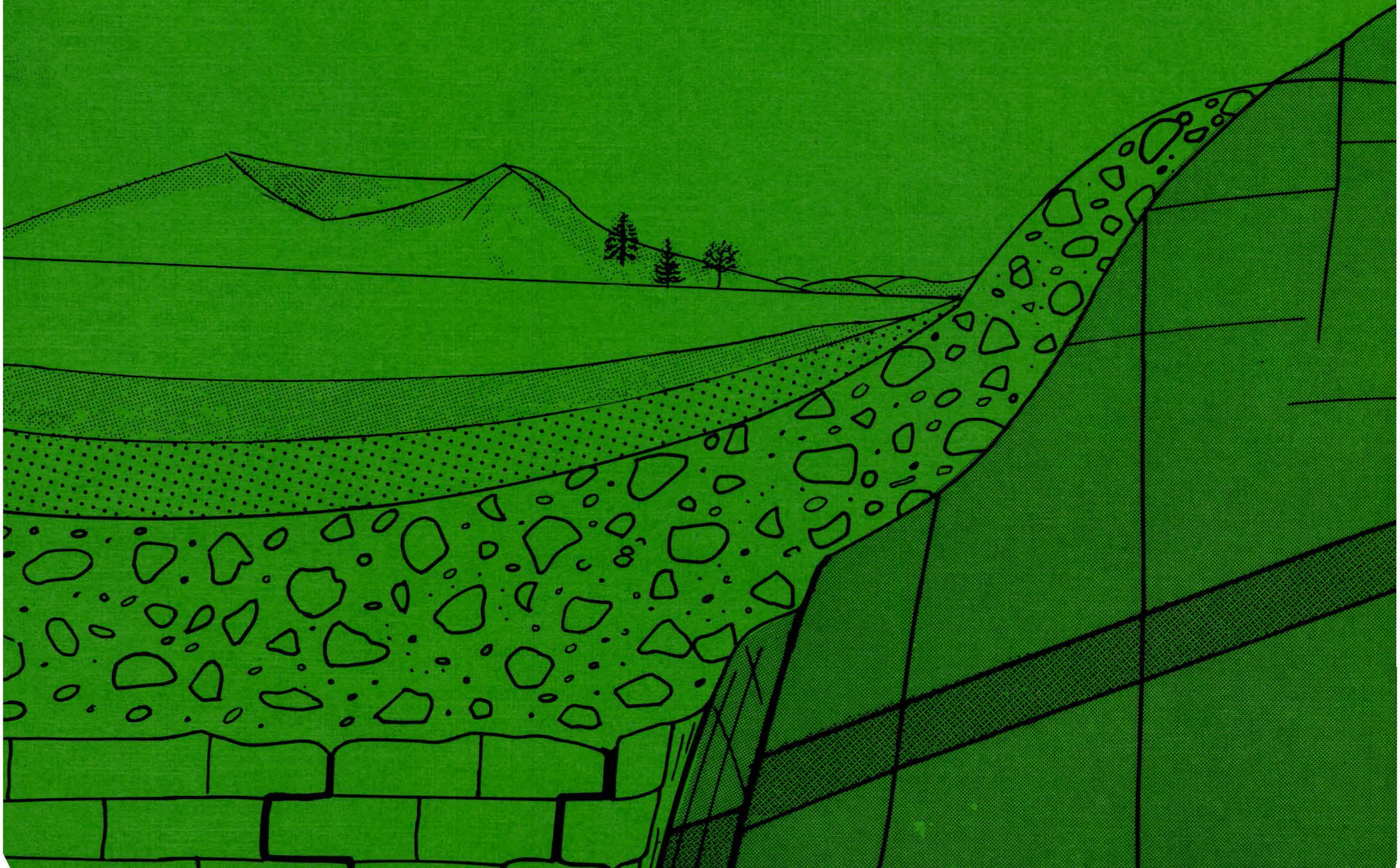
SVERIGES GEOLOGISKA UNDERSÖKNING
Rapporter och meddelanden nr 30

Gustav Åkerblom and Carole Wilson

Radon – geological aspects of an environmental problem

Uppsala 1982



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RADON - GEOLOGICAL ASPECTS OF AN ENVIRONMENTAL PROBLEM

ENVIRONMENTAL RADON INVESTIGATIONS IN SWEDEN

Gustav Åkerblom

REGIONAL ENVIRONMENTAL DOCUMENTATION OF NATURAL RADIATION IN SWEDEN

Carole Wilson

Papers presented at the International Meeting on Radon - Radon Progeny Measurements, Montgomery, Alabama, August 27-28 1981.

The papers cover all aspects of the work being carried out by the Geological Survey of Sweden in relation to radon and other natural radiation hazards.

Uppsala 1982

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ENVIRONMENTAL RADON INVESTIGATIONS IN SWEDEN

Gustav Åkerblom

ABSTRACT

In Sweden, radon daughter concentrations of 200-800 Bq m^{-3} (0.05-0.2 WL) are known to occur in buildings constructed of aerated concrete which has been manufactured from alum shale, a Cambrium, uranium-rich black shale. As a result of these alarmingly high levels, the Swedish Government set up, in 1979, a Commission whose task is to initiate research around the problem of radon, and to recommend remedial measures against natural radiation in dwellings.

Based on the recommendations of the Commission, the Government proposed the following measures:

- the introduction of provisional limits for permitted radon daughter concentrations in dwellings. These limits are 400 Bq m^{-3} (0.11 WL) for existing buildings and 70 Bq m^{-3} (0.02 WL) for new development

- the use of specific building techniques when developing areas with high soil gas radon contents

- an immediate search for all buildings constructed of alum shale based aerated concrete.

About 300 000 houses in Sweden are constructed entirely or partially of aerated concrete containing alum shale. During 1980, radon daughter levels have been measured in 20 000 of these houses by Local Health Authorities. The first results show that about 14 % of the measured houses have radon daughter levels exceeding 400 Bq m^{-3}. In about 2 % of the investigated houses the value exceeded 1 000 Bq m^{-3} (0.27 WL), and maximum values of 4 000 to 9 000 Bq m^{-3} (1.1-2.4 WL) have been measured in some houses.

Radon daughter levels exceeding 800 Bq m^{-3} are not caused entirely by radon emanating from building materials. A contribution of radon from the ground is necessary. Most of the houses with values exceeding 800 Bq m^{-3} have proved to be sited on ground containing alum shale, uranium-rich granite, uranium-rich pegmatite or on eskers. Many thousands of houses in Sweden are built in such situations.

The measurements so far obtained indicate that the problem of radon penetrating into buildings from the ground is a far greater problem than that of radon emanating from building materials. Geological and geophysical investigations of risk areas are of the utmost importance if all new development is to comply with the provisional limits for radon daughter levels proposed by the Radon Commission.

INTRODUCTION

Approximately 300 000 dwellings in Sweden are constructed, either partially or entirely, of radioactive aerated concrete. This concrete is manufactured

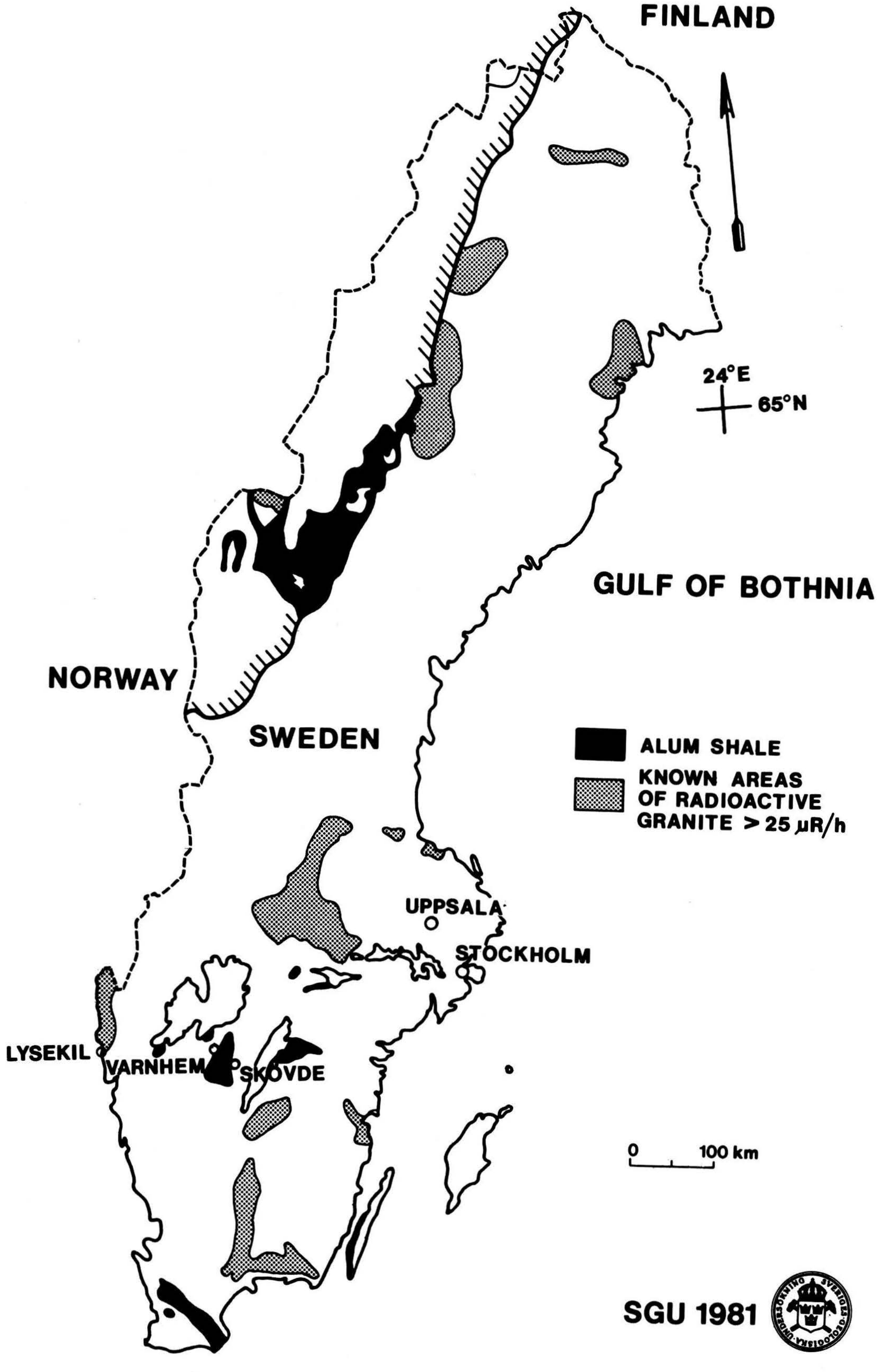

Fig.1. Distribution of the alum shale formation and of areas known to contain radioactive granites.

from alum shale, a uranium-rich (U 50-350 ppm), Upper Cambrian, black shale which is sometimes sufficiently rich in organic matter that it may be used as a fuel. Alum shale occurs as a horizontal layer which varies in thickness from 2-75 metres. The distribution of the alum shale occurrences in Sweden is shown in Fig.1.

The manufacture of alum shale based aerated concrete dates back to 1928. It was known at the time, that the concrete and the alum shale from which it was produced, had high uranium contents, but it was not until during the 1950's that the suitability of alum shale as a building material was questioned (Hultqvist, 1958).

During the early 1970's, high indoor radon levels were measured in houses built of alum shale based concrete, but manufacture of this material continued until 1975. Indoor radon measurements made by the National Institute of Radiation Protection during the 1970's revealed that radon levels in houses increased in connection with energy saving measures. Houses were being made more air-tight and rates of ventilation were being lowered. In some of the houses investigated by the Institute, radon levels of 200-800 Bq m^{-3} (Becquerels per cubic metre) were encountered (Swedjemark 1977, 1978 a and b, 1980).

A new dimension to the radon problem became apparent in 1978 when the National Institute of Radiation Protection measured radon levels in houses built of normal materials on a foundation of alum shale tailings. The measured levels were found to be between 400 and 1 600 Bq m^{-3} (Swedjemark et al 1979).

RADON COMMISSION

In February 1979, the Swedish Government appointed a Commission to investigate measures against radiation hazards in buildings. The Commission was also instructed to initiate a search for all such buildings, and to promote research around the radon problem. The Commission is assisted by various experts, for example from the National Institute of Radiation Protection, the National Board of Urban Planning, the Geological Survey of Sweden, the building industry and the Swedish Association of Local Authorities. A preliminary report from the Commission was presented in May 1979 (Radonutredningen 1979). The report contains proposals on: provisional limits for maximum radon daughter levels in dwellings; maximum permitted radium content in building materials and gamma radiation from these materials; searches for houses with high radon daughter levels; and research programmes.

A further proposal made by the Commission in its report was that maps, termed GEO-radiation maps, should be prepared to show the distribution in Sweden of all areas with particularly radioactive rocks and soils (alum shale and uranium-rich granites and pegmatites). A full description of these maps is given in Wilson (1981).

LIMITS

Acting on instructions from the Government, the National Board of Health and Welfare and the National Board of Urban Planning in consultation with the National Institute of Radiation Protection have issued provisional regulations based on the proposals presented by the Radon Commission (Socialstyrelsen 1980, Statens planverk 1980). In short, the regulations are as follows (complete text is given in appendix 1).

Existing houses

400 Bq m^{-3} (0.11 WL) is a provisional limit for the annual average of the equilibrium concentration of radon. Houses with levels exceeding 400 Bq m^{-3} are declared to be insanitary.

After remedial action or building alterations, the annual average of the equilibrium equivalent concentration of radon shall not exceed 200 Bq m^{-3}.

New development

70 Bq m^{-3} (0.02 WL) is the maximum permitted limit for the annual average of the equilibrium equivalent concentration of radon in rooms which are in continual use.

50 μR/h (micro Roentgen per hour) is the maximum permitted gamma radiation for rooms in continual use.

Building materials

Building materials for use in continously inhabited constructions shall not have a gamma index or radium index exceeding 1.0. It is also recommended that gamma radiation shall not exceed 100 μR/h for outdoor areas which are in regular use, for example, playgrounds.

The gamma and radium indices are defined as follows:

$$\text{Gamma index} = \frac{C_K}{10\ 000} + \frac{C_{Ra}}{1\ 000} + \frac{C_{Th}}{700}$$

$$\text{Radium index} = \frac{C_{Ra}}{200}$$

where C_K, C_{Ra} and C_{Th} are the concentrations of potassium-40, radium-226 and thorium-232 expressed in terms of Bq m^{-3} of building material.

70 Bq m^{-3} (0.02 WL), the maximum permitted level for new development, is a functional requirement implying that technical measures may be necessary against all sources of radon gas, for example, radon in the ground, in building materials and in household water supplies. This regulation supercedes the proposal from the Radon Commission that, in areas where gamma radiation in the ground at foundation level exceeds 30 μR/h, houses shall either be constructed "radon safe" or the site investigated to determine whether a "radon safe" construction is necessary.

SEARCHES FOR "RADON HOUSES"

Searches for houses with high radon daughter levels have been in progress since the spring of 1979. Initially the search was aimed at finding houses with alum shale based aerated concrete, but more recently attention has been focused on the search for houses where high indoor radon levels are related to high soil gas radon concentrations.

The search for houses constructed with radioactive concrete faced certain problems. As house deeds generally contain no information as to the type of concrete used, most houses in the country need to be visited in order to determine whether or not they are constructed of radioactive concrete.

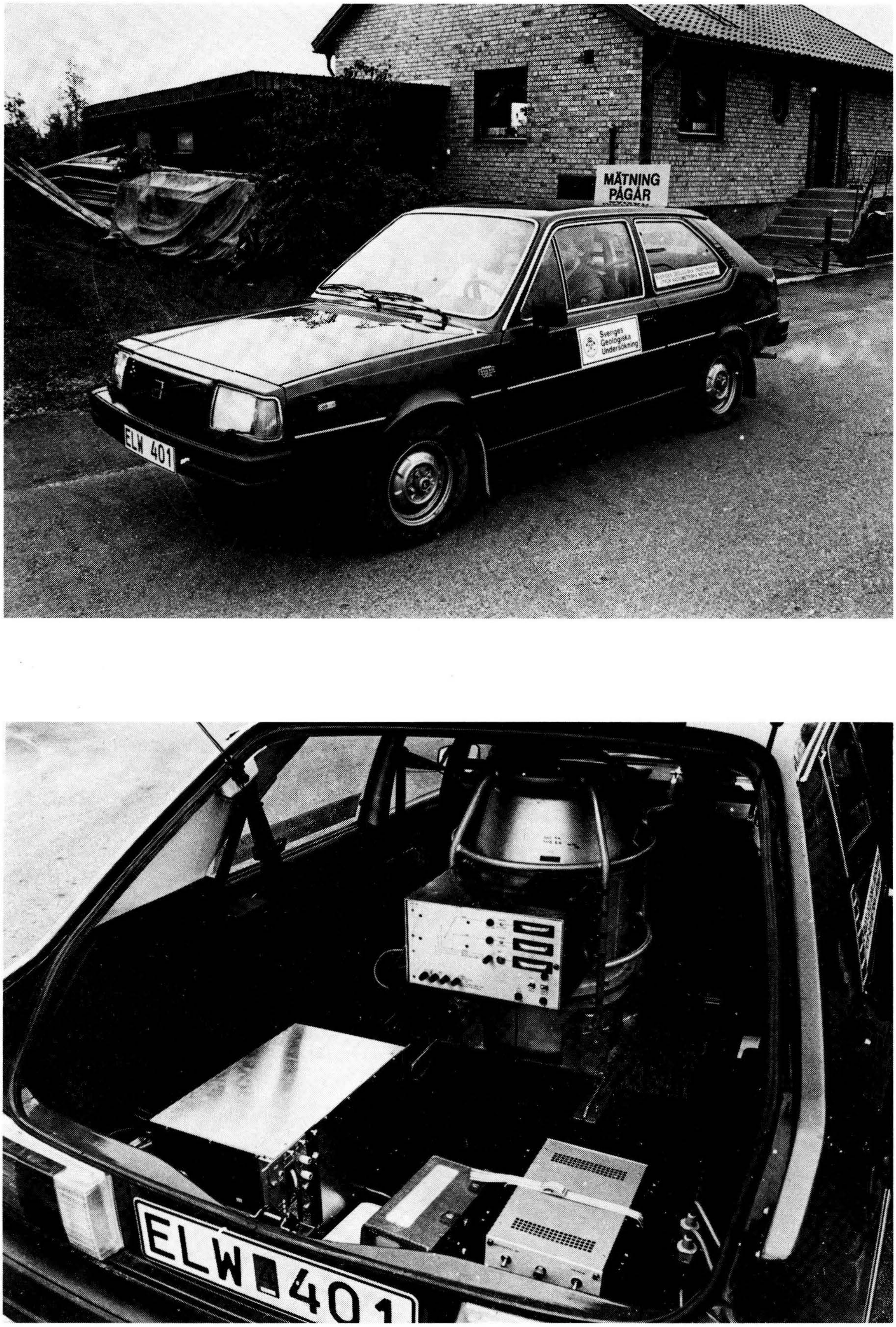

Fig.2. Car and equipment used in the search for houses with aerated concrete.

The searches have been the responsibility of the Local Health Authorities. These authorities have relied upon information from householders and measurements of gamma radiation using handborne scintillometers or carborne scintillometer measurements (Wahren et al 1979). The latter method has proved to be very effective, permitting control of radiation from the outer walls of 600-1 000 houses per day.

The carborne measurements carried out by the Geological Survey of Sweden use a scintillometer with a sodium iodine (NaI) crystal which has a volume of 6.130 cubic centimetres. The instrument is mounted in a car with a shield against radiation from the ground in order to reduce the background radiation contribution (Fig. 2).

A follow-up programme of measurements of indoor radon daughter levels has commenced for those houses which are judged to have a problem.

To date (spring 1981), radon daughter measurements have been performed in approximately 20 000 houses. Most of the measurements have been made using alpha-sensitive film. On a more limited scale, measurements have been made using the filter method or thermo-luminescence detectors (TLD).

For most of the film measurements, Track Etch films have been used. The films (2 per house) have been used without radon daughter filters. The measuring period has generally been 3 months, summers preferably being avoided. The results of the two measurements for each individual house have been converted to give an average annual radon daughter concentration (Samuelson 1980).

RESULTS OF INDOOR RADON MEASUREMENTS

The first compilation of measurements of radon daughter concentrations from 5 600 houses built of radioactive aerated concrete gives the following results: 46 % of the houses have levels exceeding 200 Bq m^{-3} (0.05 WL), 14 % levels exceeding 400 Bq m^{-3} (0.11 WL) and 2 % levels exceeding 1 000 Bq m^{-3} (0.27 WL) (Hildingsson 1981). A more recent compilation for 12 000 houses gives very similar results: 48 % with levels exceeding 200 Bq m^{-3}, 13 % levels exceeding 400 Bq m^{-3} and 1 % levels exceeding 1 000 Bq m^{-3} (Hildingsson, pers. comm.).

Clear geographical variations in the radon daughter levels are apparent from the results so far obtained. These variations are caused, either by variations in the radium content of the aerated concrete used, or by variations in the soil gas radon concentrations, the latter being closely related to the geology. Variations in the radium content of the aerated concrete are due to the fact that this type of concrete was manufactured in different parts of Sweden using alum shale with widely varying uranium contents.

There is a marked increase in the number of houses with high indoor radon levels in areas where the bedrock consists of alum shale or uranium-rich granites or pegmatites (Table 1). It has been found, however, that sporadic occurrences of high indoor radon levels also occur in areas with normal uranium contents in the bedrock or soils. Enhanced soil gas radon levels have been noted in glacial eskers with normal uranium contents of 3-8 ppm U in the soil and in areas with scattered occurrences of uranium-rich pegmatites.

The initial results of the programme of indoor measurements show clearly that the problem of radon emanation from the ground is greater than that from building materials. At a rough estimate, 3 000-15 000 houses in Sweden are in need of remedial measures against radon penetration from the ground. Tracing these houses will be difficult. One way, would be to carry out indoor measurements in all houses built in areas known to have high uranium contents in the bedrock or soil cover. Tracing of the sporadic occurrences is however a problem. It should also be borne in mind that exceptionally high soil gas radon levels are not necessary to produce high indoor radon levels if a house is ventilated in such a way that large quantities of air are drawn into the building through cracks etc. in the foundation or cellar walls.

RESEARCH

A research programme, initiated by the Radon Commission, is underway to investigate the relationship between radon concentrations and uranium content in the ground and indoor radon and gamma ray levels. 100 houses with high indoor radon daughter levels from areas of alum shale or uranium-rich granite have been selected for detailed studies of the bedrock, soils, groundwater and building techniques. These houses are not constructed from radioactive aerated concrete. The investigations will include in situ determinations of the U-, Th- and K-content of the rocks and soils using gamma spectrometers, gamma logging, measurements of the soil gas radon content and/or radon emanation from the

Locality	Building material	Radon daughter levels, Bq m^{-3}, in the investigated houses and apartments				Geology
		% > 200	% > 400	% > 1 000	no. houses investigated	
Uppsala (houses)	aerated concrete	3,5	1,0		516	Till, sand, gravel, and clay overlying granodiorite and acid to basic volcanics. (U in bedrock 1-8 ppm)
Skövde (houses and apartments)	"	79	42	9[1)]	380	Sand, clay and alum shale overlying sandstone, alum shale and limestone. (U in alum shale 50-300 ppm)
Stockholm suburb (houses)	"	65	42	6[2)]	278	Till, sand and clay overlying gneisses, younger U-rich granites and pegmatites. Well exposed. (U in gneiss 2-6 ppm, in granites 10-20 ppm)
Varnhem (houses)	other type of building material	90	48	22	31	Alum shale rich till, sand and gravel overlying sandstone and alum shale. (U in alum shale 50-300 ppm)
Lysekil (houses)	"	20	10	2	63	Uranium-rich granite, exposed. (U content 12-37 ppm)

1) 6 houses 4 000 Bq m^{-3}, 1 house 8 000 Bq m^{-3}

2) 1 house 6 000 Bq m^{-3}

Table 1. Variations in indoor radon daughter levels reflecting the geology

surface, measurement of radon content in the groundwater and in the drainage layer under the houses, and measurements of radon daughter levels in the houses. The results of the investigations should be available in 1982.

Other research programmes are also in progress where various types of remedial measures are being studied, including means of ventilation and the laying of aluminium foil on the floor to prevent radon penetration from the ground.

SITE INVESTIGATIONS

In order to comply with the regulations concerning radon daughter levels in new buildings (70 Bq m^{-3}), one needs either to build houses "radon safe", or to know that the soil gas radon content is so low that no indoor problem will arise. In the case of building on ground with enhanced radon concentrations, the type of "radon safe" construction used may be varied according to the actual soil gas radon levels.

The purpose of the site investigations is to determine whether or not the soil gas radon concentrations within a planned area will give rise to high indoor levels once the houses are built.

Account must be taken of the changes in the soil gas radon concentrations which will be caused by the actual process of building, for example, lowering of the water table or removal of some of the soil cover so that the foundations lie at a deeper level.

For the site investigations carried out by SGU, soil gas radon measurements are made at a depth of one metre in order to minimise temporary fluctuations caused by variations in wind, temperature and precipitation without increasing the measuring costs to unacceptable levels. In conjunction with the radon measurements, observations are made on soil types, bedrock geology, ground water and gamma radiation both above the ground and in the soil.

The methods used by SGU are ROAC-cups which are filled with activated charcoal (Hambleton-Jones and Smit 1980), Track Etch alpha sensitive film (Gingrich and Fisher 1976) and emanometers. The measuring time for ROAC-cups is 5-7 days, and for Track Etch film 3 weeks. These methods were tested during 1980 in a research project initiated by the Radon Commission (Hesselbom et al 1981). Measurements were performed in both granite and alum shale environments. The

ROAC and Track Etch cups gave comparable results, but the emanometer readings varied, compared with ROAC and Track Etch, from area to area probably because varying amounts of atmospheric air were pumped into the instrument. The amount of interference from atomspheric air will depend on the porosity and permeability of the soil in which the measurements are made. The advantage of the emanometer method, is that it is quick, and it gives an idea as to whether radon levels in the soil are enhanced or not. Fig. 3 shows the results of the test measurements carried out by SGU in an area of alum shale.

The bedrock along the profile consists of alum shale (U 150-300 ppm) overlain to the west by limestone (U less than 2 ppm). The soil cover is 5-10 metres thick and consists of clayey to sandy till, and in the central part of the profile of clay. The water table lies 2-3 metres above the bedrock surface. In the western part of the profile the till is comprised of limestone fragments, alum shale fragments are absent. This also applies to the upper 4 metres of the till in the eastern part of the profile. Here the content of alum shale fragments increases successively with depth.

The radon measurements show that the radon concentration in the soil for the western part of the profile is low, approximately 3 000 to 30 000 Bq m^{-3}. This can be related to the low uranium content of the till combined with the shielding effect of the limestone horizon, the till cover and the high water table all of which prevent radon from the alum shale horizon from reaching the surface. In the eastern part of the profile the shielding effect is no longer present and the soil gas radon content is approximately 120 000-160 000 Bq m^{-3}.

The results show a good correlation between the measurements performed with ROAC and Track Etch cups and the emanometer.

None of the methods used by SGU are calibrated to give absolute concentrations of radon in the soil in Becquerels per cubic metre. Track Etch, however, quote an average value of approximately 6 000 Bq m^{-3} for all soil gas radon measurements performed by their method. Of the measurements carried out by SGU at a depth of one metre in till or gravel containing alum shale, values some 30 to 300 times larger than the average value quoted by Track Etch have been obtained. For till or gravel containing fragments of uranium-rich granite, values 25 to 75 times the average Track Etch value have been measured. In other words, soil gas radon levels in areas of alum shale can be as high as approximately 500 000-

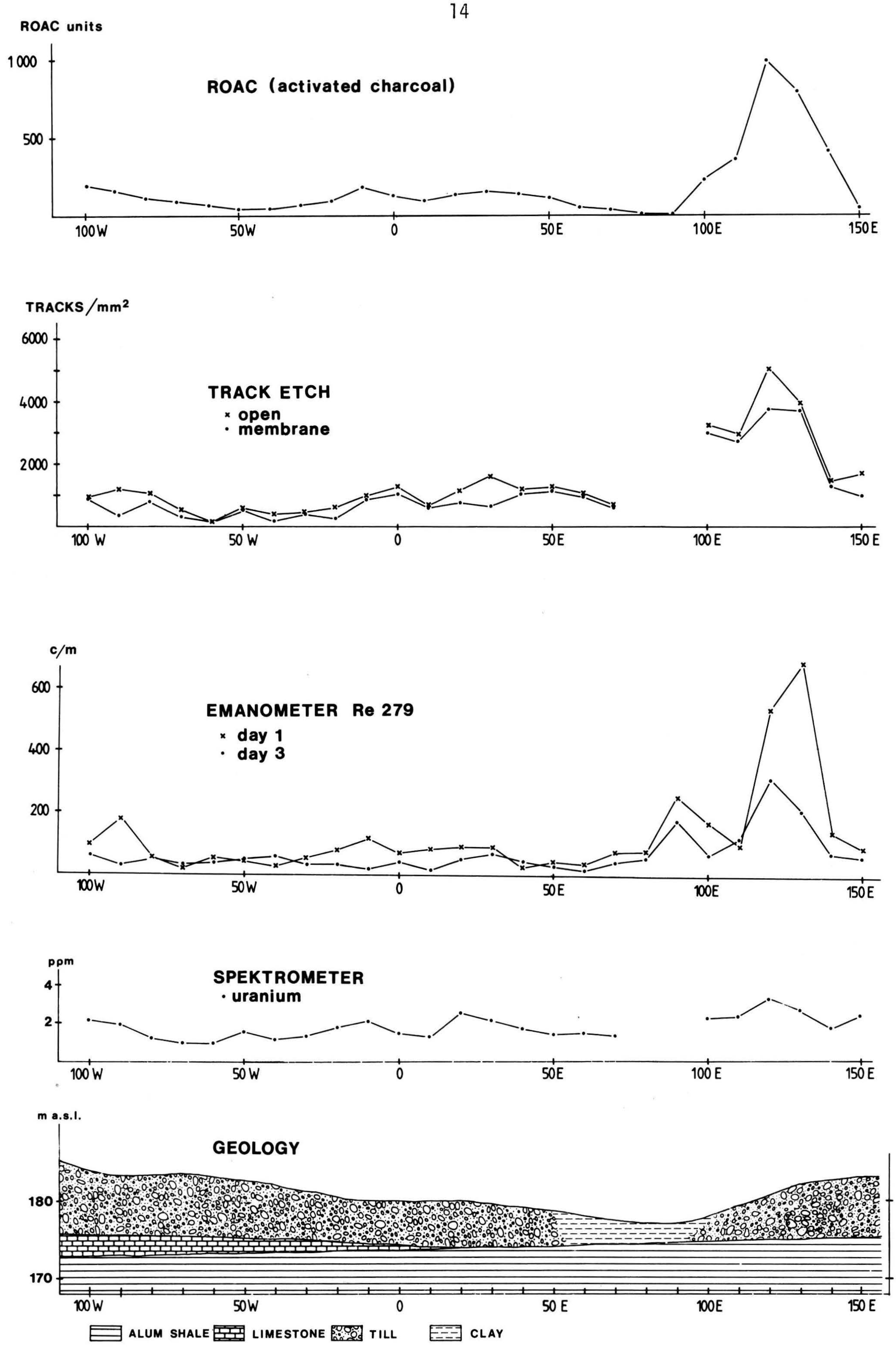

Fig.3. Results of test measurements made in an area of alum shale, (after Hesselbom et al. 1981).

1 800 000 Bq m^{-3}, and in areas of uranium-rich granites 200 000-500 000 Bq m^{-3}. With such high soil gas radon levels, intake of more than 70 litres per hour of soil air (radon content 500 000 Bq m^{-3}) into a house with a ventilation rate of 0.5 air exchanges per hour will be sufficient to produce indoor radon levels exceeding 70 Bq m^{-3}.

Fig. 4 illustrates an area investigated by SGU in the county of Närke, central Sweden. The purpose of the investigation was to determine the radon content in the soil air in an area planned for development. The investigation included radon measurements using both an emanometer and Track-Etch film, gamma-radiation measurements with a handborne scintillometer, and gamma-logging of drill holes.

The bedrock of the area consists of alum shale which is overlain to the west and north by limestone. The bedrock is covered by till and sand. In the eastern part of the area, layers of clay occur interbedded in the sand. The surface of the till lies at 1-3.4 metres depth. In the northern and western parts of the investigated area, the till is dominated by limestone fragments, whereas in the southern and eastern part alum shale fragments dominate. The water table lies at a depth of 0.4-1.1 metres. Tailings of burnt alum shale (rödfyr) have been tipped in the northern part of the area.

The gamma radiation measurements made at ground level gave low readings of 6-11 μR/h, except for the area with rödfyr where the radioactivity is 90-115 μR/h. The gamma-log results also gave low readings of 3-10 μR/h with a slight increase to 14-19 μR/h for soils containing a few fragments of alum shale. It should be noted, however, that the drill holes only penetrated the upper soil layers down to the upper surface of the till. The readings therefore do not apply to the radiation levels of the till.

The radon measurements were made at the greatest possible depth (0.9 metres for Track Etch and 0.7 metres for the emanometer) but the high level of the water table often prohibited this.

On the basis of the results of the radon measurements, the investigated area can be subdivided into three (Fig. 4). In the north and northwest where the till is dominated by limestone fragments, the radon concentration in the soil gas is normal to slightly raised.

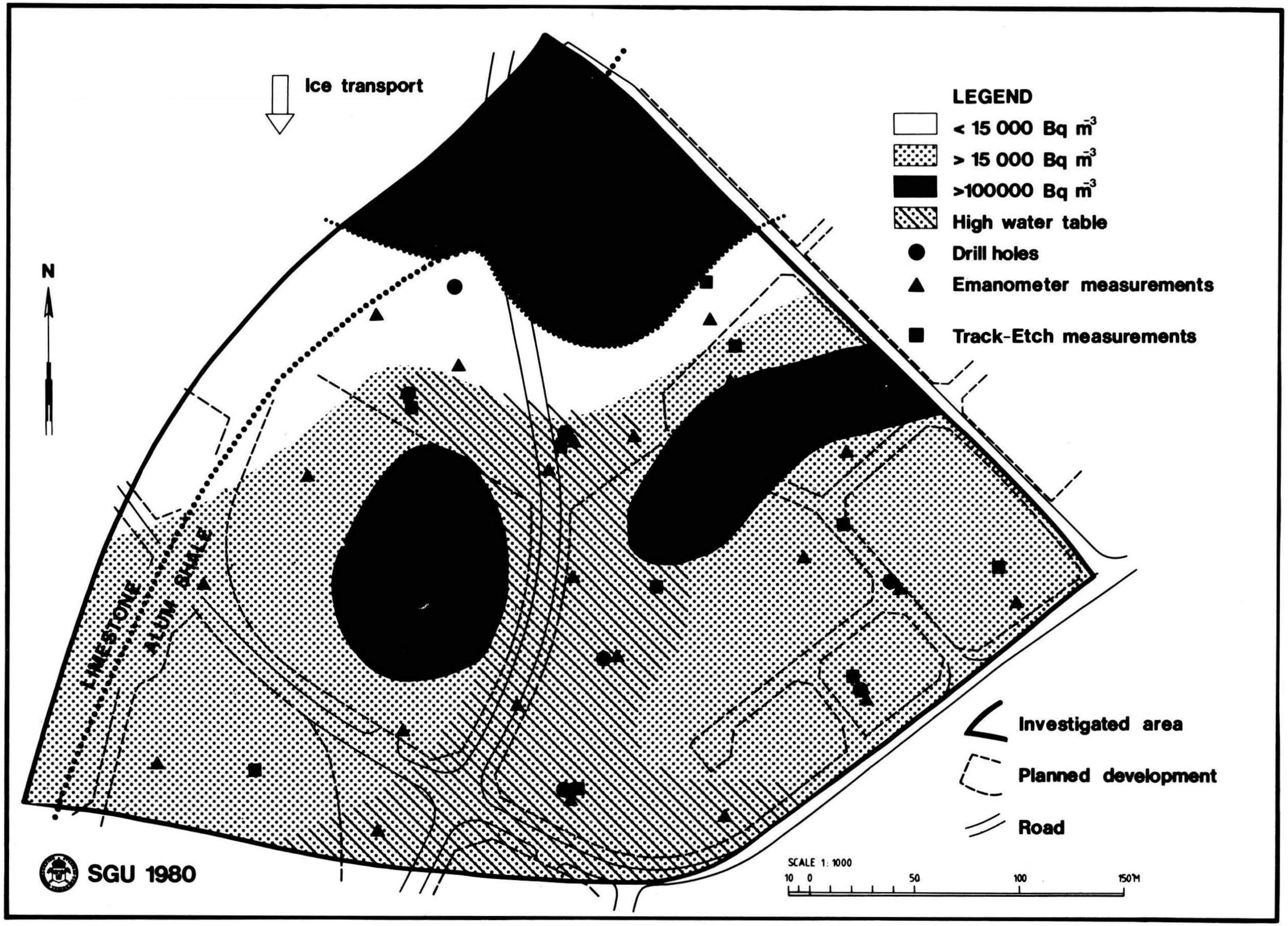

Fig.4. Map showing the results of radon measurements in an area planned for development.

In the southern and eastern parts of the area, where the till is dominated by alum shale fragments, the soil gas radon level is higher than normal, 30 000-100 000 Bq m^{-3}. Within the latter area however, lower values were obtained where the water table was very near the surface. The high groundwater level hinders the radon gas from the alum shale till from reaching ground level. If, however, the water table is lowered, either naturally or as a result of construction work, the content of radon in the soil gas will increase in these areas. Soil gas radon levels in the area of tipped rödfyr exceed 100 000 Bq m^{-3}.

In the areas with high levels of soil gas radon, the planned dwellings should be so constructed as to prevent infiltration of radon from the ground into the dwellings.

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Appendix: Summary of provisional regulations and recommendations concerning radiation hazards in buildings in Sweden

1. Directions issued by the National Board of Health and Welfare, in force from September, 1980.

   A building is regarded as insanitary when the radon daughter concentrations in rooms in continual use exceed an annual average of 400 Bq m^{-3}. SOSFS(M) 1980:71 (Socialstyrelsen 1980).

2. Mandatory regulations issued by the National Board of Urban Planning, SWEDISH BUILDING CODE (SBN) 1980, in force from January 1, 1980. National Board of Urban Planning Statute Books 1980:1 (Statens planverk 1980).

New buildings

Buildings shall be so constructed that the annual average concentration of radon daughters in rooms in continual use shall not exceed 70 Bq m^{-3}. The annual average concentration of radon daughters is determined according to methods laid down by the National Board of Urban Planning in consultation with the National Institute of Radiation Protection.

SBN 36:41

The regulation relating to a maximum permitted indoor radon daughter concentration of 70 Bq m^{-3}, according to 36:41, can require the application of remedial measures against sources of radon in the ground, in household water supplies and in building material.

SBN 31:142

A building shall be so constructed that gamma radiation in rooms in continual use shall not exceed 50 μR/h.

SBN 31:141

A satisfactory level for gamma radiation is achieved if the regulation relating to building materials, 31:143, is applied, and if gamma radiation from the ground is screened by a concrete structure or filling of low radioactive material.

SBN 31:1411

Rebuilding

Buildings shall be so constructed that the annual average concentration of radon daughters in rooms in continual use shall not exceed 200 Bq m^{-3}. Exception is made where the radon daughter concentration cannot be brought below this level by means of increased ventilation and remedial measures according to 31 rebuilding: 14.

SBN 36: Rebuilding: 41

Exception to the regulation quoted in SBN 31:141 may be granted. (That is to say, there are no regulations which apply to lowering of gamma radiation levels in cases of rebuilding.

SBN 31: Rebuilding: 141

Exception to the regulation quoted in SBN 31:143 regarding existing building materials, may be granted. However, an accessible, strongly radon emanating filling material shall be removed where required in order to conform with the regulation concerning radon daughter concentrations quoted in SBN 36 Rebuilding: 41.

Easily accessible filling may be found against cellar walls, and in the framing of joists and in the crawl space.

SBN 31: Rebuilding: 143

Building materials

Building materials used in buildings in continual use shall not have gamma or radium indices exceeding 1.0.

SBN 31:143

Filling materials and material used in the drainage layer under the foundations also come under the heading building materials.

SBN 31:1431

Gamma and radium indices are defined as follows:

$$\text{Gamma index} = \frac{C_K}{10\ 000} + \frac{C_{Ra}}{1\ 000} + \frac{C_{Th}}{700}$$

$$\text{Radium index} = \frac{C_{Ra}}{200}$$

where C_K, C_{Ra} and C_{Th} are the concentrations of potassium-40, radium-226 and thorium-232 expressed as Bq kg^{-1} of building material.

Out of doors

There are no regulations which apply to gamma radiation levels out of doors. However, it is recommended that in areas which are in regular use, for example playgrounds, gamma radiation should not exceed 100 μR/h.

REGIONAL ENVIRONMENTAL DOCUMENTATION OF NATURAL RADIATION IN SWEDEN

Carole Wilson

ABSTRACT

In 1979, when the problem of high radon daughter levels in Swedish houses became widely publicised, the need for information on variations in the natural radiation environment became very apparent. The radon problem was at first attributed to radon emanation from alum shale based aerated concrete, but it was soon obvious that ground with an abnormally high uranium content constitutes an even greater risk for high radon daughter levels in houses. The Geological Survey of Sweden was commissioned to produce a documentation in map form of all areas and rock types with gamma ray levels exceeding 30 μR/h, with the intention of delimiting risk areas for high soil gas radon contents.

The maps, known as GEO-radiation maps, are produced at a scale of 1:50 000. They are based primarily upon airborne radiometric surveys, ground measurements of gamma radiation and geological mapping. To date some 450 map sheets have been published covering approximately 55 % of the country. The maps provide primary information to local planning, health and building authorities as to variations in the natural radiation environment. Within the so-called risk areas marked on the maps, local authorities are recommended to investigate the soil gas radon content prior to any new development.

Geological environments known, in Sweden, to be associated with radon daughter problems in dwellings are alum shale, a Cambrian, uranium-rich black shale, uranium-rich granites and uranium-rich pegmatites. Both alum shale and uranium-rich granites constitute extensive areas of bedrock. More recently it has been established that high soil-gas radon concentrations are also associated with glacial eskers.

INTRODUCTION

In 1978, the National Institute of Radiation Protection measured radon daughter levels in a number of houses built on uranium-rich alum shale tailings (Swedjemark et al. 1979). The measured levels exceeded the maximum level of 1110 Bq m^{-3} (Becquerels per cubic metre) of radon in equilibium with radon daughters permitted in Swedish mines. This was the first proof in Sweden that radon emanating from the ground can give rise to such high concentrations of radon daughters in dwellings. Earlier, the radon problem in houses was attributed to radon emanation from building materials containing unusually large amounts of radium, for example, alum shale based aerated concrete (Swedjemark 1978 a, 1979 b, 1980).

Early in 1979, a Government Commission, termed the Radon Commission, was set up to investigate the problem of radiation risks in dwellings (Radonutredningen 1979). At an early stage in the Commissions work, it became apparent that radon emanating from the ground could constitute as great , if not greater problem

	U ppm	Th ppm	K %	m_{Ra}	μR/h
Granite, normal	2 - 10	5 -20	2 -6	0,1 - 0,6	5 - 20
Granite, U- and Th-rich	8 - 40	10 -90	4 -6	0,5 - 2,5	12 - 65
Gneiss	2 - 10	5 -20	2 -6	0,1 - 0,6	5 - 20
Diorite	0,1- 2	1 -10	1 -3	0,01- 0,1	2 - 10
Sandstone	0,5- 5	1 -10	1 -5	0,03- 0,3	2 - 15
Limestone	0,5- 2	0,1- 2	0,1-0,5	0,03- 0,1	0,5- 3
Shale	1 - 10	2 -15	2 -6	0,06- 0,6	5 - 18
Alum shale	10 -350	2 -10	3,5-6	3,1 -21,5	10 -230

Table 1. Uranium, thorium and potassium contents, radium index and gamma radiation for different rock types in Sweden.

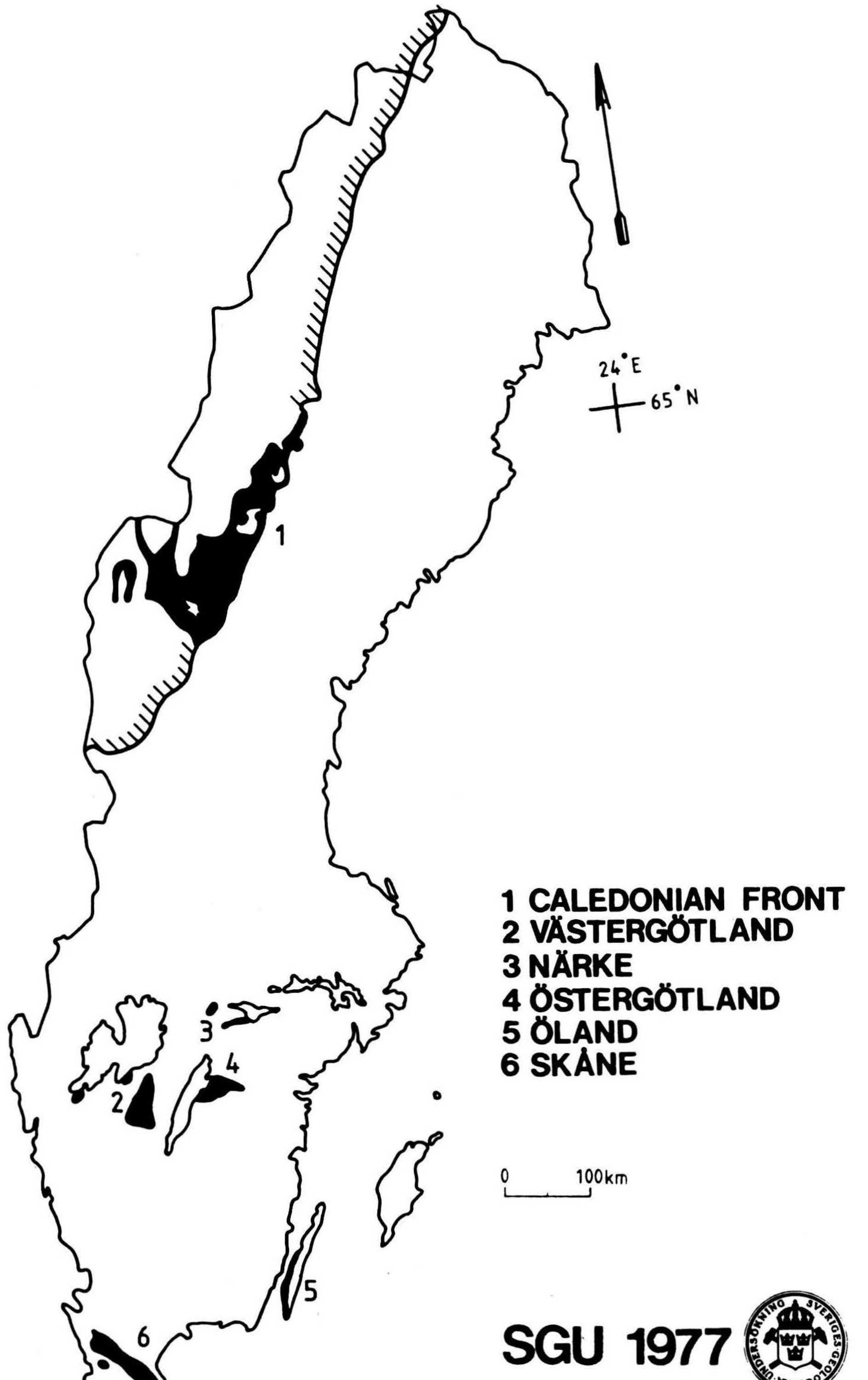

Fig.1. Distribution of the alum shale formation.

than radon emanation from building materials. Measurement programmes carried out by Local Health Authorities during the last year have proved this to be true. In Sweden, areas with particular risk for high soil gas radon contents are considered to be those with a bedrock of uranium-rich alum shale (a Cambrian, black shale), uranium-rich granites or uranium-rich pegmatites and areas of glacial drift cover comprised largely of these rock types, and glacial eskers. Knowledge of the geographical distribution of these areas became thus necessary in order, at least, to prevent future building without the use of necessary technical measures against radon penetration from the ground.

NATURAL RADIATION ENVRONMENT

The source of natural radiation from the ground is almost entirely related to the presence in the bedrock or drift cover of the radioactive elements uranium and thorium, and their daughter products including radon, and potassium-40. Their concentrations in various rock types in Sweden is very variable (Table 1).

The geographical distribution of the uranium-rich alum shale formation (Fig. 1) is fairly well-known due to mapping and prospecting activities, the latter owing to the rock's unusually high contents of uranium, vanadium, molybdenum and organic matter. The uranium content can range from 50 - 350 ppm (Armands 1972, Andersson et al. in press).

Uranium- and thorium-rich granites and pegmatites are known from a number of areas in Sweden (Fig. 2). The granites (and pegmatites) occur in a variety of geological settings in the Swedish Precambrian, and represent a variety of granite types and ages, 1 750-890 Ma (Wilson and Åkerblom 1980). Knowledge of the occurrence and extent of the granites and pegmatites has been obtained mainly from airborne radiometric surveys and uranium prospecting carried out principally by the Geological Survey of Sweden (SGU).

For the purpose of documenting the natural radiation environment in Sweden and for delimiting risk areas for high soil gas radon contents, the Geological Survey of Sweden was commissioned to produce a documentation in map form of all areas and rock types known to be particularly radioactive. The maps, known as GEO-radiation maps, are produced at the scale of 1:50 000. They are based primarily upon airborne radiometric surveys, ground measurements of gamma radiation and geological mapping.

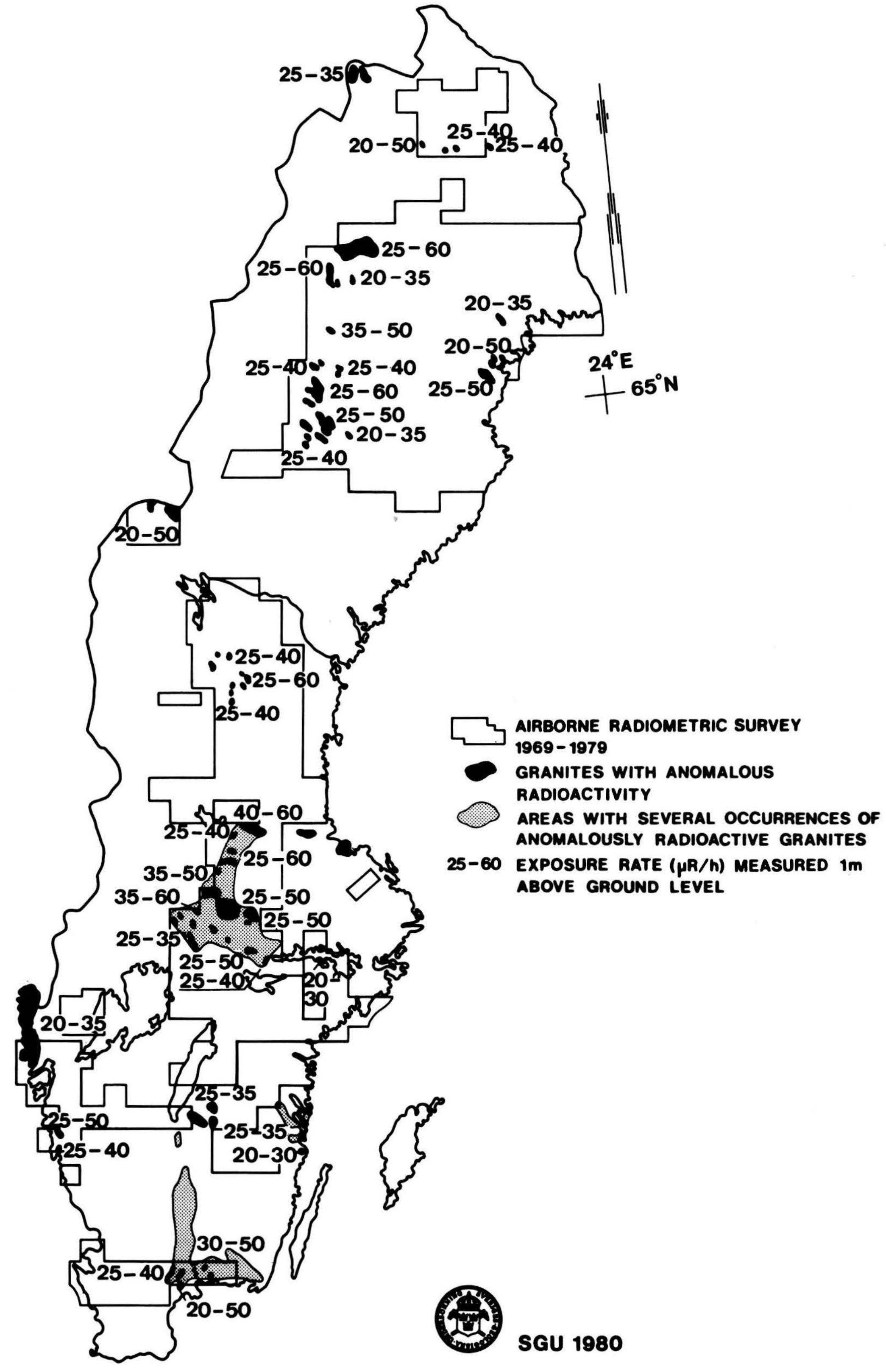

Fig.2. Distribution of known radioactive granites.

The choice of this method for delimiting risk areas for high soil gas radon contents was determined by:

1. the assumption that the greatest concentrations of radon in the soil are directly related to rocks and soils rich in uranium,
2. availability of regional information on gamma radiation from the airborne and ground radiometric surveys carried out by SGU. These surveys cover to date approximately 45 % of the country.

AIRBORNE RADIOMETRIC SURVEYS

Airborne gamma-ray spectrometry carried out by SGU is used primarily for regional prospecting for uranium, and as a complementary geophysical method to geological mapping. The instrumentation has been designed to cope with the special problems of prospecting in areas of glaciated terraine. Most of the bedrock in Sweden is covered by glacial till which can vary in thickness from 4 to 10 metres. Much of this material is of relatively local derivation, but it has always been transported to some extent. This latter factor is of special interest with regard to the radon problem as will be shown later.

The SGU technique (Lindén and Åkerblom 1976) is to use four sodium iodide crystals giving a total volume of 17 litres. Gamma spectra between 0.45 and 2.85 MeV are recorded on 258 channels. The plane flies at an altitude of 30 metres along profiles 200 metres apart, and at a speed of 70 m/sec. Registration takes place digitally with a measuring time of 400 msec, readings being taken every 40 metres. After computer processing of the data from all the channels, the results of the measurements are plotted automatically as maps using an ink-jet colour plotter. Gamma radiation from uranium, thorium and potassium for each measuring station is marked on the maps as coloured lines (U red, Th blue and K yellow), the lengths of which are proportional to the registered equivalent contents of these elements (U and Th as ppm and K as %). The three-component, coloured gamma radiation maps give a detailed picture of the distribution of the radioactive elements over large areas, as well as locating point anomalies (Fig. 3 a and b).

Follow-up of the anomalous points or areas for each gamma radiation map is carried out on the ground using handborne scintillometers. Observations as to terraine, bedrock geology, Quaternary geology and gamma-ray levels are noted

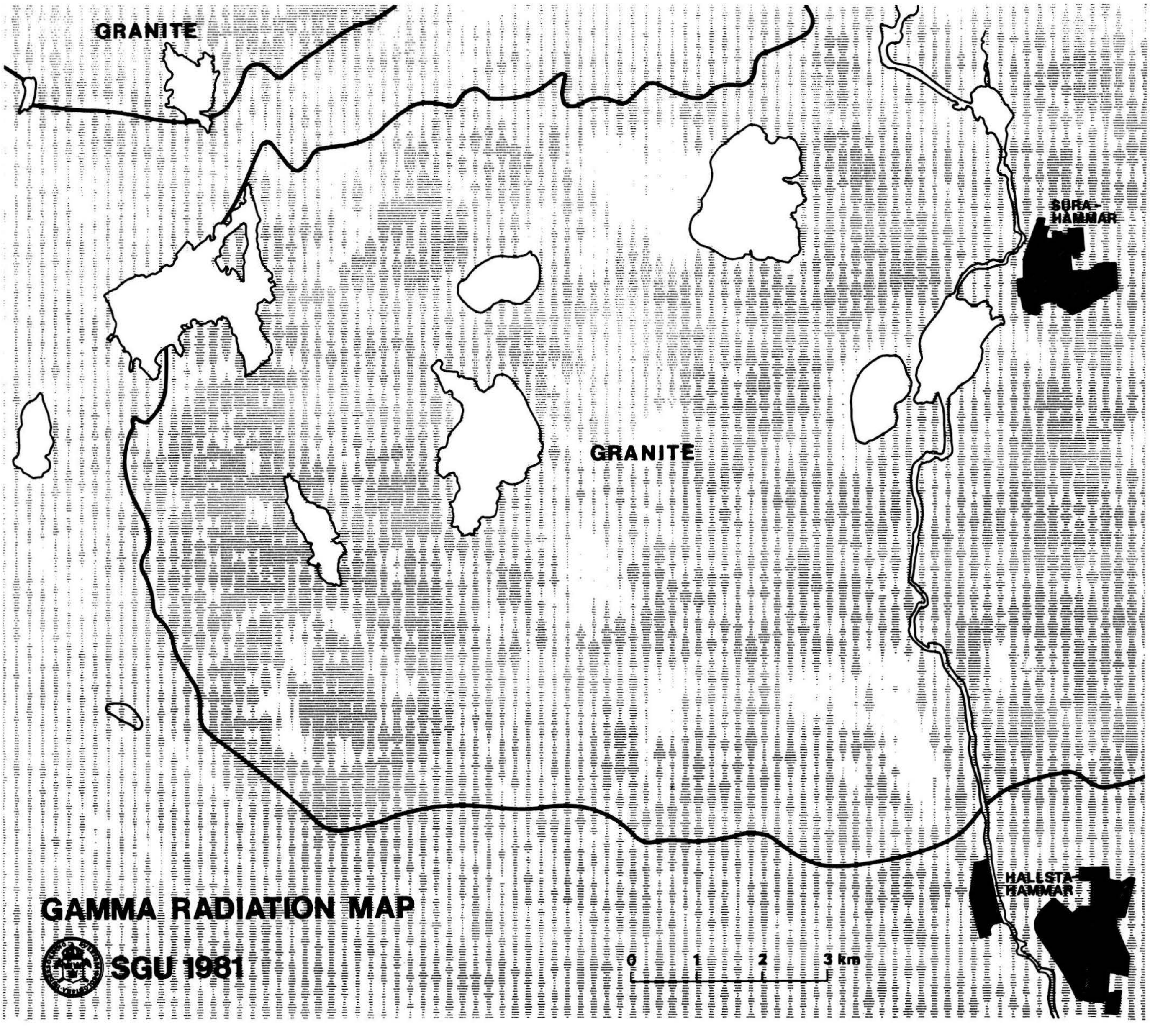

Fig.3a. Uranium-component gamma radiation map over a uranium- and thorium-rich granite near Västerås, central Sweden. Original scale 1:50 000.

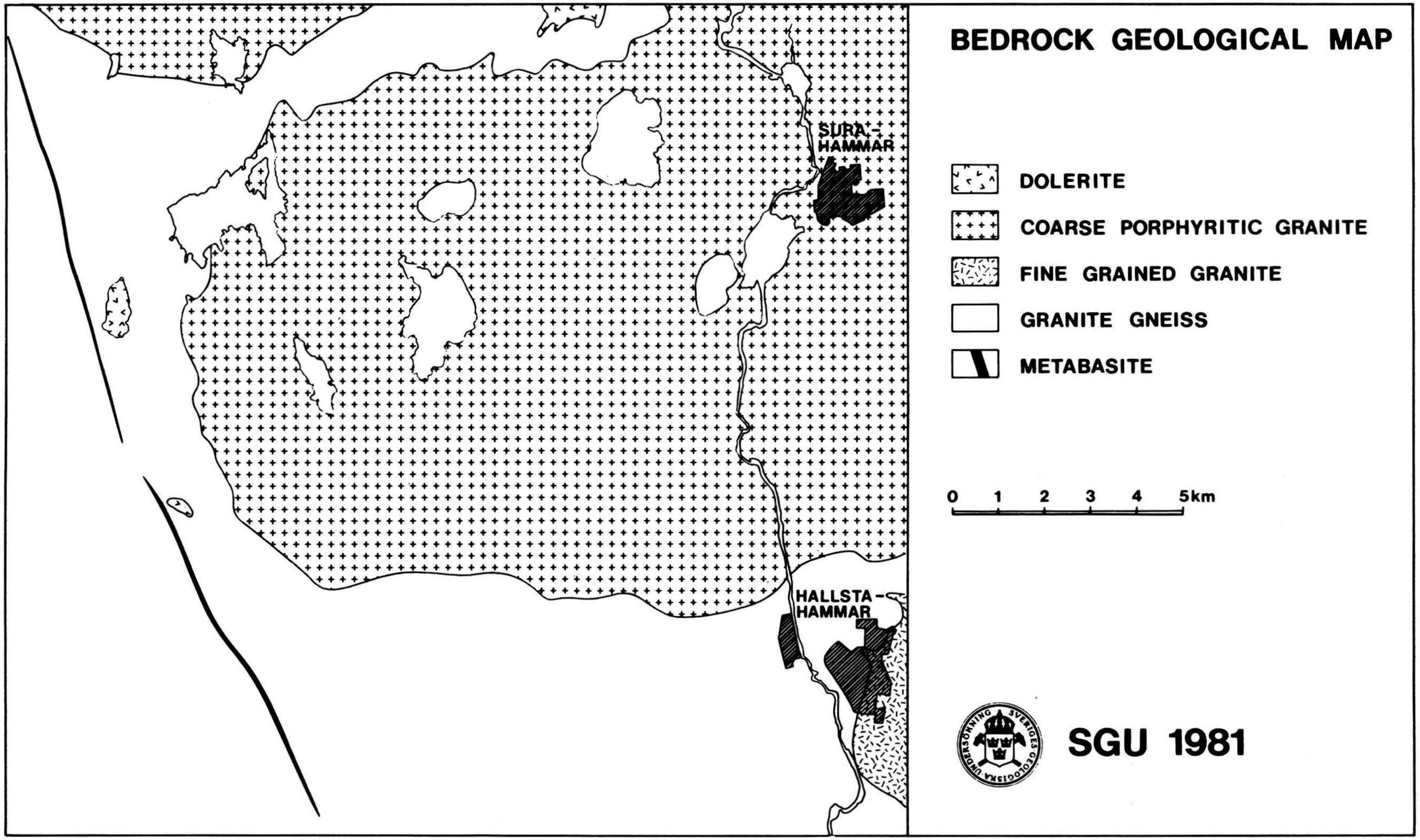

Fig.3b. Geological map over the same granite. Original scale 1:50 000.

for areas where gamma-spectrometry measurements on the ground have been carried out. In the compilation of the GEO-radiation maps, all this material is used together with published geological and Quarternary geological maps (where available), and detailed local knowledge of the geologists mapping specific areas.

GEO-RADIATION MAPS

Maps showing radon contents in the ground would be the ideal for environmental purposes. Such maps cannot be produced owing to the enormous costs involved and the length of time necessary to carry out measurement programmes. An alternative would be to produce maps showing the uranium content (in ppm) of the ground, but again, this is not yet feasible for more than limited areas in Sweden.

The GEO-radiation maps in their present form are intended as key maps to show areas where the level of gamma radiation from uranium and/or thorium in the bedrock or drift cover is particularly high. For this purpose the limit of 30 µR/h has been arbitrarily selected. To date some 450 maps have been produced covering approximately 55 % of the country. The maps cover initially areas of alum shale and known uranium-rich granites. The latter category coincides in general with areas covered by airborne radiometric surveys. The maps are accompanied by short commentaries on the geology and radioactivity of the areas concerned. Examples of the maps will now be discussed.

Fig. 4 shows the geological map over part of the alum shale occurrence in Östergötland, southeastern Sweden, and Fig. 5 is the GEO-radiation map over the same area. An enlarged detail from the gamma radiation map over Fornåsa is shown in Fig. 6. The lines on this map are related to gamma radiation from uranium in the near surface alum shale.

The profile in Fig. 7 shows how Quarternary ice transported fragments of alum shale from the bedrock exposure up towards the surface of the till in a southerly direction. The alum shale fragments are successively mixed with other material during transport.

One can see how individual "nappes" of the shale material developed in the drift cover, the latter being about 15 metres thick. Comparison between the bedrock

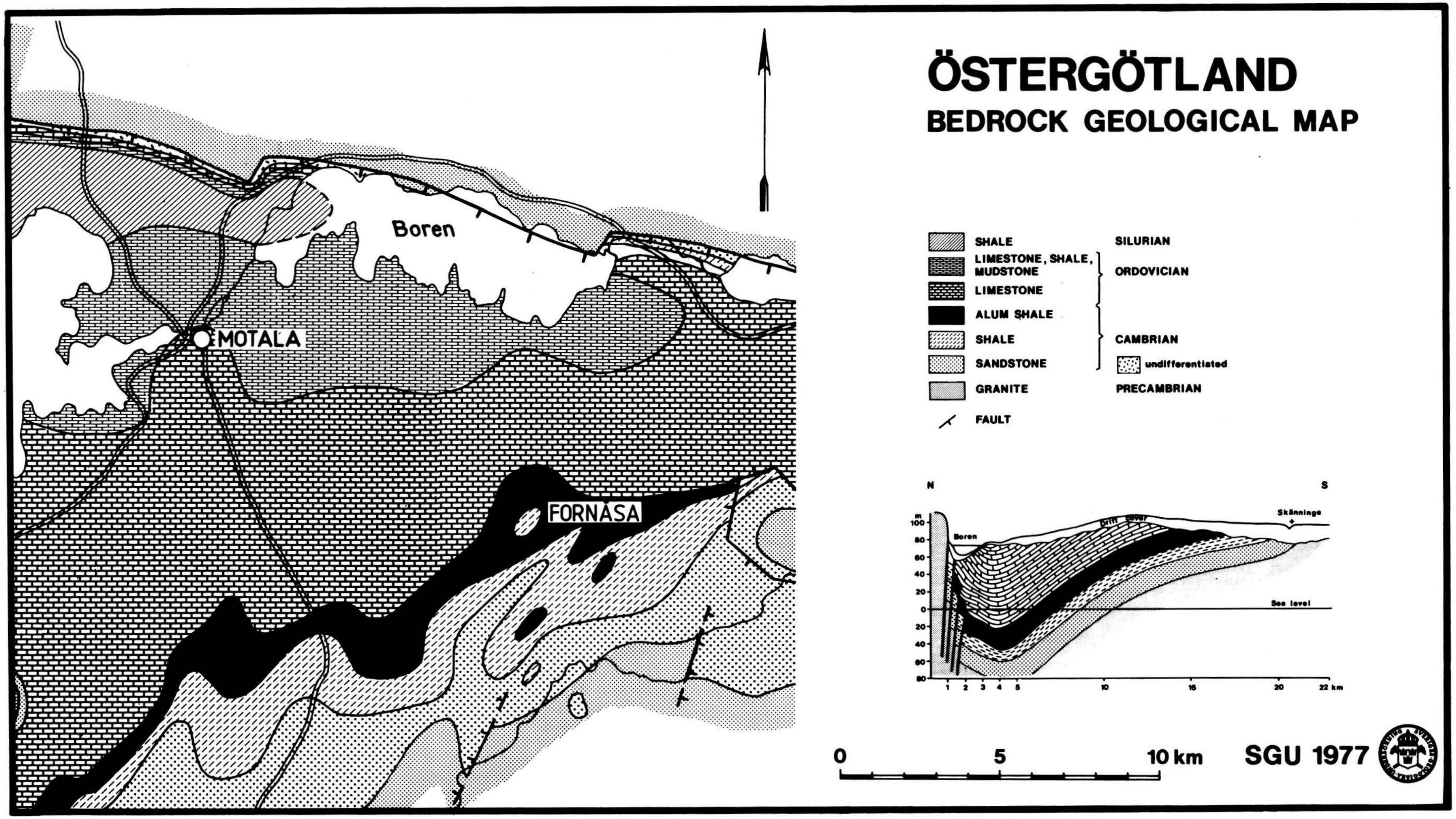

Fig.4. Geological map for the map sheet Linköping NW, southeastern Sweden.
Original scale 1:50 000.

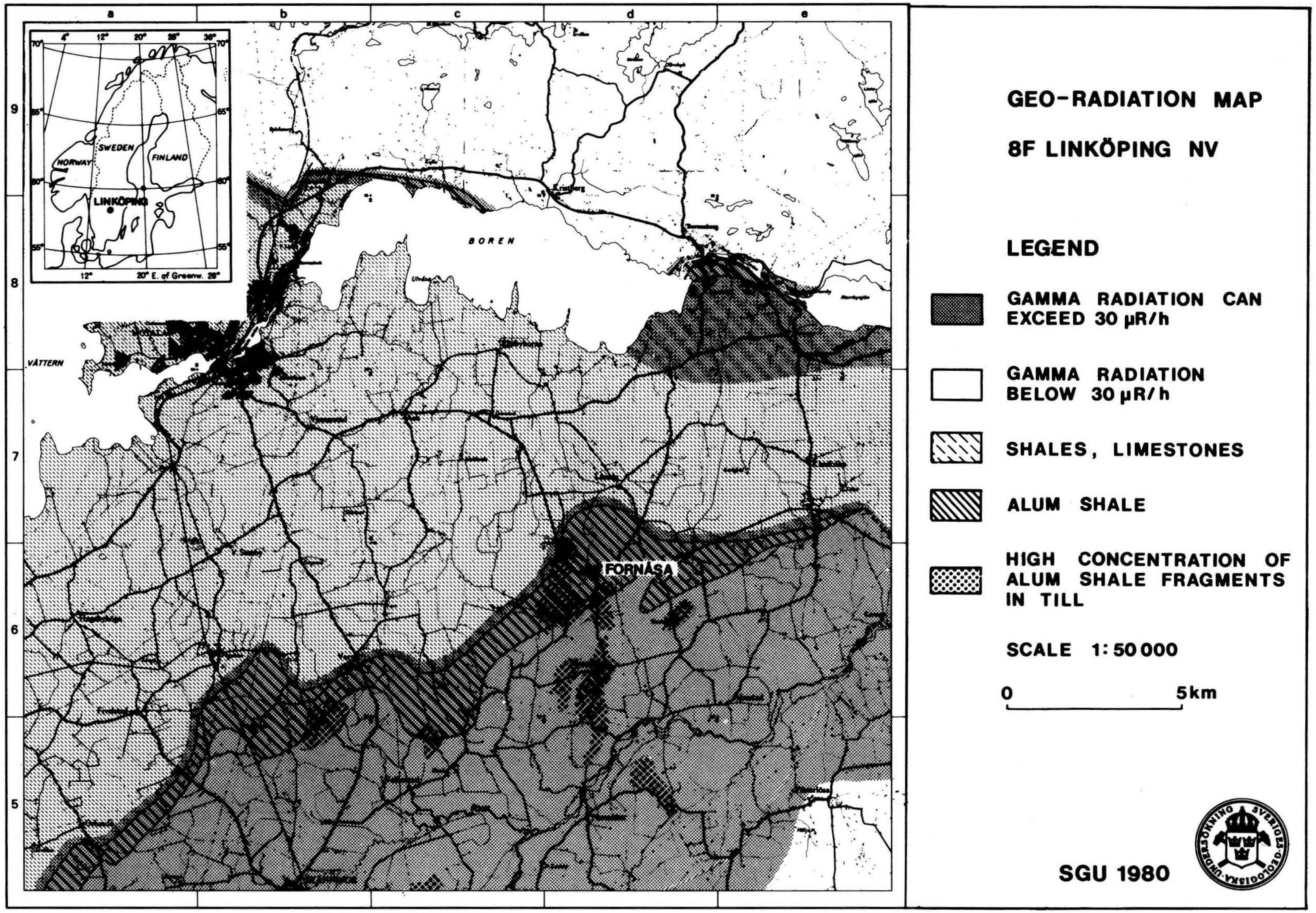

Fig.5. GEO-radiation map for the map sheet Linköping NW, southeastern Sweden. Original scale 1:50 000.

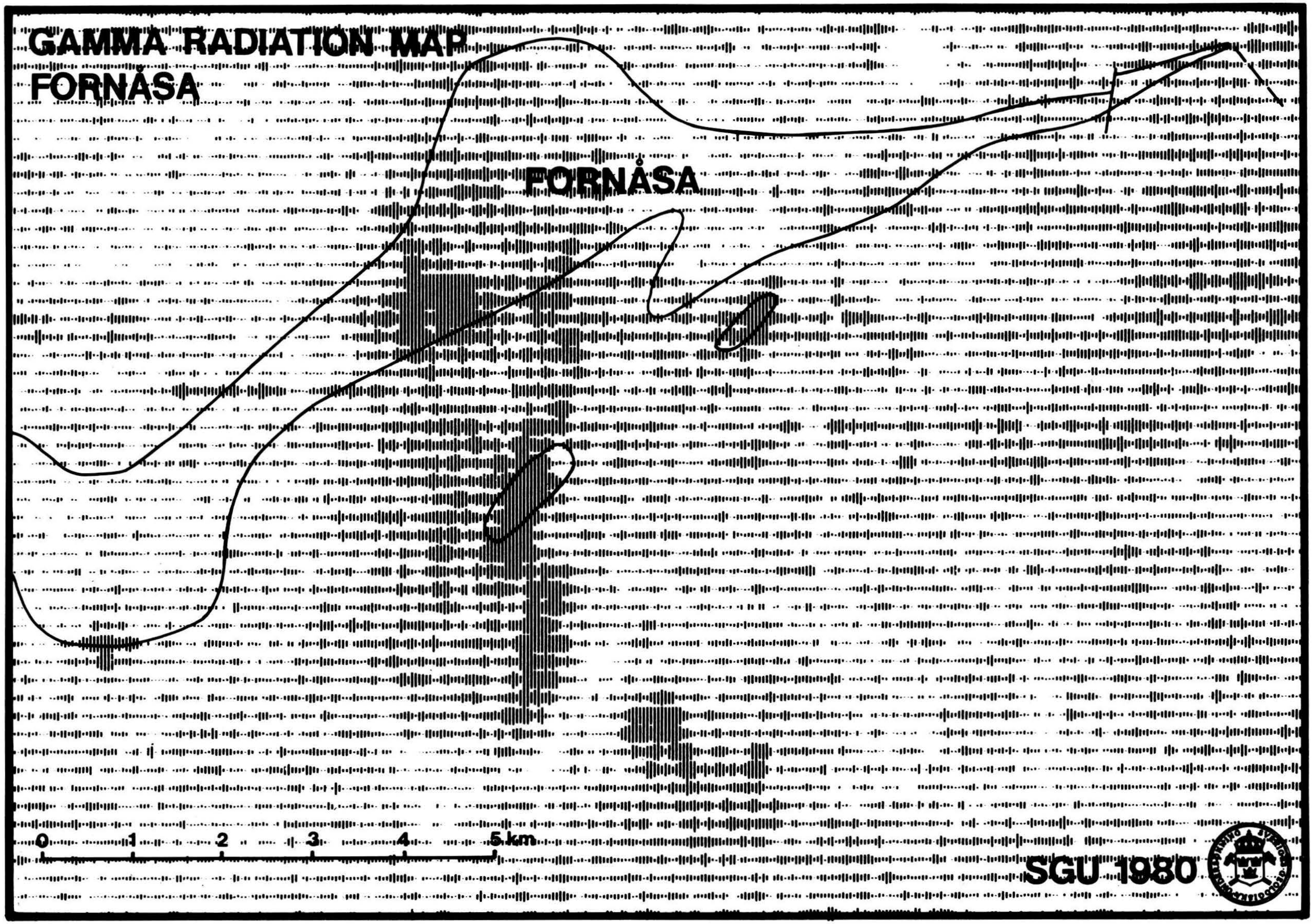

Fig.6. Uranium-component gamma radiation map over Fornåsa, Östergötland.
Original scale 1:50 000.

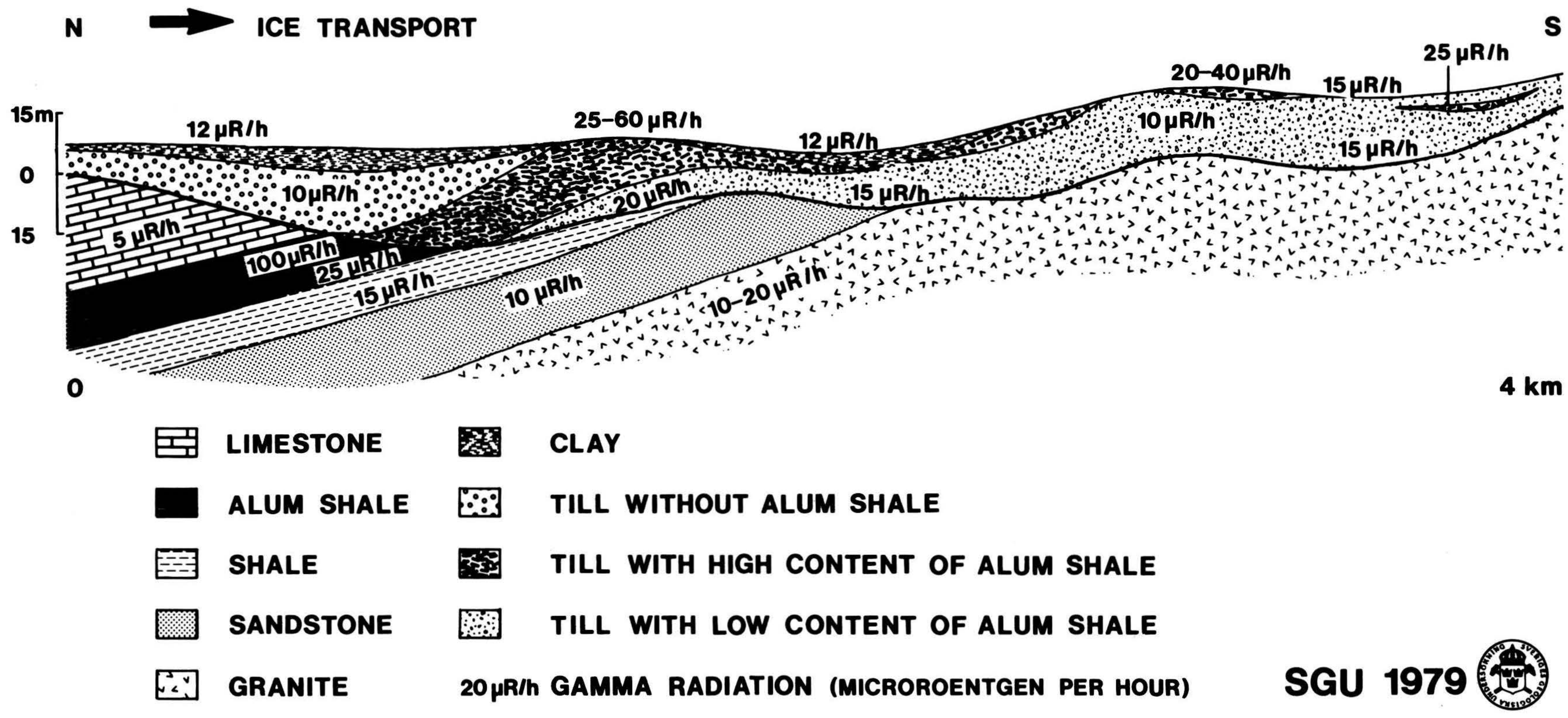

Fig.7. Profile illustrating the distribution of alum shale fragments in the Quaternary drift cover.

geological map and the gamma radiation map reveals that alum shale fragments are present in the drift cover several kilometrés south of the bedrock source. In consequence, higher than normal levels of gamma radiation, and probably enhanced soil gas radon concentrations, can occur beyond the area of the bedrock exposure of a radioactive rock. Consideration must therefore always be given to the direction and length of transport of rock fragments when judging the risks for high soil gas radon contents.

A further illustration to this point is made in Fig. 8 which shows the gamma radiation map from an area of granite gneiss in central Sweden. The bedrock is largely concealed by a drift cover of glacial till. A clearly uranium anomalous area is distinguished south of Svennevad. This area coincides with a glacial esker and post glacial washed sands. The esker has its occurrence some 10 kilometres to the north of Svennevad in an area of alum shale bedrock. The gamma radiation map therefore indicates spread of alum shale fragments in the esker and related sands. Enhanced gamma radiation from uranium concentrations in the granite gneiss bedrock is otherwise only a local feature in connection with pegmatites and zones of migmatisation.

The gamma radiation, geological and GEO-radiation maps over a uranium- and thorium-rich granite in Mölndal, south of Gothenburg, are shown in Figs. 9, 10 and 11. The suburb of Balltorp is planned to house 15 000 people.

The granite in question is a red to grey alkali granite which partially weathers to a coarse sand. The granite has a uranium content of 10-30 ppm, a thorium content of 30-70 ppm and radioactivity of 30-60 µR/h. The granite is bounded to the east by gneissose granodiorite and to the west by a porphyritic granite with normal uranium and thorium contents. The whole area is well exposed and the till cover, where present, is only a half to two metres thick. The valleys contain sediments, mainly clay. Glacial transport of till materials was from east to west.

A programme of radon measurements was carried out in the area during the summer of 1980 (Hesselbom 1981). The results indicate soil gas radon levels ranging from 30 000 to 500 000 Bq m^{-3} (relative values).

RECENT RESEARCH

During the last twelve months, a research programme has been initiated to in-

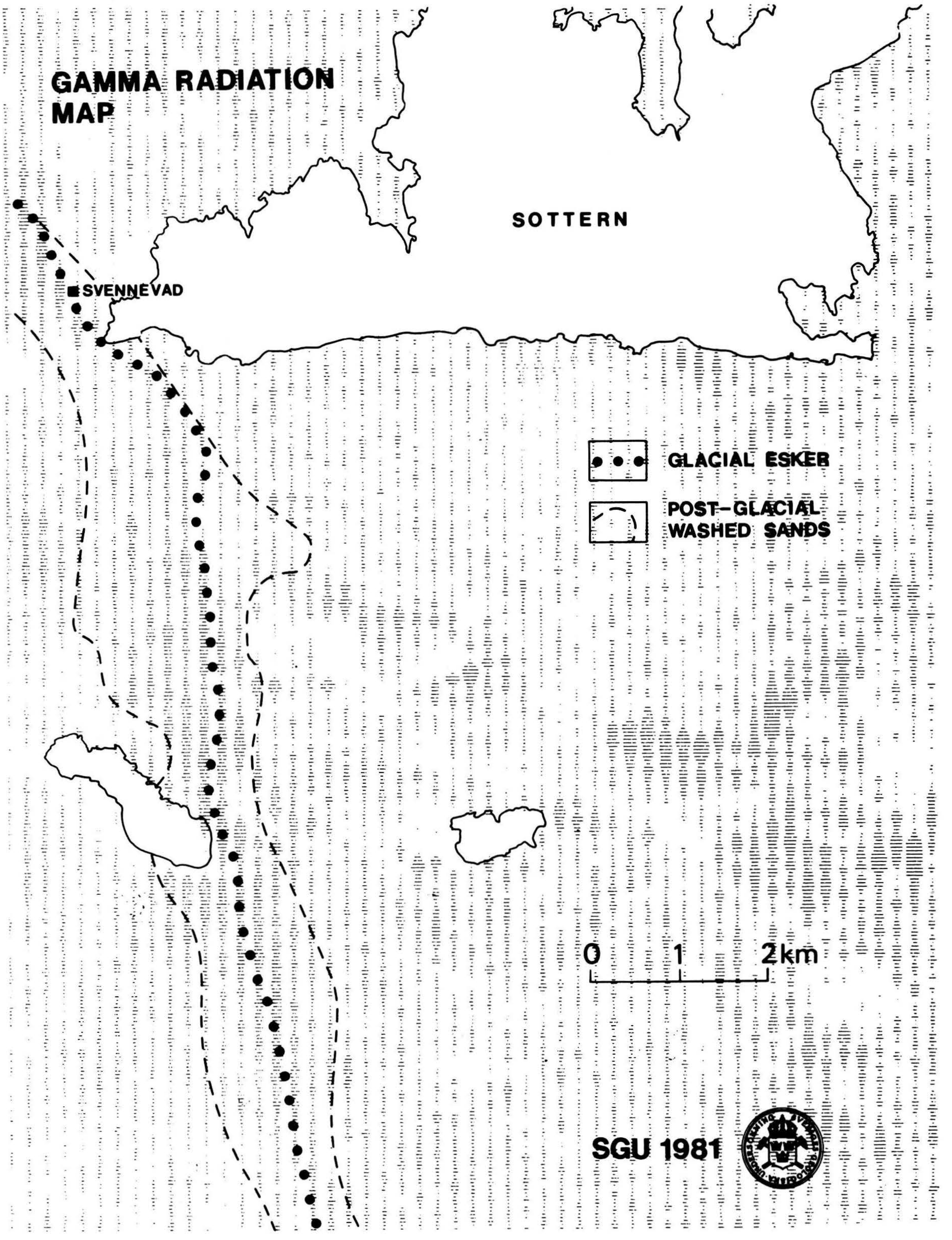

Fig.8. Uranium-component gamma radiation map over Svennevad, southeastern Sweden. Original scale 1:50 000.

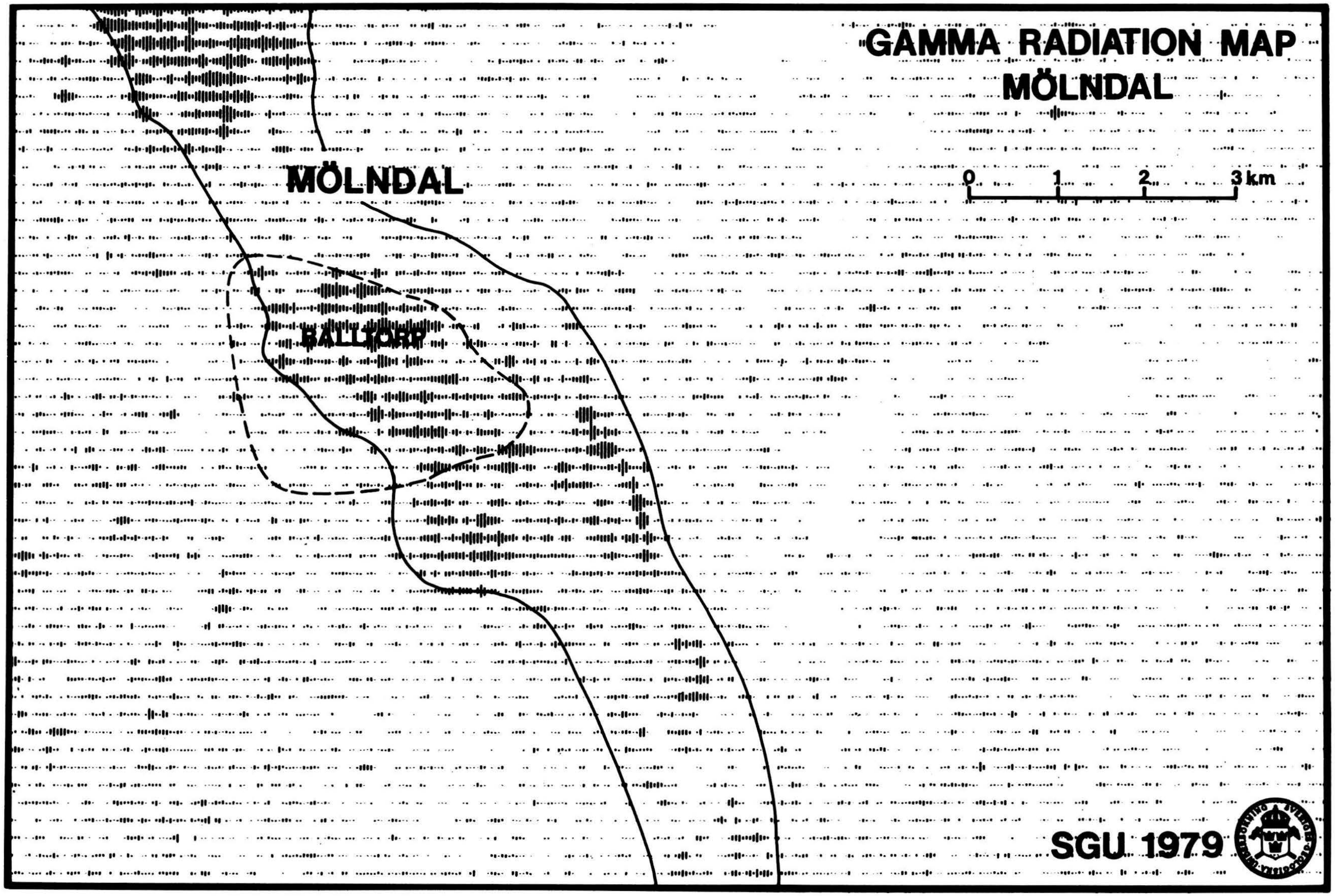

Fig.9. Uranium-component gamma radiation map over Mölndal, Gothenburg.
Original scale 1:50 000.

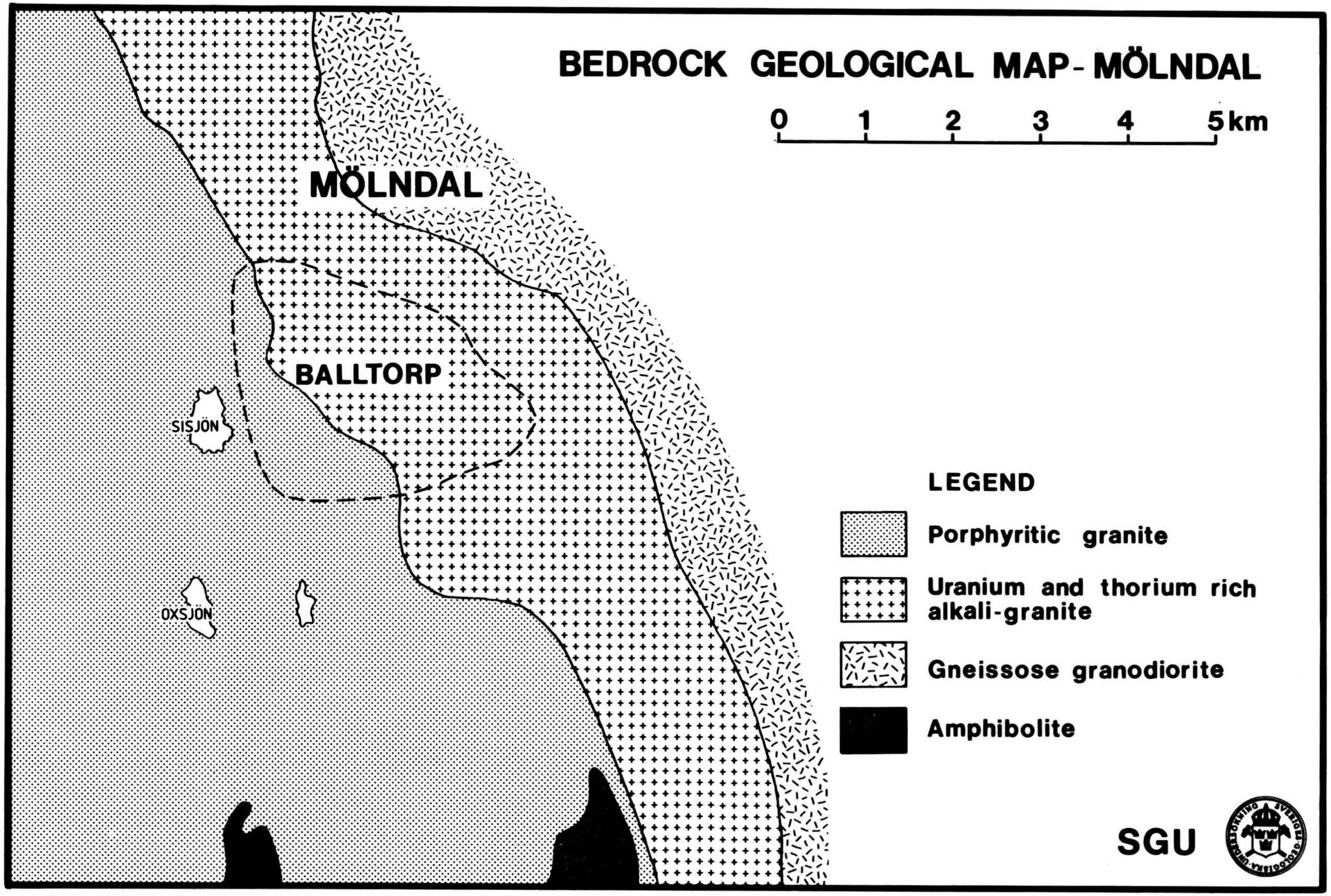

Fig.10. Geological map over Mölndal, Gothenberg. Original scale 1:50 000.

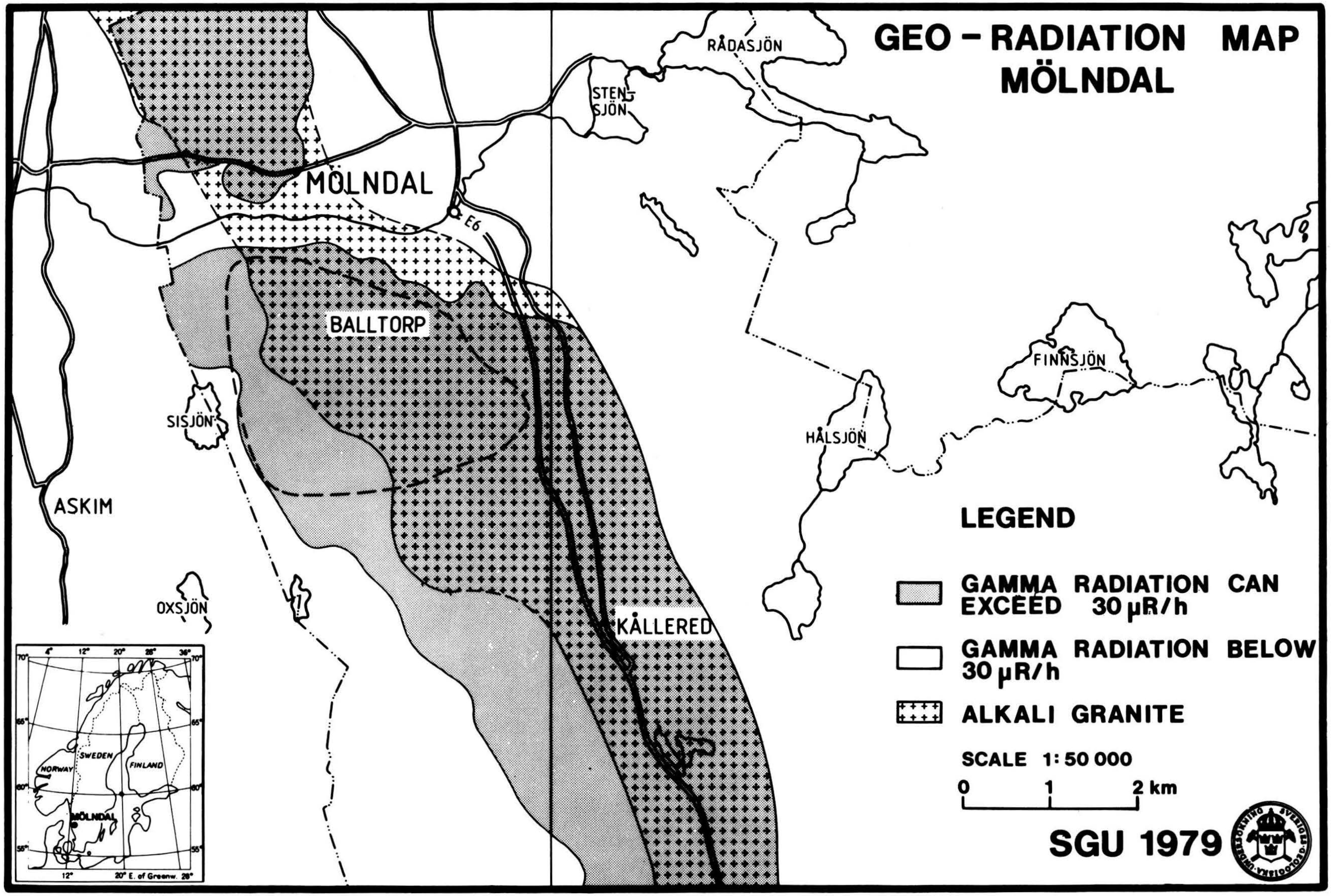

Fig.11. GEO-radiation map over Mölndal, Gothenburg. Original scale 1:50 000.

vestigate the relationship between radon concentrations in soil gas and radon/ radon daughter levels in dwellings, and to test the validity of the GEO-radiation maps. Test areas were selected in areas of both uranium-rich granite (Lysekil) and alum shale (Fjugesta). The houses contain no radioactive concrete.

Lysekil

In the town of Lysekil, radon daughter concentrations have been measured in 60 selected houses. 70% of these houses have radon daughter levels exceeding the permitted limit for new development (70 Bq m^{-3}, Swedish Building Code, 1981), and 10% have levels exceeding the permitted limit for existing dwellings (400 Bq m^{-3}).

The town of Lysekil lies on the west coast of Sweden in an area of granite known as the Bohus granite complex (Fig. 12). The granite occupies an area of about 20 km by 90 km in Sweden and extends into SE Norway. It has the form of a large flat-lying, sheet-like intrusion consisting of a series of granite types ranging in colour from red to grey, and in texture from coarse-grained, sometimes porphyritic to extremely fine-grained (Asklund 1947). Chemically and mineralogically, however, the granite is fairly homogeneous and the whole of the granite belt has enhanced uranium and thorium contents (Wilson and Åkerblom 1980). The GEO-radiation maps covering the granite mark the entire complex as having gamma-ray levels exceeding 30 µR/h. In reality, gamma radiation from the ground varies between 10 and 50 µR/h, the lower values from areas where the granite is covered by loose sediments, sands and clays, and the higher values from the exposed bedrock. Numerous ground spectrometer measurements over the granite give the following uranium-, thorium- and potassium contents: U 9-37 ppm, Th 25-90 ppm and K 3.5-5.0 %.

Airborne radiometric surveying has been carried out over the southern part of the granite. Fig. 13, showing the U-component of the gamma radiation map, illustrates clearly the intensity of gamma radiation from the granite compared with that from the adjacent gneisses with normal U and Th contents.

Measurements of radon concentrations in well waters from the Bohus granite give, in general, high levels. In the Lysekil area, 50 % of the investigated wells (ca 200) have levels exceeding 1 000 Bq l^{-1}. The levels recorded compare with those obtained from uranium-rich granites in Maine (Hess et al. 1980). In the

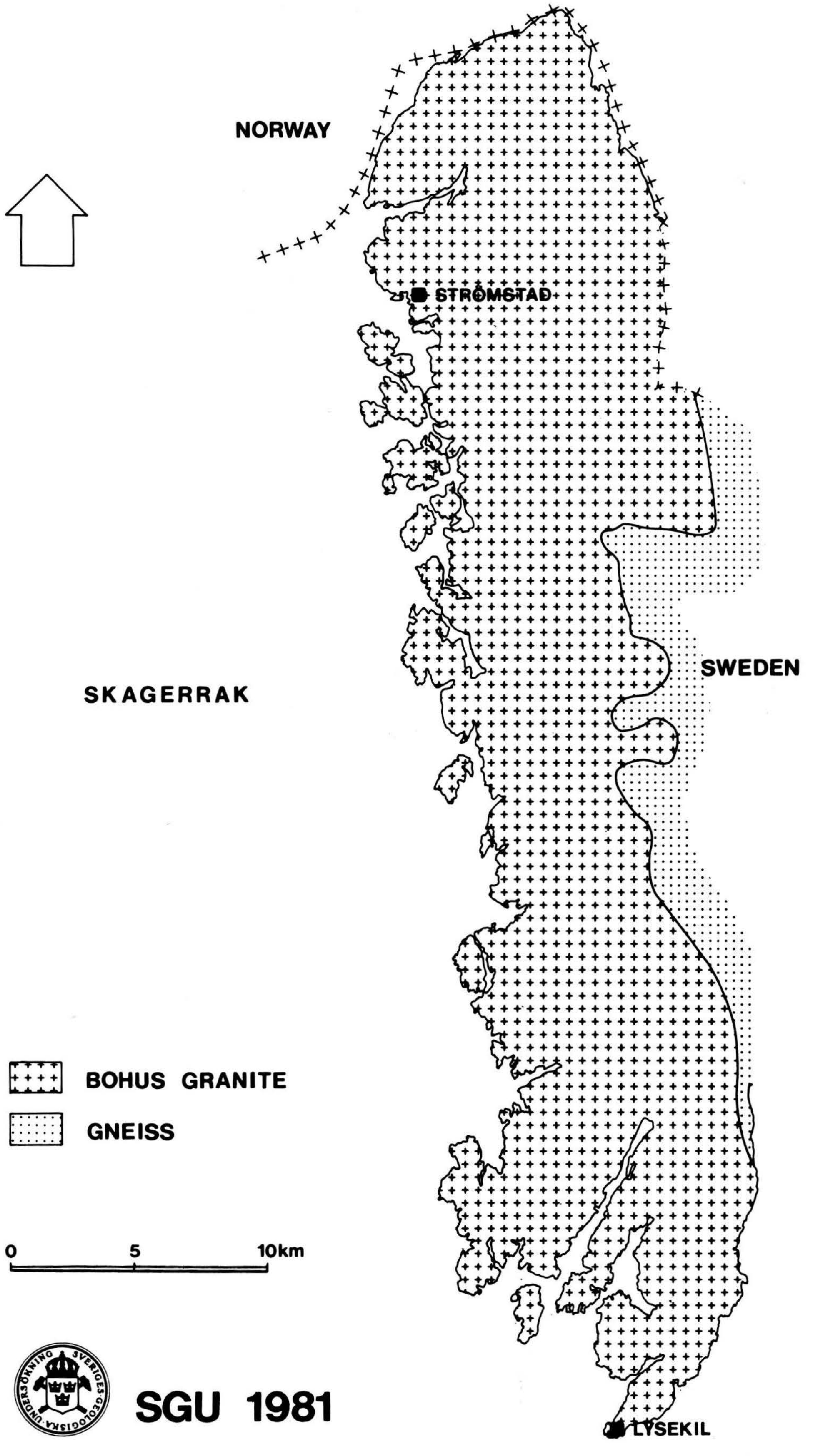

Fig.12. Geological map over the Bohus granite complex, western Sweden.

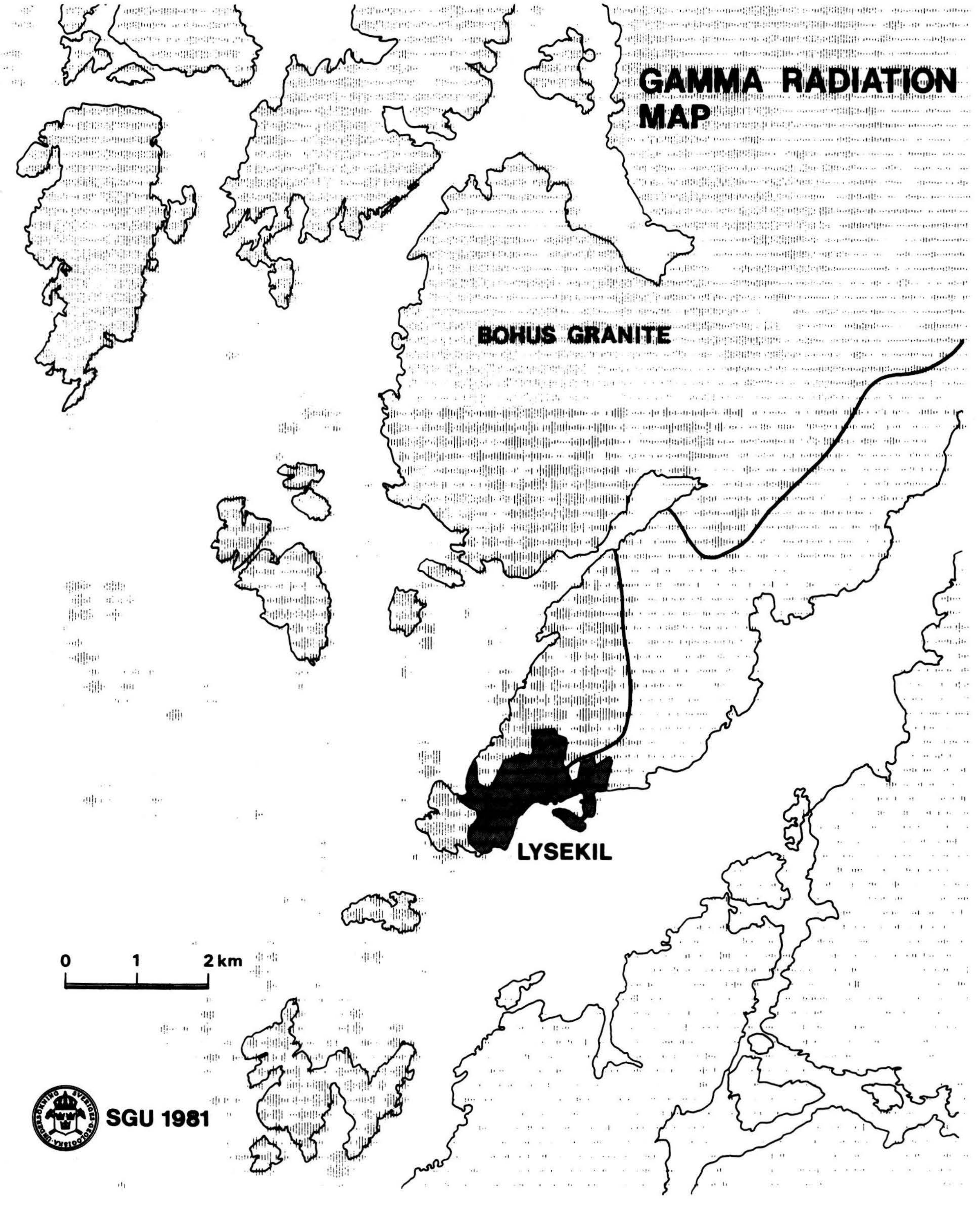

Fig.13. Uranium-component gamma radiation map over the Bohus granite around Lysekil. Original scale 1:50 000.

gneisses adjacent to the Bohus granite, radon levels in well waters are low.

Fjugesta

The indoor measurements of radon daughter concentrations carried out in Fjugesta (45 houses) show that 80 % of the houses have levels exceeding the permitted limit for new development and 12 % have levels exceeding the permitted limit for existing dwellings. The bedrock of the area, consisting of flat-lying Cambro-Ordovician sediments including alum shale, is largely covered by up to 10 metres of glacial till and post glacial sediments. Fig. 14, showing the U-component of the gamma radiation map and the bedrock outcrop of the alum shale formation, indicates clearly the spread of alum shale fragments in the till. The geological map over the area is shown in Fig. 15.

CONCLUSIONS

The problem of high soil gas radon levels in Sweden is seen now to be acute. Rocks and soils with enhanced uranium contents occur fairly extensively in the country. The normal background gamma radiation in Sweden is 6-10 µR/h, and vast areas have gamma-ray levels of 12-20 µR/h. Investigations so far carried out indicate that the GEO-radiation maps, based on gamma-ray measurements and with an arbitary limit of 30 µR/h for risk areas, adequately define the areas with particular risk for high soil gas radon contents due to high uranium contents in the bedrock or soil cover. However, extensive programmes of indoor measurements carried out during the past year by Local Health Authorities and by the National Institute of Radiation Protection, reveal that levels exceeding the permitted limits occur sporadically even in areas where gamma-ray levels for the bedrock and drift cover are considerably lower than 30 µR/h. A number of soil gas radon measurements carried out by SGU in areas with normal uranium content, 2-10 ppm in the bedrock or soil, show that radon concentrations in the ground can vary between 1 000 to 200 000 Bq m^{-3}. In particular, glacial eskers are now seen to be a problem. Not only have high indoor radon daughter levels been recorded in a large number of existing houses which are built on eskers, but even recent field measurements carried out by SGU confirm that soil gas radon levels are often high in eskers in spite of low uranium contents 3-8 ppm, and, consequently, low gamma radiation. The problem relating to eskers was not known at the time that most of the GEO-radiation maps were produced. Eskers should now be included as risk areas on the maps.

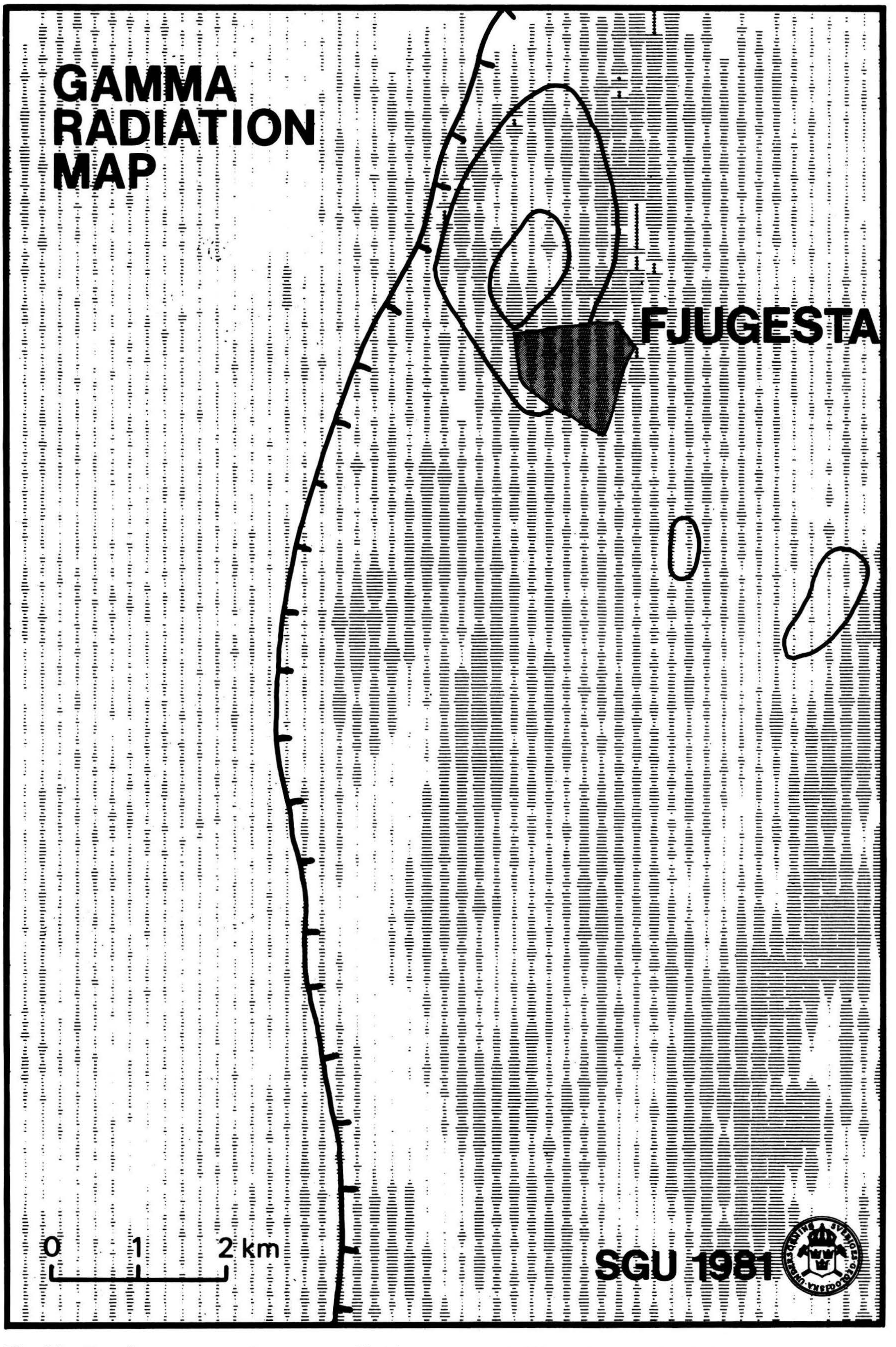

Fig.14. Uranium-component gamma radiation map over Fjugesta, central Sweden. Original scale 1:50 000.

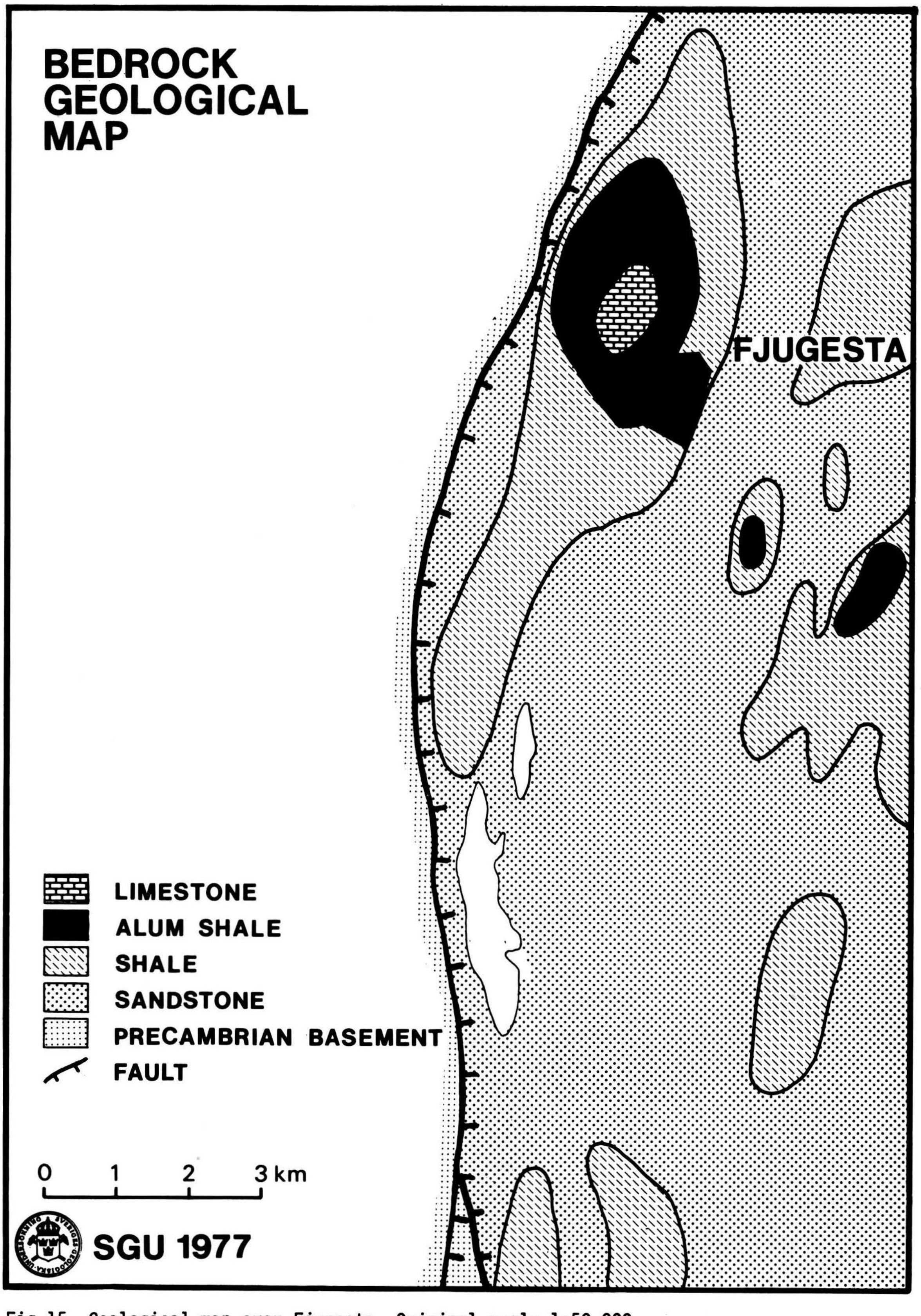

Fig.15. Geological map over Fjugesta. Original scale 1:50 000.

A lower gamma-ray level could be adopted for the GEO-radiation maps, for example 20 μR/h, but the consequences of this would be that vast areas of the country would be placed under stringent building restrictions which are probably not warranted.

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