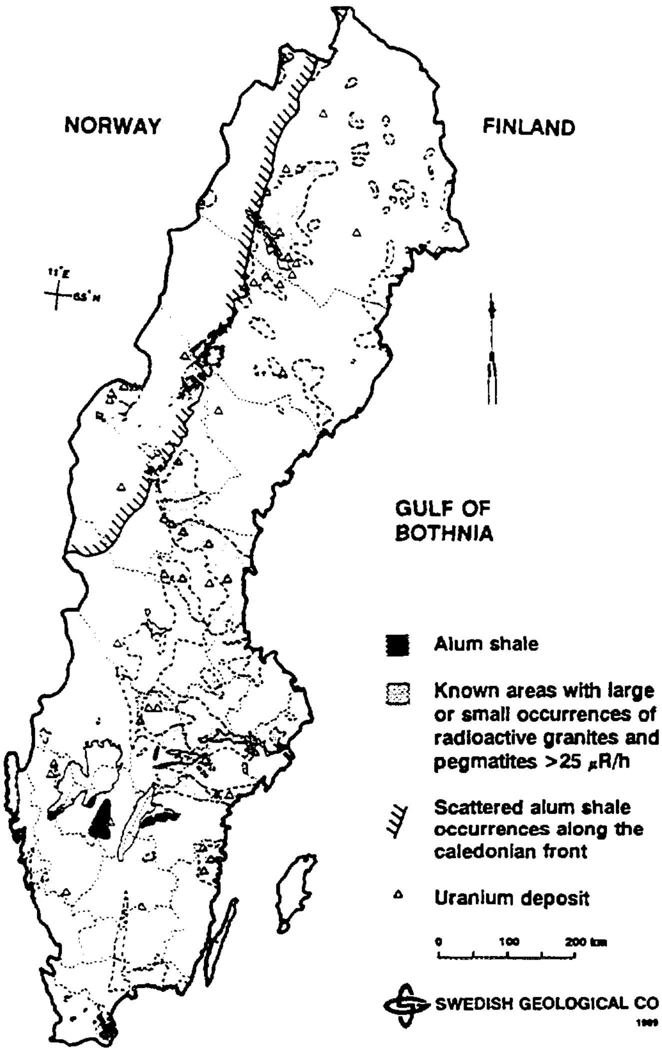

FIG. 3. Distribution of uranium-rich bedrock in Sweden.

5. USE OF DATA FROM GEOLOGICAL AND GEOPHYSICAL SURVEYS

5.1. Airborne radiometry

The Geological Survey of Sweden (SGU) is routinely carrying out airborne gamma spectrometric measurements over the Swedish territory since the late 60's. Details on the airborne equipment can be found in [16]. Today, the measurements are carried out at an altitude of 30–60 m with a line spacing of 200 m and a sampling frequency of 4 Hz, implying a sampling distance of 16 m along the flight line. These measurements are generally reprocessed to generate a 40 m sampling distance along the flight line to achieve sufficient counting statistics. While some 60% of Sweden's 410 934 km^2 is covered with digital radiometric information up to now, 75% is expected to be covered within the next ten years.

While the only airborne radiometric surveys carried out today are performed by SGU, some other surveys have been conducted by ore prospecting companies over specific regions in Sweden. Until 1984, when the Swedish programme for uranium exploration was brought to an end, most surveys were carried out for the purpose of uranium exploration. Today, the measurements are conducted within the national airborne geophysical mapping programme. The system used today is based upon a 256-channel Exploranium GR-820 with a 1024 cuin downward looking crystal package and a 256 cuin upward looking detector.

Swedish authorities have recognised airborne radiometric mapping as an important tool for the detection of radon prone areas; thus, the Survey has obtained a general permission to fly at an altitude of 50 m over urban areas provided that the information is used for predicting radon risk. After two serious accidents in recent years, it has been decided to increase the altitude to 60 m over rural areas, while the altitude over urban areas is decided upon at the pilot's discretion.

The spatial resolution of the airborne measurements enables the detection of even relatively minor geological objects with elevated levels of radioactivity, such as radioactive springs and pegmatites [17]. Moreover, a number of anomalies of anthropogenic origin are generally seen on the resulting maps. This includes roads and squares paved with material with elevated content of radioactive isotopes, arenas covered with ashes of burnt alum shale and buildings made up of radiating building material. Between the years 1929 and 1975, a type of light-concrete made from uranium-rich alum shale was produced and extensively used as building material. Today, it is estimated that one inhabitant out of ten is living in a dwelling partly made up of this material, something which significantly has increased the radiation exposure to the Swedish population, both through the direct exposure to gamma radiation emitted from the material and from radon being released to the indoor air.

There is evidence that, under favourable circumstances, even single buildings made up of uranium-rich alum shale-based light concrete may be identified from the airborne radiometric measurements.

5.2. Bedrock and quaternary geology

The Geological Survey has continuously been mapping the geology of Sweden since 1858. It is, however, not until recently that the Survey has moved to the production of geological information in digital form. The Swedish territory is covered as a whole with digital bedrock and quaternary geologic information, but only in the scale of 1:1 000 000, which is not sufficient for radon prognostics. Quaternary information in the scale 1:50 000 is rapidly becoming available, while the process of converting bedrock information to digital form is still somewhat in its infancy.

5.3. Geochemistry

Within the framework of the programmes for ground geochemical and biogeochemical mapping, samples are being analysed with respect to uranium among other elements. The former programme samples a silt and clay fraction of till from the undisturbed C-horizon, while the latter samples roots from stream plants. Both programmes provide information on uranium concentrations, the former on till and the latter on bioaccessible uranium in streams.

More research is needed to illuminate to what extent the results from geochemistry may be considered to be representative of the uranium/radium content of the underlying bedrock.

5.4. Ground radiometry

During the national uranium prospecting, extensive work were carried out to identify possible sites of interest for uranium mining. A large number of outcrops were visited and radiometrically investigated, although only to a lesser extent with the help of gamma spectrometry. These results are, however, not readily available in digital form.

Today, ground follow-up of anomalies identified from the airborne radiometry are performed to a limited extent, the principal aim being the detection of possible radon prone areas.

5.5. Hydrogeology

In Sweden there exists no obligation to report analyses of radon in water to the Survey. To get a general overview of the regional trends in the distribution of wells with elevated radon levels, the Survey in co-operation with the Radiation Protection Institute has collected a data set based upon analyses of radon in some 1200 wells drilled into the bedrock, randomly selected in the south and central part of Sweden as described above. Moreover, within the framework of the regional hydrogeological mapping programme, some selected wells are being analysed with respect to radon among other parameters.

5.6. Other sources of information

It is not until recently that local authorities have initiated ground water radon mapping programmes. The major part of analyses of radon in water, however, resides in databases maintained by these authorities. While some municipalities only measure upon request, others have chosen to analyse all known drilled wells within the municipality, thus providing an unbiased material of great value for correlation with geology.

Juridical obstacles have so far hampered the access to this information, since the individual measurements are considered to be the property of the customer and not as information available to the public. It is, however, believed that the measurements in the near future may become accessible to the Survey for the purpose of radon prognostics.

6. GROUND WATER RADON PROGNOSTICS

Following the forthcoming implementation of compulsory limits for radon in water, local authorities, charged with the tracing and identification of possible public health hazards, have manifested an increasing interest in material showing the spatial distribution of ground water radon risk. In analogy with traditional radon risk maps, used in the urban planning process to delimit areas where special building construction protocols should be followed to prevent the occurrence of elevated indoor radon levels originating from the ground, there is a demand for maps where ground water radon prone areas may be identified. To meet this demand, the established Swedish practice for the compilation of radon risk maps must be enlarged to allow for the focusing upon features of relevance for the problem of radon in water, which essentially is a problem related to the bedrock.

6.1. National risk maps

To meet the demand, essentially from the public, when the problem of radon in water first was invoked, the Survey in co-operation with the Radiation Protection Institute decided to compile a map showing the main trends of occurrence of wells with elevated radon content. The first version of this map was presented in August 1994, and was based upon airborne radiometry, the limited data set of direct measurements of radon in drilled wells described above, along with the knowledge gathered during the Swedish programme for uranium exploration. The public debate following the publication of the map, including the possible health hazard that radon in water may represent, put a considerably pressure upon national as well as local authorities to delineate ground water radon prone areas in more detail. A second version of the national map is presented in Fig. 4.

6.2. Regional risk maps

Although of public interest, national overviews as described above are of limited interest to local authorities involved in the detection and prevention of radon hazards. Maps on a regional scale with a correspondingly higher spatial resolution are therefore needed.

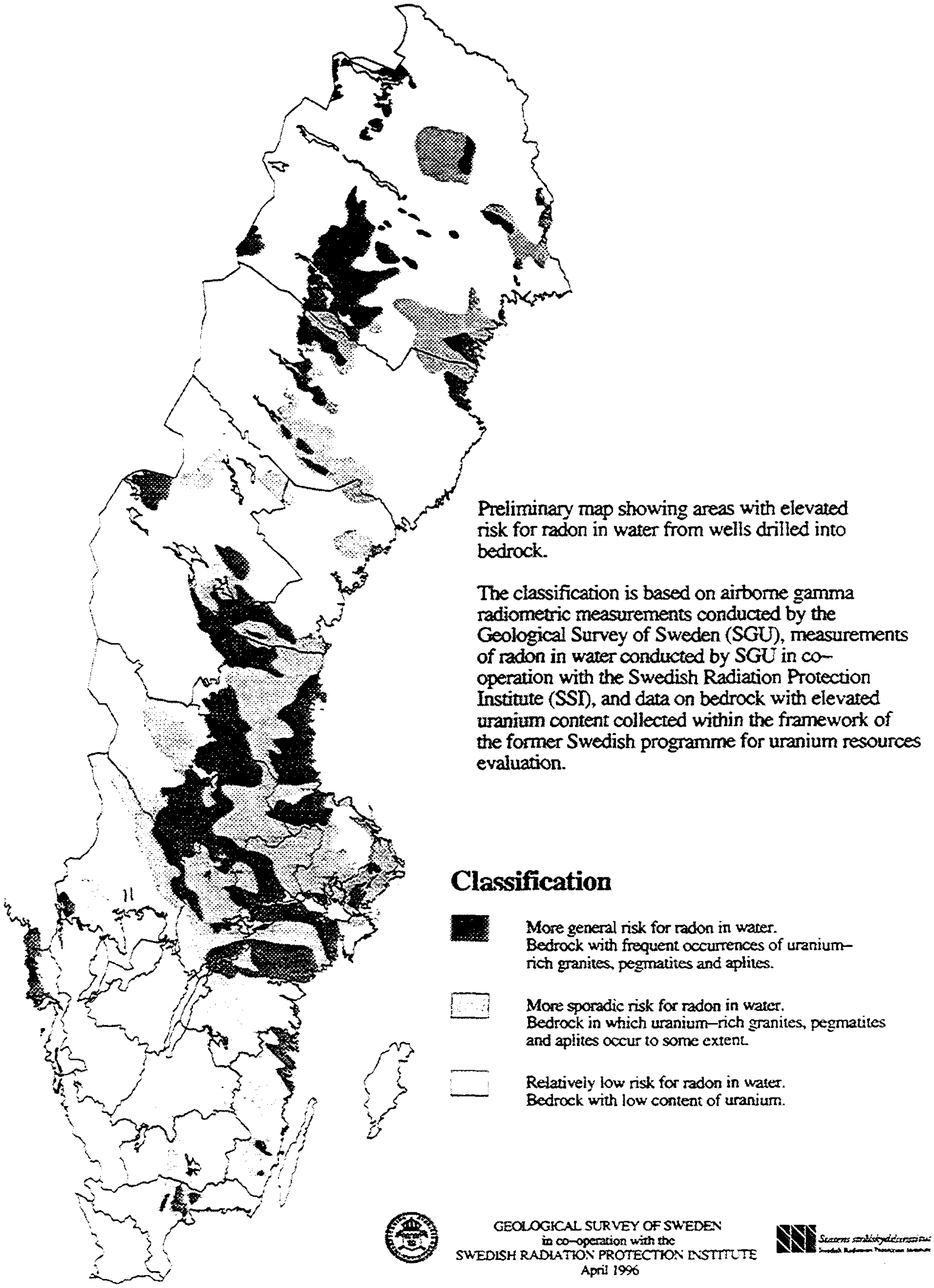

FIG. 4. Preliminary ground water radon risk map of Sweden.

At the Survey, ongoing research are currently addressing the question to what extent existing digital geoscientific information, in particular high spatial resolution airborne data, can be used to delineate risk areas with respect to ground radon. The work is being carried out within the framework of a geographical information system, and aims at the compilation of radon prognosis maps in the scale 1:50 000, suited to meet the demands from local authorities in the urban planning process, and in particular to serve as baseline information for the compilation of radon risk maps. Reflecting the current focusing upon radon in water, the aim of the research has been extended to incorporate the prognostics of ground water radon prone areas.

To develop the methodology, a 25 × 25 km test area in Central Sweden has been chosen (Fig. 5). The northern part of the area is mainly covered with postglacial clays, slightly enhanced in thorium, while the southern part is dominated by till. As the whole area is situated below the highest shoreline, the till in large areas is wave-washed and especially in the highest parts redeposited as beach sediments. Crossing the area from north to south is the esker[1] Köpingsåsen, which can be clearly identified on the topographic map in Fig. 5.

The bedrock of the area belongs to the Svecofennides of Central Sweden and was developed 1700-2100 millions of years ago. The principal rocks are metamorphosed volcanics and sediments, synorogenic granitoides, most frequently gneissic, migmatites, serorogenic granites and associated pegmatites.

The area is well covered with geoscientific information in digital form, and is known to comprise areas with serious ground and ground water radon problems. In particular, several bedrock units within the area manifest elevated uranium levels.

The quaternary and bedrock maps of the area are shown in Figs. 6 and 7 [18, 19], while the uranium component of the airborne radiometric measurements is shown in Fig. 8. When addressing the problem of radon in ground water, one needs to establish a map showing the uranium (radium) content of the bedrock. This is achieved as follows:

- the quaternary map is reclassified into two classes, the first comprising outcropping bedrock and till, and the second containing all other quaternary units

- the reclassified quaternary map is applied as a logical mask to the uranium component of the airborne radiometric data, retaining measurements over outcrops and till only, thus rejecting all other data

- the remaining radiometric data are processed together with the bedrock data to yield estimates of the mean radiometric signal over the individual bedrock units

In such a way, a uranium map of the bedrock is compiled, bearing information on all units that are exposed, either directly through outcrops or indirectly through overlying tills, assumed to be representative of the underlying bedrock. To yield a smoother map, radiometric means are calculated rather than cell-by-cell values. This approach also allows the information to be extrapolated beneath the quaternary cover.

The resulting radiometric map of the bedrock, presented as a ground water radon risk map, is shown in Fig. 9. Note that features and trends appear which are not readily visible on the raw radiometric map due to signals originating from the quaternary overburden.

Shown also in Fig. 9 are the limited number of wells that have been sampled so far within the study area. As for the wells above 500 Bq/l, they fall into two distinct classes: (1) situated in

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[1] glacial ridge formation comprised of gravel and coarse sand

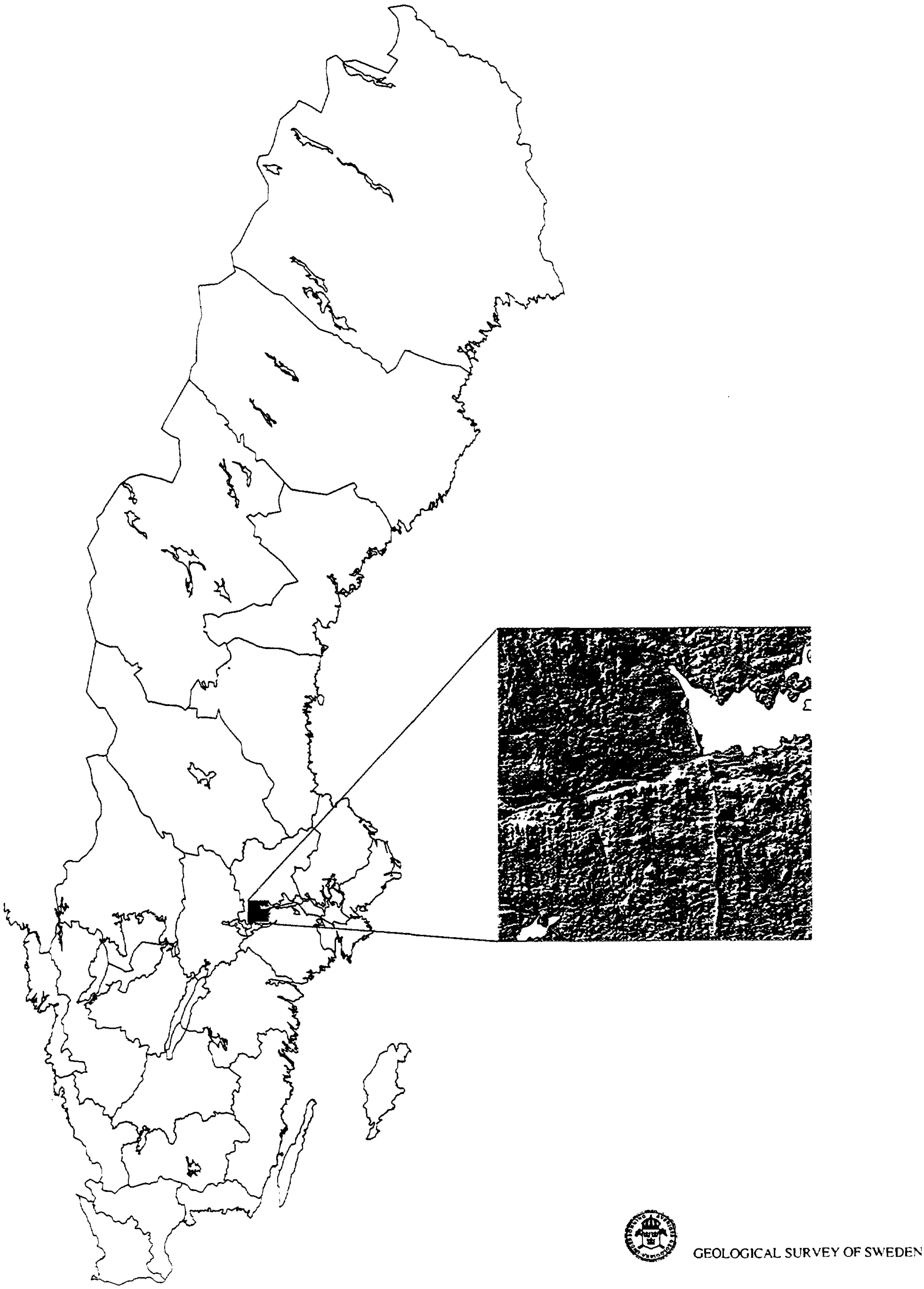

FIG. 5. Study area for regional ground radon prognostics with topographic map.

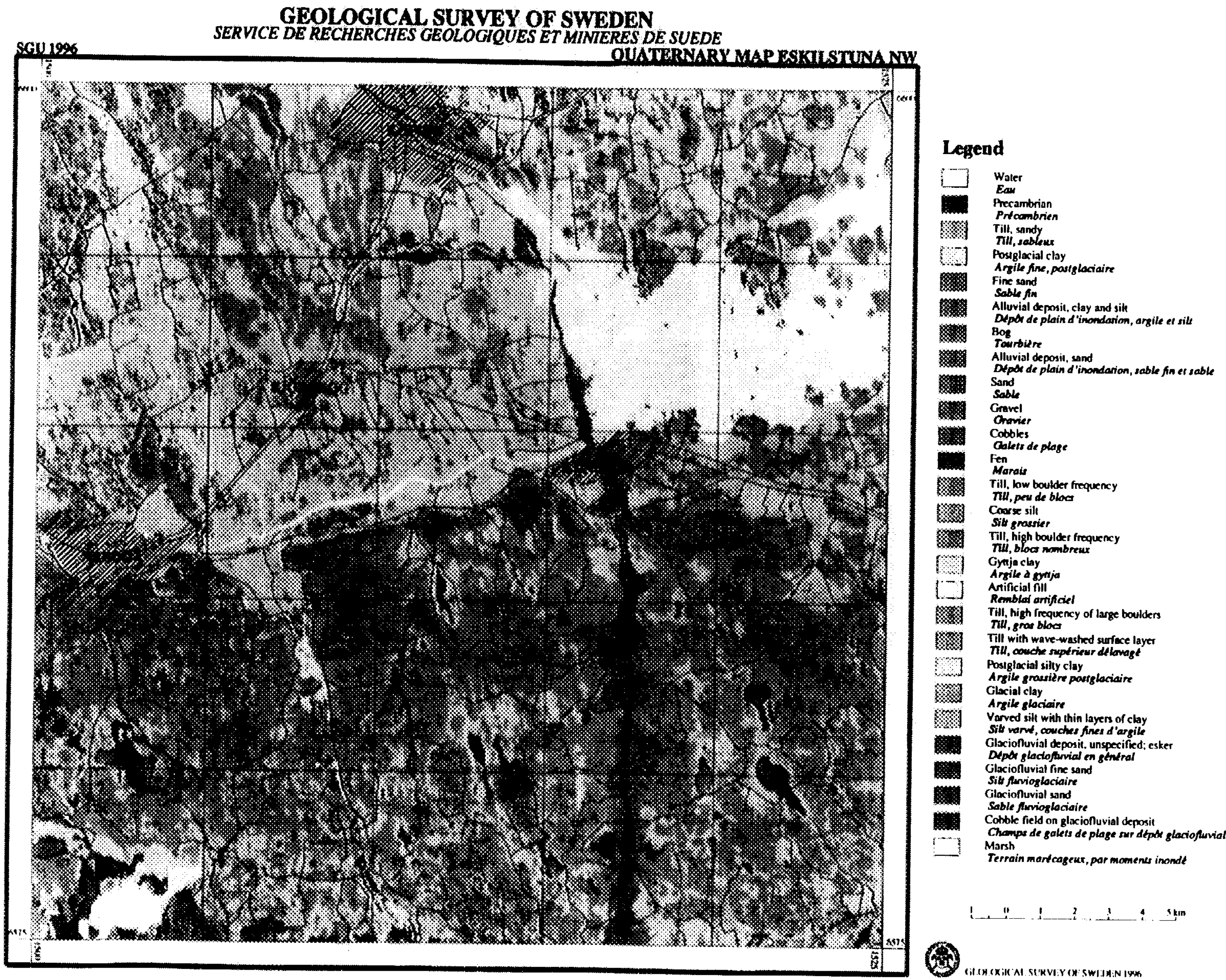

FIG. 6. Quaternary map Eskilstuna 10G NW.

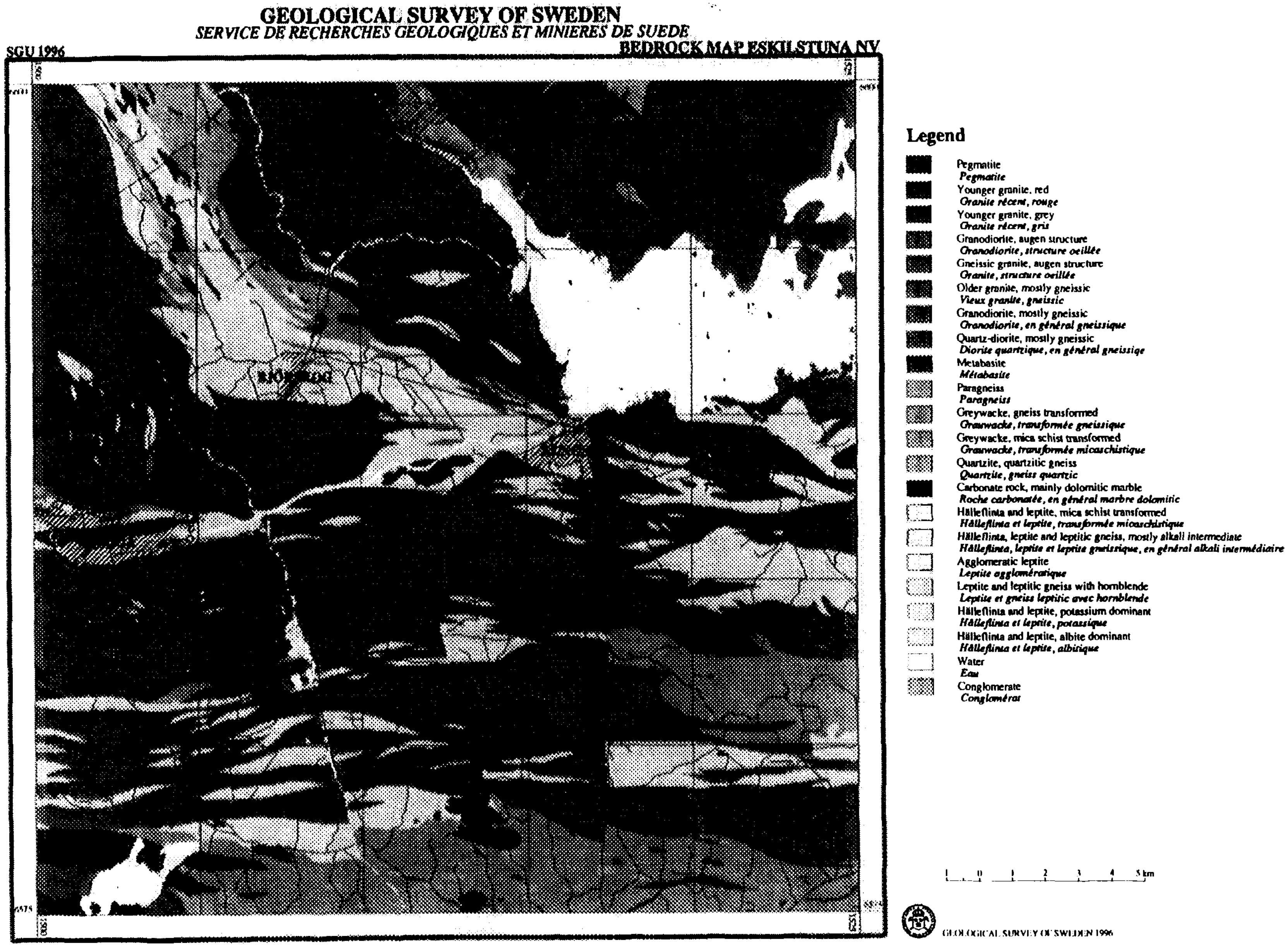

FIG. 7. Bedrock map Eskilstuna 10G NW.

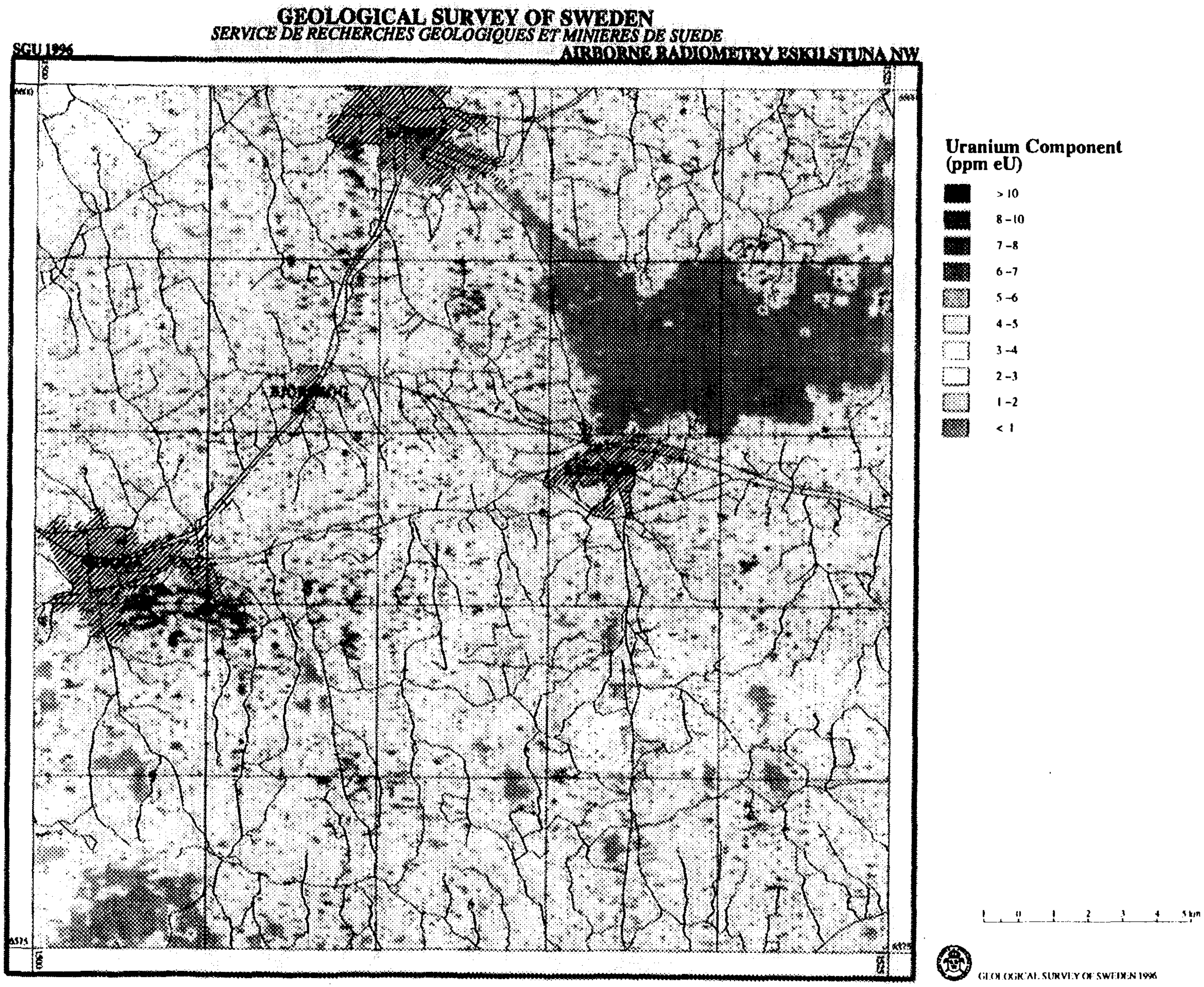

FIG. 8. Airborne radiometric map (uranium component) Eskilstuna 10G NW.

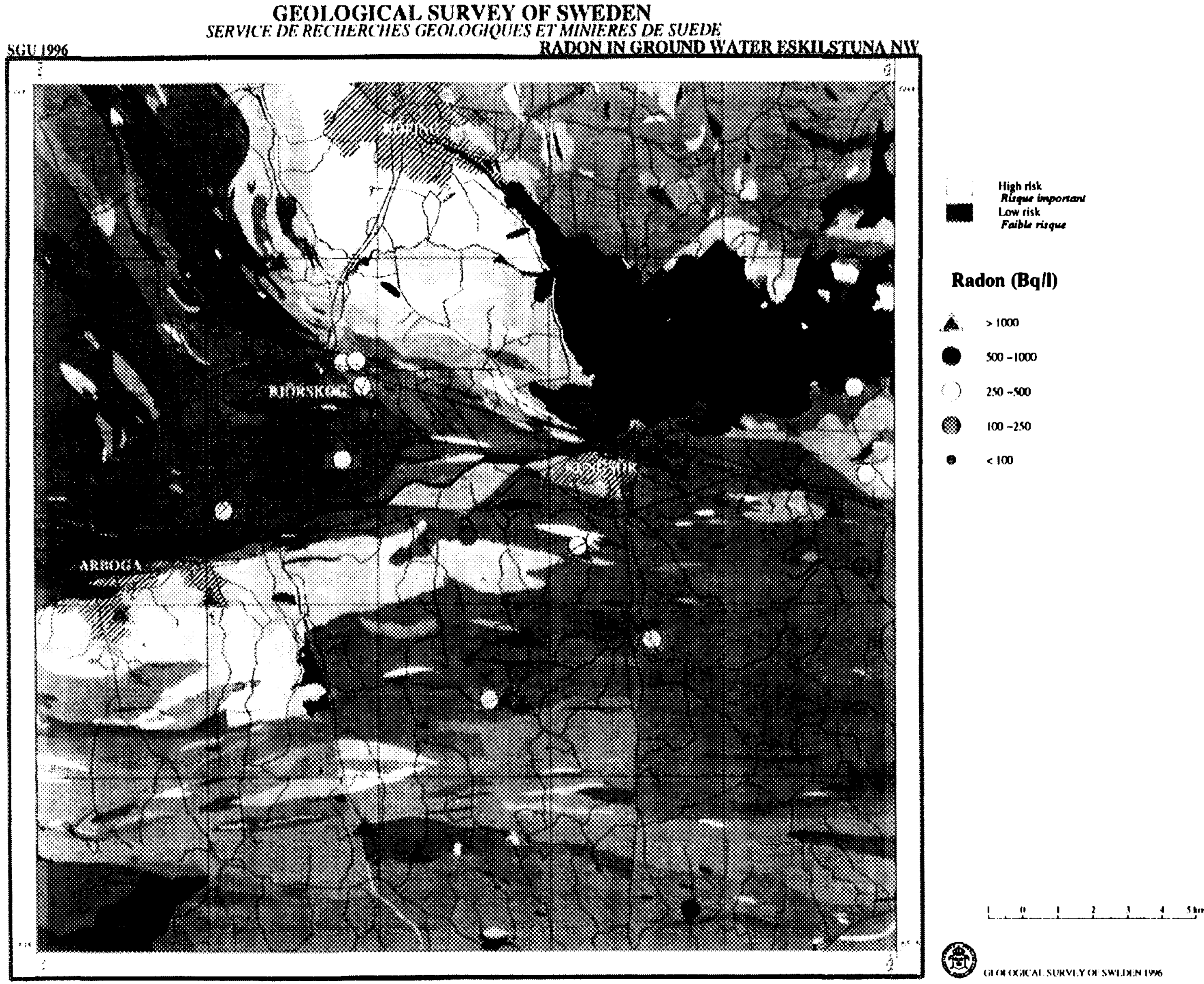

FIG. 9. Ground water radon prognosis map Eskilstuna 10G NW. Shown also on the map are wells drilled in bedrock analysed with respect to radon.

uranium-rich bedrock, or (2) situated in bedrock where the bulk rock manifests no elevated uranium content, but where there is an abundance of pegmatitic intrusions (not seen on the simplified bedrock map shown in Fig. 7). These pegmatites are known often to be fairly radioactive, but they seem not to appear to a sufficient extent to have any major influence on the airborne radiometric measurements and/or not to be enough exposed as outcrops.

The limited control obtained so far regarding the validity of the prognosis thus indicate that it is possible to predict to some extent areas where the relative probability of encountering radon problems is higher. A prognosis based upon airborne information should, however, be modified to include areas where the bedrock information suggest that uranium-rich intrusions may be present, even if they do not have an impact on the airborne radiometric signal.

Future research will incorporate the sampling of outcrops with the help of ground gamma spectrometry as well as the evaluation of the geochemical information over the area.

7. FUTURE ASPECTS

The implementation of compulsory limits for radon in drinking water will probably trigger an avalanche of measurements of public and private water in Sweden, leading to a better understanding of the distribution of wells with elevated levels. The medical implications of the radiation doses caused by radon in water have already drawn a considerable amount of attention from the public, forcing governmental as well as local authorities to put priority to the problem.

The occurrence of drilled wells with elevated radon content is well correlated with geological conditions. Any attempt to identify areas with ground water radon problems should therefore incorporate all available geoscientific information of relevance to the occurrence of radon, and in particular high spatial resolution airborne radiometry.

It is the definite conviction of the authors that ground water radon prognostics, based upon available geological, geophysical and geochemical information in connection with ground water radon mapping programmes will play an increasingly important role in the regional and municipal planning process with respect to radon risk.

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