SVERIGES GEOLOGISKA UNDERSÖKNING
Rapporter och meddelanden nr 19

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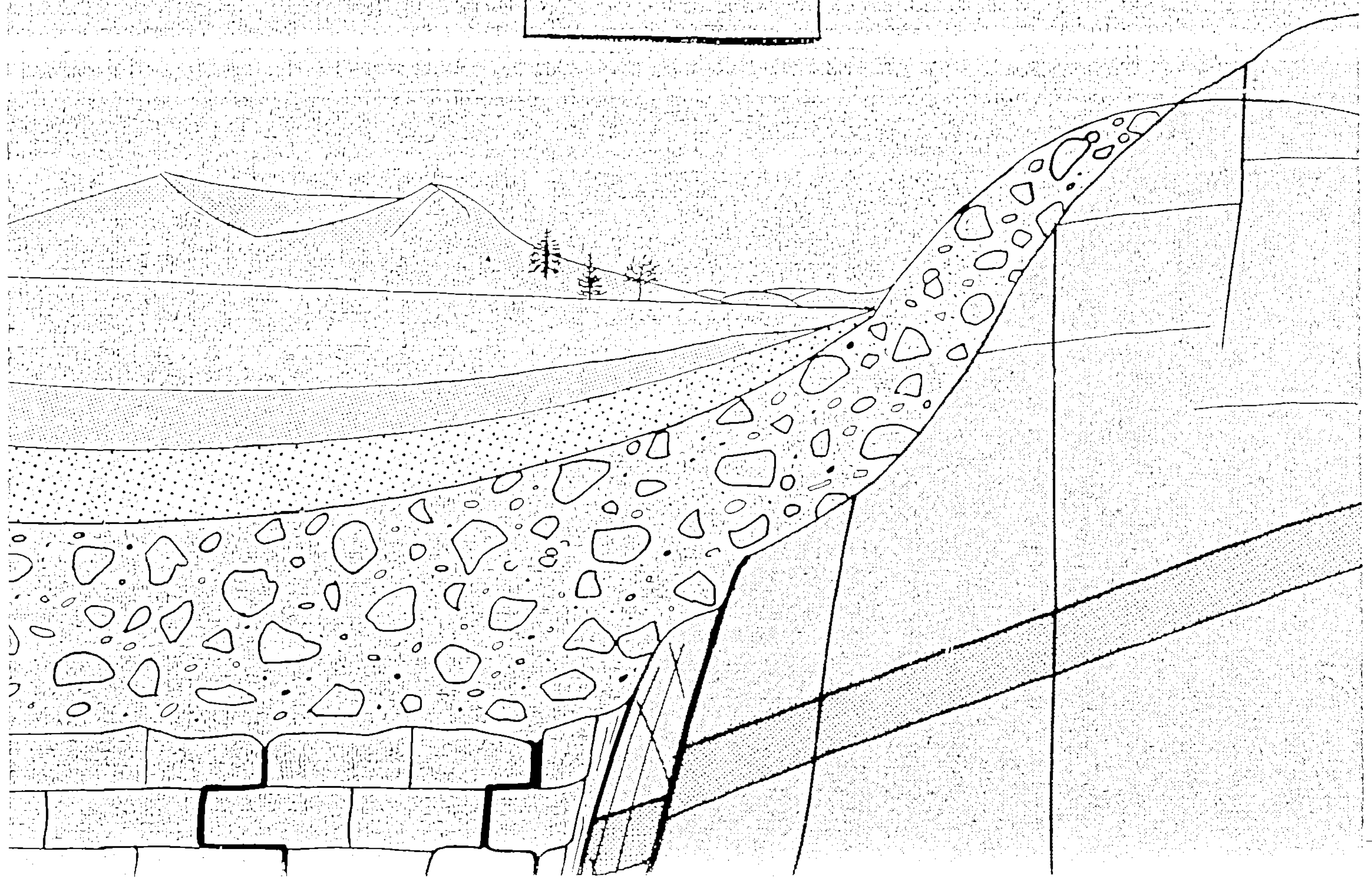
Uppsala 1980



SGU--19

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URANIUM-ENRICHED GRANITES IN SWEDEN

Paper presented at a meeting of the Mineral Deposits Studies Group of the Geological Society of London entitled "Problems of mineralization associated with acid magmatism", Exeter, December 1979.

A contribution to the NEA-IAEA R&D project "Uranium in granites"

Uppsala 1980

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Uranium-enriched granites in Sweden

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Abstract

Granites with uranium contents higher than normal occur in a variety of geological settings in the Swedish Precambrian, and represent a variety of granite types and ages. They may have been generated by (1) the anatexis of continental crust (2) processes occurring at a much greater depth. They commonly show enrichment in F, Sn, W and/or Mo. Only in one case is an important uranium mineralization thought to be directly related to a uranium-enriched granite, while the majority of epigenetic uranium mineralizations with economic potential are related to hydrothermal processes in areas where the bedrock is regionally uranium-enhanced.

Introduction

Figure 1 is a map showing the known distribution of granitoids and other crystalline bedrock with radioactivity over 25 µR/h. The map has been produced by the Geological Survey of Sweden (SGU) for the purpose of delimiting areas within which abnormally high radon contents may occur in buildings. The map is based mainly upon an airborne radiometric survey carried out by SGU for the purpose of uranium prospecting (Lindén and Åkerblom, 1976). This survey covers only about 40 % of the country and there are considerable areas of Precambrian granite terrain from which there is little information. In the map only those crystalline rocks with activities over 25 µR/h were included. This means that many granites with slightly enhanced uranium contents are not shown. It also means that some small areas of radioactive migmatite and neosomes are included. No attempt has been made to separate U-enriched from Th-enriched granites on the map. Geological boundaries, as shown in Fig. 2, are included on the map.

The uranium-enriched granites have been intruded into rocks in a variety of geological settings and show a wide range of ages and granite types. Sometimes these granites are isolated occurrences (e.g. Götemar granite) and sometimes they are grouped together (as in N. Västerbotten and S. Norrbotten). Some of the granites are evenly enhanced in uranium over wide

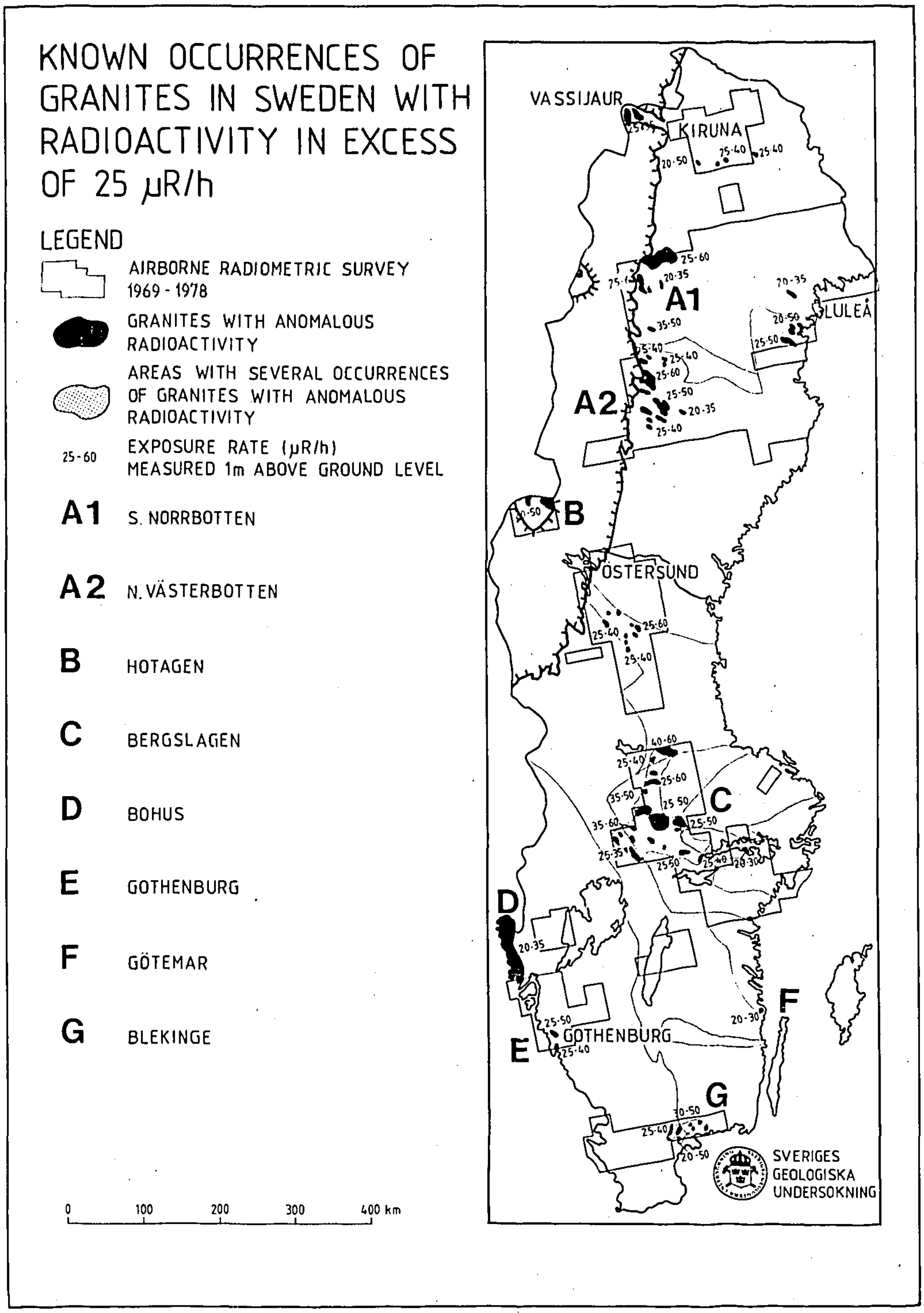

Fig. 1. Location of granitoids and other crystalline bedrock in Sweden with radioactivity over 25 μR/h. Areas A-G are described in the text.

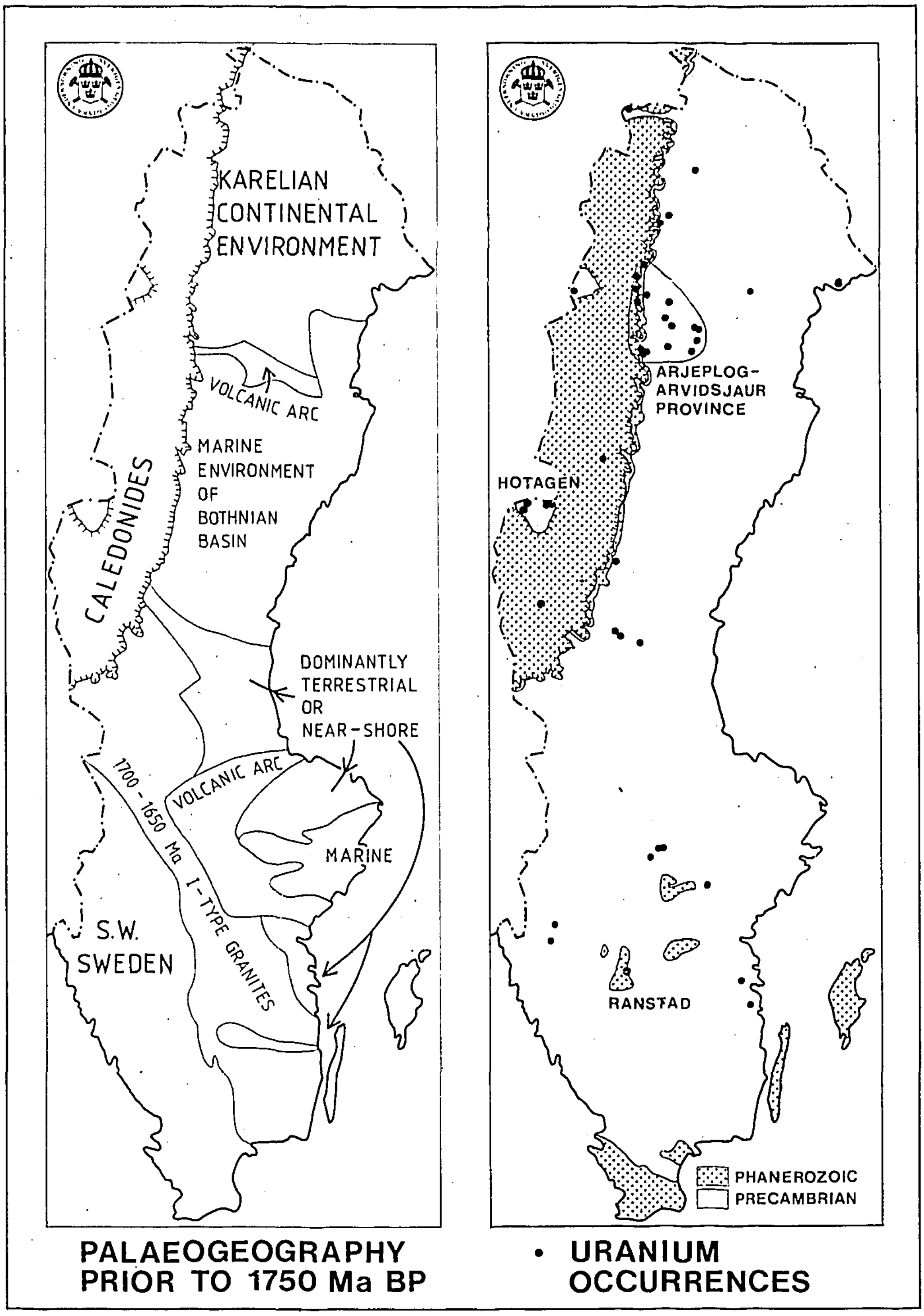

Fig. 2. Precambrian palaeogeography and uranium occurrences in Sweden. The areas of bedrock marked Phanerozoic include, in the Caledonides, some late-Precambrian sediments and some Precambrian nappes.

areas (e.g. Bohus granite) and in other cases the uranium enrichment appears to be restricted to the more differentiated parts of the bodies (e.g. Malingsbo granite).

This paper represents a first attempt to interpret the map from a geological and geochemical point of view. We have collected together published data and the more accessible unpublished data concerning the geological setting, age, Sr isotope composition, geochemistry, genetic type, and relationship to known uranium mineralizations. No new analyses have been conducted and the material is therefore rather heterogeneous. This paper is a contribution to the OECD(NEA)-IAEA R&D project 'Uranium in granites'.

Current ideas on the genesis of uranium-enriched granites

Two opposing hypotheses are currently discussed with respect to granites enriched in elements such as uranium and tin. One hypothesis is that U or Sn granites are found in areas of thickened sialic crust, where they are generated by anatexis (Tischendorf 1977, Moreau 1976, Beckinsale et al. 1979) while the alternative is that these granites have a much deeper origin (Stemprock 1963, 1979, Simpson et al 1979). The debate is thus closely linked to the general problem of granite genesis.

Granite genesis

It has long been recognised that there are two main families of granites: alkali granites and calc-alkaline granitoid suites, (Eskola 1932, Moreau 1976, Ishihara 1977, Shpetny et al 1974, Chappell & White 1974, Pitcher 1979). In recent years considerable progress has been made in the geochemical and isotopic recognition of these two groups and in the interpretation of their origin, particularly in terms of plate-tectonic theory. Current discussions are presented at length in Cox, Bell and Pankhurst (1979), Atherton and Tarney (1979) and Pitcher (1979).

Criteria for the fundamental division of granite types are presented by Chappell and White (1974) on the basis of studies of granites in eastern Australia, and developed further by White and Chappell (1977). They distinguish I- and S-type granites, derived from Igneous and Sedimentary sources respectively and which correspond roughly to the calc-alkaline and alkali granite types respectively. I-type granitoids have a wide compositional range from gabbro to granite and low initial $^{87}Sr/^{86}Sr$ ratios, comparable to mantle material. S-type granitoids show a restricted compositional range, depletion in Na and Ca due to involvement in the sedimentary cycle, and high $^{87}Sr/^{86}Sr$ ratios. The two granite types can also be distinguished on the basis of their characteristic xenoliths and xenocrysts, their oxygen isotopic compositions, degrees of oxidation and, according to Atherton and Tarney (1979) by their trace element compositions.

S-type granites are related to the 'Hercynotype' orogen (Pitcher, 1979) and are regarded as having been generated through anatexis in areas of thickened crust. One possible cause of this thickening is continental collision. I-type granitoid suites are characteristic of the "Andinotype" orogen (Pitcher, 1979). In Phanerozoic orogens they are usually developed over subduction zones and have been generated at subcrustal or lower crustal levels. Their source may be mantle material, subducted altered ocean floor or crustal material which has been depleted in Rb due to high grade metamorphism.

While the I-S concept has already gained wide acceptance and usage there do seem to be a number of problems in its application. A number of granites in the Swedish Precambrian show high SiO_2 contents and high initial $^{87}Sr/^{86}Sr$ ratios and yet do not show the Na and Ca depletion which characterises the Australian S-type granitoids (White and Chappell 1977). Many of these granites are discussed in more detail in this paper as they are enriched in U. Other granite types are illustrated by the "Perthite granite" (Witschard 1975, tab. 2) which shows wide range of SiO_2, high Na_2O, is not peraluminous (mol $Al_2O_3/Na_2O+K_2O+CaO = 0.94$) and is not reduced ($Fe^3/Fe^3+Fe^2 = 0.84$). These are all typical I-type features, yet the initial $^{87}Sr/^{86}Sr$ ratio is 0.713 (Gulson 1972), a distinctly S-type value. In many of these cases it is believed that the granites may have been generated through the anatexis of old Rb-rich volcanics and other igneous rocks, with only a minor contribution of sedimentary material. In addition many of the granites such as the Perthite granite are intruded into a continental environment and the only sediments involved in its genesis are likely to have been continental, not marine, and therefore not depleted in Na and Ca. Such granites seem to fall outside the I-S classification.

U and Sn granites

The question of the genesis of the Sn-U-F bearing granites of Cornwall is a good example of the current dispute on the origin of granites. Studies of the oxygen isotopes in whole rock and mineral samples by Sheppard (1977) show high ^{18}O values implying generation through melting, assimilation or exchange with argillaceous-rich sediments at depth. The ^{18}O rich characteristics cannot be due to post-magmatic alteration and exchange processes as they are also observed in quartz from unaltered granite. These granites would therefore seem to be of S-type comparable with the uranium-rich Hercynian granites of the Massif Central of France, which Moreau (1976) attribute to anatexis in areas of thickened crust. White and Chappell (1977) cite the Cornubian granites as typical examples of S-type granites. The connection between Sn and S-type granites is mentioned by Chappell and White (1974) and further discussed by Beckinsale (1979) and Beckinsale et al (1979), with reference to the tin belt of S.E. Asia.

Simpson et al (1979) dispute that the Cornubian granites are of S-type, citing the low initial $^{87}Sr/^{86}Sr$ ratio of 0.706 for the St Austell granite as evidence that the granites were not generated through crustal anatexis. They mention but do not explain the high ^{18}O values and favour a derivation from sub-continental oceanic lithosphere underplated onto pre-existing Precambrian basement. They also describe uranium-enriched granites from the Scottish Caledonides. All the British uranium-enriched granites are characterised by low initial $^{87}Sr/^{86}Sr$ values, high ^{18}O values, low K/Rb and high levels of incompatible elements (Sn, F, Li, Be, Th and Pb).

The association of Sn-bearing granites with deep mantle material has been repeatedly emphasised by Stemprock (1963, 1979). The geochemical characteristics of ore-bearing granites described by Stemprock (1979) (based on Tauson 1977) are very similar to those of the Cornubian batholiths and, as will be shown in this paper, to those of Swedish uranium-enriched granites. The geochemistry of Sn granites from Nigeria and Australia is also described in Imeokparia (1980) and Juniper & Kleeman (1979) respectively. Juniper and Kleeman suggest that ternary plots of 7 major elements can be used for distinguishing Sn-mineralising granites from barren granites.

Geological setting of the uranium-enriched granites

All the known uranium-enriched granites in Sweden are of Precambrian age. The Precambrian geology of Sweden has recently been described by Lundqvist (1979) and therefore only a few relevant points will be mentioned here, particularly palaeogeography and granite genesis (Wilson in press).

An attempt to reconstruct the palaeogeography of Sweden prior to 1750 Ma ago is shown in Fig. 2. From north to south the following environments can be distinguished:

An area of continental vulcanism and sedimentation was located in the far north, on what is termed the Karelian continent. Archaean basement has been verified from this area through U-Pb zircon dating (Skiöld 1979b). Along the southern margin of this continent was situated a narrow volcanic arc, the Skellefte district (Rickard and Zweifel 1975 and Lundberg, in press), which is probably part of an island arc system. A major marine basin (the Bothnian basin) which may have been underlain by ocean floor was located south of the arc. The eastern part of Central and Southern Sweden contained a variety of environments, including a volcanic arc (Löfgren 1979, Loberg 1980), terrestrial, near shore and marine environments. Åberg (1978) was able to show that Archaean basement was present in the southern part of the area and was subjected to erosion. The situation in SW Sweden at this time is not clear because of the effect of later orogenies, but a variety of environments are indicated.

These supracrustal rocks have been subjected to metamorphism and deformation prior to about 1750 Ma. Later metamorphism and deformation is restricted entirely to SW Sweden and appears to fall into at least two phases, between 1400 and 900 Ma ago.

A useful picture of magmatic evolution in the Precambrian is given by the plot of initial $^{87}Sr/^{86}Sr$ ratios against ages for all Swedish acid magmatic rocks that have been dated by the Rb-Sr isochron method (Fig. 3), assuming that the data is reliable and representative. In some cases the age plotted has been determined by U-Pb study of zircons. There are two distinct periods of generation of granitoids with low initial $^{87}Sr/^{86}Sr$ ratios: 2000-1650 Ma and 1450-1400 Ma (Fig. 3). These granitoids commonly show I-type chemical

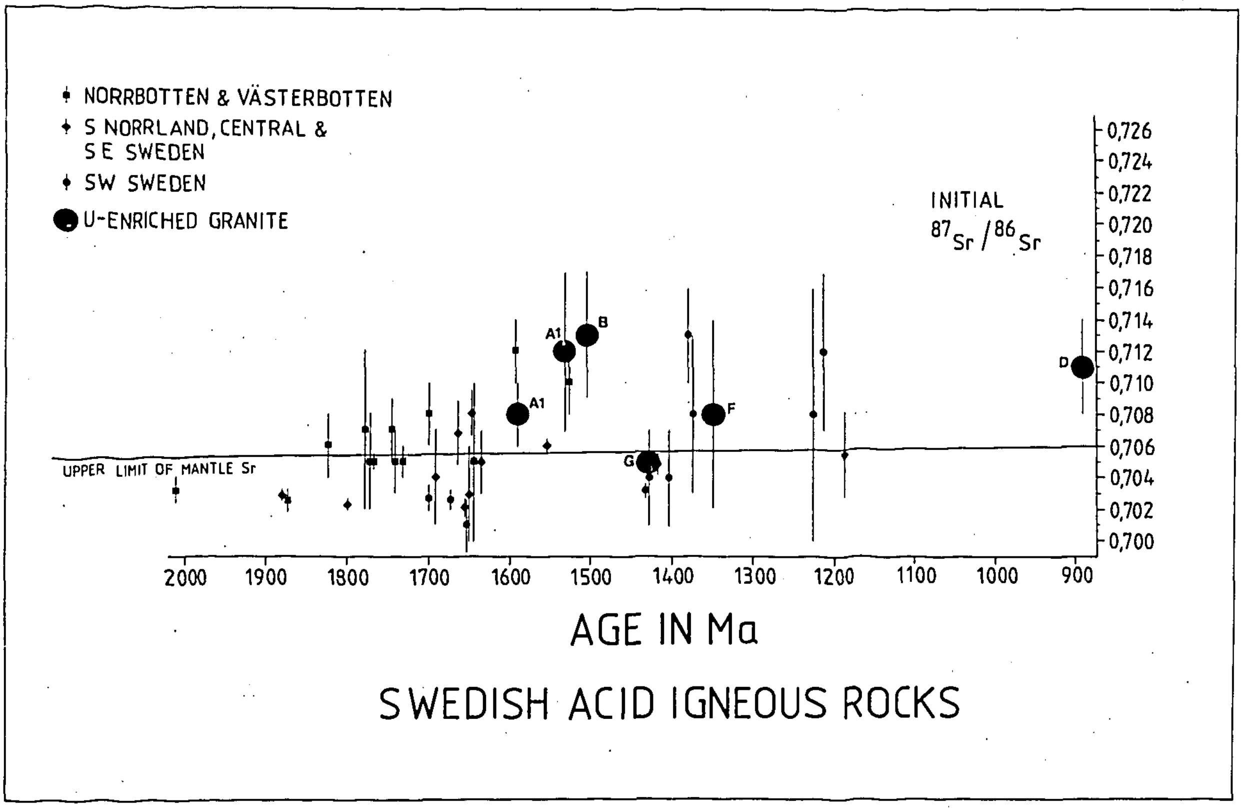

Figure 3. Age and initial $^{87}Sr/^{86}Sr$ ratios for granites with enhanced uranium contents, compared to all other acid igneous rocks in Sweden. Reference to sources in Wilson and Sundin (1979). Upper limit for the composition of mantle Sr taken from Faure (1977). No account is taken in the diagram of the analytical error in the age determinations.

characteristics in particular a wide range of SiO_2 contents. The first of these periods encompasses (a) granitoids and related calc-alkaline volcanics generated prior to 1750 Ma isolated representatives of which occur in north, central and southeastern Sweden, (b) a belt of I-type granitoids and related volcanics extending from Östersund to the southeast of Sweden and dated to 1700-1650 Ma, thereby post-dating the regional metamorphism and deformation of their host rock and (c) isolated granites in the SW of Sweden. The second priod of generation of low $^{87}Sr/^{86}Sr$ granitoids (1450-1400 Ma) is restricted to SW Sweden and Blekinge.

The several phases of metamorphism in Sweden are accompanied by granite generation, usually granites with a relatively restricted SiO_2 range and initial $^{87}Sr/^{86}Sr$ ratios greater than 0.706. These granites are frequently undeformed, exhibit chilled contacts and cause local contact metamorphism and are therefore termed "post-tectonic". Extensive areas of such granites were intruded into the marine sediments of the Bothnian basin and some of these are enriched in uranium (Section A2). Within the Karelian continent post-metamorphic granite intrusion and acid vulcanism continued until about 1500 Ma at which time this area was uplifted as is indicated by Rb-Sr dates on micas (Skiöld 1979a). The post-metamorphic intrusives in the Karelian continent show high initial $^{87}Sr/^{86}Sr$ ratios and several have anomalous uranium contents.
In SW Sweden alkali or S-type granites were generated in connection with metamorphism at about 1400 Ma, at 1200 Ma (Hästefjorden granites) and finally in connection with the uplift of SW Sweden at about 900 Ma (Bohus granite). Several of these are uranium-enriched.
Intrusions of anorogenic character include gabbro-rapakivi suites, the uranium-enriched Götemar granite, several phases of basic dykes and sills and various alkaline intrusions (Lundqvist 1979).

Various attempts have been made to apply plate-tectonic concepts to the Precambrian of Sweden for example by Hietanen (1975), Rickard & Zweifel (1975), Rickard (1978 and 1979), Adamek and Wilson (1977, 1979) and these are reviewed and discussed by Lundqvist (1979). Further evidence is presented by Löfgren (1979) and Loberg (1980). Hietanen, Rickard and Lundqvist propose models involving an easterly or northeasterly dipping subduction zone. However if plate tectonics were operative during the Proterozoic it is probable that the situation in the Swedish Precambrian would have been more complicated, with several distinct subduction zones having been operative. It may be speculated that the early (2000-1800 Ma) I-type granitoids together with the volcanic arc supracrustals of the Skellefte and Bergslagen district belong to a separate early phase with the greater part of Sweden underlain by a gently dipping subduction zone. The crustal thickening that is reflected in the 1750 Ma metamorphic event may mark cessation of subduction. A second subduction zone with an easterly dip may have been established around 1700 Ma, resulting in I-type granites in SW Sweden (the Åmål I group, Gorbatschev 1975) and the major belt of magnetic I-type granites stretching between Östersund and SE Sweden. A third period of subduction at around 1450-1400 Ma was only operative in SW Sweden. The second and third periods of subduction were separated by a major tensional part during which minor alkaline intrusions at Almunge, Västervik and N. Kärr (Doig 1970, Blaxland 1977), basic dykes (Patchett 1978) and gabbro-rapakivi granites (Kornfält 1976) were emplaced.

Description of granites with anomalous uranium contents

Seven areas, designated A-G (Fig. 1), will be described in some detail.

Table 1 presents U, Th and K values determined in-situ by gamma spectrometry. Table 2 presents averages of the major element compositions of the granites and Table 3, ages, initial Sr isotope compositions and Rb and Sr contents. These data are tabulated separately since they were determined on different samples. However there are additional areas containing uranium-enriched granites and these are briefly described first.

The most northerly radioactive granites are those at Vassijaur (Fig. 2). They are probably of "Lina" type, a granite type widespread in the Karelian continental area of Norrbotten, but which is singularly ill-defined (see for example Welin et al 1971). To the south east of the Vassijaur granites lie a number of isolated occurrences of uranium-anomalous granites in the Kiruna-Vittangi area, and these are also considered to be differentiates of the Lina type granite group. Between Piteå and Luleå occur both uranium-enriched neosomes and uranium-enriched granites probably similar to the Degerberget granite, a 1770 Ma old I-type granite type occurring north of Luleå and described and dated by Skiöld (1977).

South of Östersund occurs an area of varied Precambrian bedrock in which a variety of granites, metasediments and metavolcanics are enriched in uranium and in which can be found a large number of minor uranium mineralizations. Geochemical data is completely lacking from this area. It can be described as an area with a general enhancement of uranium in most rock types.

A. S. Norrbotten and N. Västerbotten

Uranium-enriched granites occur in an area some 250 by 70 km, lying immediately east of the Caledonian Front. Areas to the north and south have not yet been radiometrically surveyed. The eastern boundary of the area marks a real decrease in the radioactivity of the bedrock as determined by airborne radiometric survey, but the geological reason for this decrease is not apparent.

A1 S. Norrbotten

The northern part of the area formed part of a landmass, the Karelian continent, prior to 1750 Ma ago, and coincides with the Arjeplog-Arvidsjaur-Sorsele uranium province in which many rock units of varying ages and characters are enriched in uranium (Adamek and Wilson 1979). Important epigenetic and stratabound uranium mineralizations occur in the area. Many rock units are only slightly enriched in uranium and have radioactivities less than 25 μR/h and therefore are not shown on the map.

Granites with high uranium contents include the Hällnäs and Guorbavare granites. They are post-metamorphic granites with ages 1700 Ma and 1590 Ma and initial $^{87}Sr/^{86}Sr$ ratios of 0.708 and 0.712 respectively (Welin et al 1977). No chemical analyses are available. Enrichments in Mo, W and Sn are recorded. A leucocratic alkali granite with 7 ppm U, which is the host rock to some of 1750 Ma uranium mineralizations in the Arvidsjaur district, is described in Adamek and Wilson (1979, pg 359).

The most important uranium mineralizations in the Swedish Precambrian occur in this province with proved resources of nearly 10 000 tonne U, (Adamek and Wilson, 1977, 1979). Epigenetic veins and dissemination-type mineralizations, for example Pleutajokk (3 000 tonne U), are associated with Na metasomatism and are dated to about 1750 Ma, while the stratabound deposit of about 4500 tonne U in ignimbritic volcanics at Dobblon (Lindroos and Smellie 1979) is distinctly younger. Although some of the epigenetic mineralizations, for example Björklund, do occur in a leucocratic alkali granite with slightly enhanced uranium content as described in Adamek and Wilson (1979 pg 359), there is a much closer correlation on the regional scale with belts of supracrustals lying between the various granites, as is described by Gustafsson (in press). Many of the mineralizations occur in acid meta-volcanics and die out if the volcanics become more intermediate or basic, for example at Pleutajokk, (Gustafsson and Minell 1977 and Gustafsson, in press). While the Pleutajokk deposit lies adjacent to the uranium-enriched Guorbavare granite it is some 150 Ma older than the granite. Adamek and Wilson (1979) stress the ubiquitous relationship between epigenetic uranium mineralizations in this province and an earlier phase of Na metasomatism and propose that leaching and transport of uranium was accomplished by alkali solutions derived from the Archaean basement of the Karelian continent during regional metamorphism. Two possible sources for the uranium were thought to be the Archaean basement itself or early rhyolitic volcanics with enhanced uranium contents. The spacial correlation demonstrated by Gustafsson supports the latter interpretation. Adamek and Wilson (1979 p. 366) stress that the Arjeplog-Arvidsjaur-Sorsele province is characterised by anomalously high uranium contents in rocks with a wide range of type and age. The combination of regional enhancement and a metamorphogenic hydrothermal process is considered to be of great significance.

A2 N. Västerbotten

The anomalous granites in the southern half of the region post-date both deformation and metamorphism and are classed as 'Revsund granite" Similar-looking granites in the vicinity are quite barren. Samples of Revsund granite with normal radioactivity taken from some 100 km to the southeast give an age of about 1750 Ma and initial $^{87}Sr/^{86}Sr$ ratio of about 0.707 (Welin et al, 1971). It can be speculated that the enriched granites may be significantly younger. Current fieldwork suggests that the Revsund-granites were derived from considerable depth (Löfgren pers. comm.) but earlier workers favoured an anatectic origin. Five samples of one of the high Th and U granites show S-type chemistry, being peraluminous (Table 2). Th/U ratios vary considerably from area to area within the region, from 4.0 to 0.7 (Table 1). Many of the granites show extremely well-developed zoning in U and Th contents parallel to the contacts. These granites also have high contents of F, Sn and W although no analytical data is available. Sn and W mineralizations are currently being investigated by SGU.

Despite the fact that this area lies directly south of a major uranium province only a few minor uranium mineralizations have been found in the area. Why are there not more uranium mineralizations? The most significant difference between the two regions is in their palaeogeography. The N. Västerbotten granites are intruded into metagreywackes and basic volcanics of the Bothnian basin. Terrestrial deposits, such as uranium-enriched volcanics, seem to be totally lacking. Whether these greywackes are underlain by ocean-floor or by continental crust is unknown and while we favour an ocean floor interpretation, reconstructions by Hietanen (1975) and Rickard (1978) feature continental crust under the Bothnian basin. If continental basement is present it will be at considerably greater depth than in the area to the north.

The Bothnian basin is characterised by a very low and homogeneous magnetic field which can be related to the presence of metasediments and granites in the upper part of the crust. The gravity field shows a marked positive anomaly implying basic rocks such as ocean floor material at depth (Leif Eriksson pers. comm.). According to Husebye (1979) this is the thickest part of the Baltic shield. The magnetic and gravity characteristics are distinctly different from those of the Karelian continent to the north.

Any explanation of the origin of the N. Västerbotten - S. Norrbotten uranium province must take into account that it continues right across this major palaeogeographic divide and also that equivalent rocks to the east are not enriched in uranium and lack uranium mineralizations. One possibility is that this entire province is related to a major mantle heterogeneity (Brooks et al 1976) or mantle plume (Anderson 1975) rich in U and F and that the granites were derived from great depth.

B Hotagen

Two single granite intrusions within the Precambrian Olden window in the Caledonides north of Östersund are markedly enriched in uranium. Both show similar chemistry but the eastern intrusion has a large number of associated small uranium mineralizations, including the Lilljuthatten deposit (1600 tonne U). This granite has an area of about 16 km by 8 km but the radioactive part has a circular outcrop area about 8 km diameter in the centre of the massif. The granite has been dated by Inger Klingspor (pers. comm.) to about 1500 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.713. The dating is, however, statistically unreliable. The age and Sr composition is comparable with the youngest granites in Norrbotten, granites which post-date metamorphism and deformation in that area, and which may be related to regional uplift (Welin et al 1971, Gulson 1972). A description of the granite, including major element analyses, is presented in Troëng and Wilson (in press). While the high SiO_2 content and high initial $^{87}Sr/^{86}Sr$ ratio are typical of an S-type granite, other chemical parameters are typical of an I-type granite. The granite has anomalously high F content (0.14 %), low K/Rb ratio (111) and Sr content (64 ppm) indicating that it has been strongly differentiated. Preliminary analyses for Sn and Mo suggest slightly anomalous values.

Hotagen is the only area in which uranium mineralizations with economic potential are directly related to a uranium-rich granite. The mineralizations occur in crush and breccia zones in the granite (Troëng and Wilson, in press). The best of these mineralizations contains at least 1600 tonne U in high grade ore. Uranium is thought to have been leached from the granite and concentrated in the crush zones by hydrothermal fluids derived from the basement during Caledonian metamorphism. The granite is known to contain a high proportion of leachable uranium. The mineralization is therefore due to a secondary process and not directly related to magmatism.

C Bergslagen

An area about 150 km by 100 km contains a large number of granite intrusions which have differentiates with high uranium contents. Examples include the Malingsbo and Fellingsbro granite groups, which are apparently contemporary with metamorphism and deformation at about 1750 Ma, and representatives of the younger Filipstad and Dala granite groups.

The Fellingsbro granite has been briefly described by Gorbatschev (1972). The granite contains xenoliths of acid volcanics and is interpreted as being of anatectic origin. Average of four SGU analyses of uranium-enriched Fellingsbro granite are presented in Fig. 2. Uraninite occurs in both the Malingsbo and Fellingsbro granites (Bolin and Wahlin 1978).

W and Sn mineralizations occur in the vicinity of the Malingsbo granite but the Sn and W content of these granites is not known.

The Filipstad and Dala granite groups can also be anomalously rich in uranium. They both form part of a major belt of post-metamorphic granites with ages 1700-1650 Ma which show a wide range of SiO_2 contents and generally low initial $^{87}Sr/^{86}Sr$ ratios. They can be considered as I-types and a deep origin is probable. However some of Filipstad granites show higher initial Sr ratios (0.7068±0.0021, Welin et al, 1977), indicating a varying component of Rb-rich crustal material. The initial Sr composition of the actual uranium-enriched granites is not known.

D The Bohus granite

The Bohus granite occupies an area of about 20 km by 90 km in SW Sweden but continues into SE Norway and thereby forms part of a major belt of thorium- and uranium-enriched granites about 300 km long (Killeen & Heier 1975). The whole of the granite belt has enhanced U and Th contents. The Bohus granite has the form of a large flat-lying sheet-like intrusion (Asklund 1947, Lind 1966.) It has an age of 890 Ma with initial $^{87}Sr/^{86}Sr$ ratio of 0.711 (Skiöld 1976). The time of intrusion is coeval with mineral dates from the SW of Sweden (Magnusson 1960) indicating that it was intruded at a time of uplift. Granite genesis may be through anatexis upon release of pressure (cf. Pitcher 1979 pg 644). The granite has a restricted range of SiO_2, is peraluminous (Asklund 1947) and is an excellent example of an S-type granite (Table 2). The uranium content of the Bohus granite in the area sampled by Mellander (1978) is higher than for the five samples reported by Killeen and Heier (1975) (14 and 6 ppm respectively) but the Th/U ratio is normal (3.5).

E Gothenburg

In the Gothenburg region occurs a granite type with high uranium contents (Table. 1). This is an alkali granite probably belonging to the Åmål II unit of Gorbatschev (1975). Other Åmål II granites are dated to around 1400 Ma. The alkali granite was intruded at a time of metamorphism and folding (Samuelsson, pers. comm.) and forms a number of thin sheet-like intrusions. It has high SiO_2 contents, is slightly peraluminous and has high F, Zr and Sn contents. K/Rb, Sr and Ba are low. Rb-Sr and zircon age determinations are currently being undertaken by Welin.

F Götemar granite

The Götemar granite is an isolated single massif with a diameter of 5 km on the southeast coast of Sweden. The whole granite has an enhanced U and Th content. It has an age of 1350±35 Ma and initial $^{87}Sr/^{86}Sr$ ratio of 0.708± 0.006 and post-dates regional uplift by about 70 Ma (Åberg 1978). It is generally regarded as "anorogenic". The Tuna dolerite dykes of Central Sweden were intruded at about this time (Patchett 1978) which may therefore represent a period of tension in the crust. According to Kresten and Chyssler (1976) the Götemar granite is a highly differentiated leucocratic alkali granite with high F (0.5 %), Sn, Be, and low K/Rb. It has the composition of a eutectic melt at 2000 bars H_2O pressure corresponding to an intrusion depth of 7-8 km but is thought to be shallower. This could be a result of the high F content affecting the position of the eutectic minimum (Manning 1979).

G Blekinge

The Precambrian of the Blekinge region cannot be readily correlated either with SW Sweden or with the rest of Sweden according to Lundqvist (1979) and Wiklander (1974). A number of radioactive granites occur within a 50 km by 20 km zone. These are the Karlshamn, Jämshög, Vånga, Spinkemåla and Halen granites (Table 1).

The geochemistry and geochronology of the Karlshamn granite has recently been described by Springer (1980). The granite is calc-alkaline, has an age of 1422±31 Ma and initial $^{87}Sr/^{86}Sr$ ratio of 0.7046±0.0006. This is the only certain example of a uranium-enriched I-type granite in Sweden. Within the Karlshamn granite occur two small plutons of leucogranite of slightly younger age which may according to Springer have been formed by a partial remelting of the Karlshamn granite. The Vånga, Spinkemåla and Halen granites are thought to be related to the Karlshamn granite (Lundqvist 1979 pg. 24).

The Vånga granite has been described by Lundegårdh (1978). The granite has a high SiO_2 content and is slightly peraluminous. It has high F and slightly anomalous Sn content while the Sr content and K/Rb ratio are low. If it is related to the Karlshamn granite it must be regarded as a late differentiate of the same magma or as a product of partial remelting.

Summary of geochemistry

With the exception of the Karlshamn granite in Blekinge, all the uranium-enriched granites are well-differentiated SiO_2-rich granites, often alkali granites. They have high Rb contents and low Sr, Ba and K/Rb. F is high where determined, and fluorite is observed in most of the granites. Enrichments or associated mineralizations are commonly noted with respect to Sn, W and, in the case of the continental area in S. Norrbotten, Mo.

Further differences between the granites can be seen on Harker diagrams. Plots of TiO_2, MgO and CaO against SiO_2 distinguish three groups: 1) Vånga granite (low CaO, MgO and TiO_2), 2) Götemar granite and 3) Fellingsbro, Hotagen and Gothenburg granites. The Vånga and Fellingsbro granites show strong decreases of K_2O with increasing SiO_2 while the other granites have lower and more constant K_2O contents.

The high SiO_2 content and the Sr isotope compositions suggest that the majority of uranium-enriched granites do not belong to the 'I-type'. A clear exception is the Karlshamn granite. All the granites analysed are peraluminous but only the Götemar and N. Västerbotten granites are so peraluminous that they fall in the S field.

Relationships between uranium-rich granites and uranium mineralizations

Uranium mineralizations of economic importance generally occur in areas with enhanced uranium contents in bedrock, for example the pre-Aphebian sediments of the Athabasca basin Canada and the Cahill formation of the Pine Creek geosyncline, Australia (Smith 1974). A very clear genetic relationship between uranium-enriched granites and subsequent epigenetic uranium mineralizations is demonstrated in the Hercynian uranium provinces of Europe (Moreau 1976, Cameron in press).

Hotagen is the only Swedish area in which important uranium mineralizations are directly related to a uranium-enriched granite. The uranium has probably been leached from the granite by metamorphogenic hydrothermal solutions during the Caledonian orogeny.

Epigenetic and stratabound uranium mineralizations of considerable economic value occur in S. Norrbotten in a province with enhanced uranium contents in both plutonic and volcanic rocks. There is no direct relationship between uranium-rich granites and the mineralizations. Metamorphogenic hydrothermal processes are considered to be of great significance.

A number of uranium mineralizations are currently being investigated in a zone between Östersund and Gävle and they are related to high uranium contents in metasediments and gneisses. Uranium is often seen to be concen-trated in a coarse pegmatoid neosome. Several of the granites in the zone also have anomalously high uranium contents and it appears that this is another region in which, like the Arjeplog-Arvidsjaur-Sorsele province, many rock types have anomalously high uranium contents.

The Bergslagen area, with its many uranium-enriched granites has been intensively prospected for uranium, but the only mineralizations known are associated with skarn iron ores and are described by Welin (1966).

No uranium mineralizations at all are known from the Bohus, Gothenburg, Götemar or Blekinge granites. A number of uranium-enriched granites marked on Fig. 1 but not otherwise described in this account also lack related uranium deposits.

The lack of uranium mineralizations around uranium-enriched granites may be due to the mineral phase in which the uranium is placed and thus reflects the non-leachable nature of much of the uranium. Kresten & Chyssler (1976) show that the uranium in the Götemar granite, for example, is concentrated in zircon. While this consideration is, of course, of importance, it is more likely that the availability or non-availability of fluids for leaching and transport plays a more important role, as has been demonstrated for example in Cornwall (Simpson et al 1979) and Portugal (Cameron, in press).

We conclude that uranium mineralizations and uranium-enriched granites can occur in the same region as different expressions of a high amount of uranium in geochemical circulation but that the mineralizations are never related to the magmatic processes. The only magmatic uranium concentrations with economic potential are seen in the ignimbritic volcanics of Dobblon (Lindroos & Smellie 1979). The epigenetic uranium mineralizations of the

Swedish Precambrian are more obviously related to hydrothermal solutions of metamorphic origin moving through continental crust.

Conclusions

1. The uranium-enriched granites in Sweden fall into a wide range of age groups, from 1750 Ma to 890 Ma. They never belong to early orogenic granite groups with extremely low initial $^{87}Sr/^{86}Sr$ ratios, but are generally highly differentiated alkali granites with initial $^{87}Sr/^{86}Sr$ ratios of over 0.708. This indicates that there is a considerable crustal component involved in their genesis or that there has been considerable contamination through late-stage alteration. The Karlshamn granite is a clear exception. There is also a possibility that the U-Sn-W rich granites of N. Västerbotten are of deep origin and that the whole of the N. Västerbotten - S. Norrbotten province might be related to mantle heterogeneity.
Four groups of U-rich granites can be distinguished:
   a) Granites coeval or slightly later than regional metamorphism (Hällnäs, Guorbavare, Bergslagen, Gothenburg).
   b) Anatectic granites related to uplift (Bohus).
   c) Anorogenic granites related to tensional regimes (Götemar, possibly also Hotagen).
   d) Granites possibly of deep origin (N. Västerbotten, Blekinge).

2. Most of the granites have elevated F contents, several have anomalous Sn, W or Mo contents.

3. Only one granite (Hotagen) is directly associated with economic uranium mineralizations.

4. Uranium mineralizations in the Hotagen and S. Norrbotten areas are related to metamorphogenic hydrothermal processes. The lack of associated uranium mineralizations with many of the uranium-enriched granites is more likely to be due to the lack of such a secondary process rather than the relative leachability of the uranium in the granite.

5. The connection between U and Sn, W, Mo is rarely mentioned in the literature. We suggest that existing airborne radiometric surveys may contain information valuable to other prospectors.

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Table 1. K, U, Th and Th/U determined by in situ gamma spectrometry

Area	Granite	n	K %	s	U ppm	s	Th ppm	s	Th/U	s	source
A2	Revsund (a)	127	4.5	(0.4)	10	(5)	36	(9)	4.0		(1)
A2	Revsund (b)	47	4.3	(0.3)	9	(2)	18	(2)	2.2		(1)
A2	Revsund (c)	92	4.5	(0.3)	18	(5)	19	(5)	1.2		(1)
A2	Revsund (d)	248	4.1	(0.7)	11	(6)	12	(6)	1.3		(1)
A2	Revsund (e)	159	4.1	(0.5)	15	(6)	8	(4)	0.7		(1)
B	Hotagen	16			19	(9)	44	(18)	3.1		(2)
C	Fellingsbro	24	4.5	(0.3)	12	(4)	42	(15)	3.4		(3)
C	Malingsbo	24	4.2	(0.5)	22	(10)	47	(16)	2.1		(3)
D	Bohus	12	4.8	(0.4)	13	(4)	50	(12)	3.7		(3)
E	Gothenburg (a)		5.9	(0.3)	19	(5)	71	(4)	3.7		(4)
E	Gothenburg (b)		5.5	(0.7)	13	(5)	55	(5)	4.2		(4)
E	Gothenburg (c)		6.0	(0.3)	16	(3)	77	(3)	4.8		(4)
F	Götemar	3	4.8		15		55		3.8		(3)
G	Karlshamn	8	4.6	(0.4)	8	(2)	42	(13)	5.6		(3)
G	Halen	6	5.0	(0.1)	27	(5)	80	(6)	2.9		(3)
G	Jämshög	2	5.0		19		90		4.7		(3)
G	Spinkemåla	4	5.1	(0.3)	18	(1)	58	(7)	3.3		(3)
G	Vånga	5	4.6	(0.3)	15	(5)	47	(5)	3.0		(3)

Sources: (1) Hålenius pers. comm.
(2) Troëng pers. comm.
(3) Mellander (1978)
(4) Lindén pers. comm.

n: number of measurements
s: standard deviation

Revsund (a-c): Coarse porphyritic granite
Revsund (d): Even-grained granite
Revsund (e): Two-mica granite
Gothenburg (a-c): Red alkali granite

Table 2. Average compositions of uranium-enriched granites

Area	A2	B	C	D	E	F	G
granite	Revsund	Hotagen	Fellingsbro	Bohus	Gothenburg	Götemar	Vånga
n	5	30	4	8	51	12	12
SiO_2	72	76	69	73	73	75	74
TiO_2	0.27	0.15	0.43	0.4	0.4	0.2	0.2
Al_2O_3	15	13	15	13	13	14	14
Fe_2O_3	2.6	0.5	3.5+	1.4	1.0	0.4	0.8
FeO	-	1.1	-	1.3	1.7	0.6	1.2
MnO	0.04	0.04	0.07	0.34	0.05	0.05	0.04
MgO	0.47	0.16	0.8	0.48	0.38	0.75	0.16
CaO	0.82	0.56	1.3	1.5	1.1	0.25	0.8
Na_2O	3.5	3.6	2.9	2.6	3.2	3.9	3.5
K_2O	5.5	5.0	6.9	5.3	5.3	4.8	5.5
H_2O^+	-	0.38	-	0.6	0.6	0.4	0.4
H_2O^-	-	0.15	-	0.2	0.2	0.1	0.2
P_2O_5	-	0.05	-	0.1	0.1	0.03	0.05
CO_2	-	0.03	-	-	0.05	0.05	0.05
F	-	0.14	-	-	0.14	0.43	0.32
S	-	0.02	-	-	0.02	0.02	0.07
BaO	0.08	0.04	0.08	0.17	0.06	0.04	0.02
mol. % $\frac{Al_2O_3}{CaO+Na_2O+K_2O}$	1.14	1.02	1.03	1.04	1.02	1.14	1.05
$\frac{Fe^{3+}}{Fe^{2+}+Fe^{3+}}$	-	0.25	-	0.49	0.36	0.30	0.20
Source	SGU	Troëng & Wilson (in press)	SGU	Asklund (1947)	SGU	Kresten & Chyssler (1976)	Lundegårdh (1978)

+ Total Fe as Fe_2O_3

Table 3. Rb-Sr data on uranium-enriched granites

Area	Granite	Age in Ma	Initial $^{87}Sr/^{86}Sr$	Rb ppm	Sr ppm	Source
A1	Hällnäs	1700±25	0.708±0.002	(Rb/Sr range	1-33)	Welin et al (1977)
A1	Guorbavare	1590±35	0.712±0.002	(Rb/Sr range	2-10)	Welin et al (1977)
B	Hotagen	ca 1500	0.713	414 +	64 +	Klingspor (pers. comm.)
D	Bohus	890±35	0.711±0.003	166-407	57-262	Skiöld (1976)
F	Götemar	1350±35	0.708±0.006	340-775	50-155	Åberg (1978)
G	Karlshamn	1422±31	0.7046±0.0006	(Rb/Sr range	0.2-0.6)	Springer (1980)

\+ SGU analysis

Decay constant used: $\lambda(^{87}Rb) = 1.42 \times 10^{-11}/a$

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* Utgången

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