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Geological setting and geochemistry of uranium-rich granites in the Proterozoic of Sweden

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ABSTRACT. Uraniferous granites occur in several different geological settings in the Swedish Precambrian and represent a variety of granite types and ages. Granites with > 10 ppm U are highly differentiated leucocratic alkali granites with initial $^{87}Sr/^{86}Sr$ ratios over 0.708. They commonly show enrichment in F, Sn, W, and/or Mo, while mineralization of these elements may, in some cases, be found in the nearby country rock. Radiogenic heat from the granites may have assisted hydrothermal circulation. In only one case, Hotagen, is important U mineralization thought to be directly related to a U-rich granite, while the majority of epigenetic U mineralizations with economic potential are related to hydrothermal processes in areas where the bedrock is regionally enhanced in U.

THIS paper presents a summary of the geological setting and geochemistry of anomalously radioactive granites in the Proterozoic of Sweden (see also Wilson and Åkerblom, 1980). It is based on published literature and unpublished documentation from the Geological Survey of Sweden (SGU) and provides an introduction to detailed local studies (Troëng, 1982) and a comparison with geochemically specialized granites in other countries (e.g. Tauson and Kozlov, 1974; Moreau, 1976; Stemprock, 1979; Plant *et al.*, 1980). A major investigation of the Sn, Mo, and W contents of Swedish granites and their relationship to major and trace element concentrations has recently been completed by Armands and Drake (1978), Drake (1980). Although the location of some radioactive granites has been known for many years (Stålhös, 1959) most information has come from airborne radiometric surveying carried out for the purpose of uranium prospecting (Lindén and Åkerblom, 1976) which covers about 40% of the country.

Radioactive granites are currently attracting interest in Sweden because buildings sited on bedrock or soil with more than 25 μR/h radioactivity may contain abnormally high concentration of radon (Åkerblom and Wilson, 1981); these studies are supported by radiometric mapping of various kinds (e.g. Mellander, 1978).

All the known radioactive granites in Sweden occur in the Proterozoic. The areas of Archaean in N. Sweden which have been covered by airborne radiometric survey do not show anomalously high activities and the Caledonian belt contains few granites. The Proterozoic of Sweden ranges in age from over 1900 Ma to about 850 Ma and U enrichment occurs in rocks of all ages and in a variety of geological settings. The geological, geochemical and geochronological information available is of variable quality and coverage: the best information is available for southern Norrbotten (area A1, fig. 1) and from Hotagen (area B). Economic or subeconomic U mineralization occurs in both areas although only in the Hotagen area are the mineralizations thought to be genetically related to the uraniferous granite.

Evolution of the Swedish Proterozoic. The Precambrian of Sweden is described in Lundqvist (1979) and briefly in Rickard (1979). Isotopic age determinations (IUGS recommended contents) are compiled in Welin (1979) and Wilson and Sundin (1979). Magmatic evolution is discussed in Wilson (1980 and in press). The evolution of S. Sweden is described in Gorbatschev (1980), and of northernmost Sweden in Witschard (1980).

The greater part of the Swedish Proterozoic was probably formed between about 2000 Ma and 1500 Ma, while the SW Swedish province formed between 1700 Ma and 850 Ma (Table I). The earliest Proterozoic magmatic activity resulted in the formation of greenstone belts in northern Sweden, probably in the age range 2500-2100 Ma (stage 1). This was followed at about 1900 Ma by a period with 'andinotype' magmatic activity (Pitcher 1979), i.e. calc-alkaline volcanism (stage 2) and I-type granitoids (stage 3). Some of the most differentiated members of these series are enriched in U. Stage 4 was a hercynotype event with metamorphism leading to migmatization and the intrusion of granite diapirs at about 1750 Ma. Several stage 4 granites are enriched in U and in F, Sn, and W.

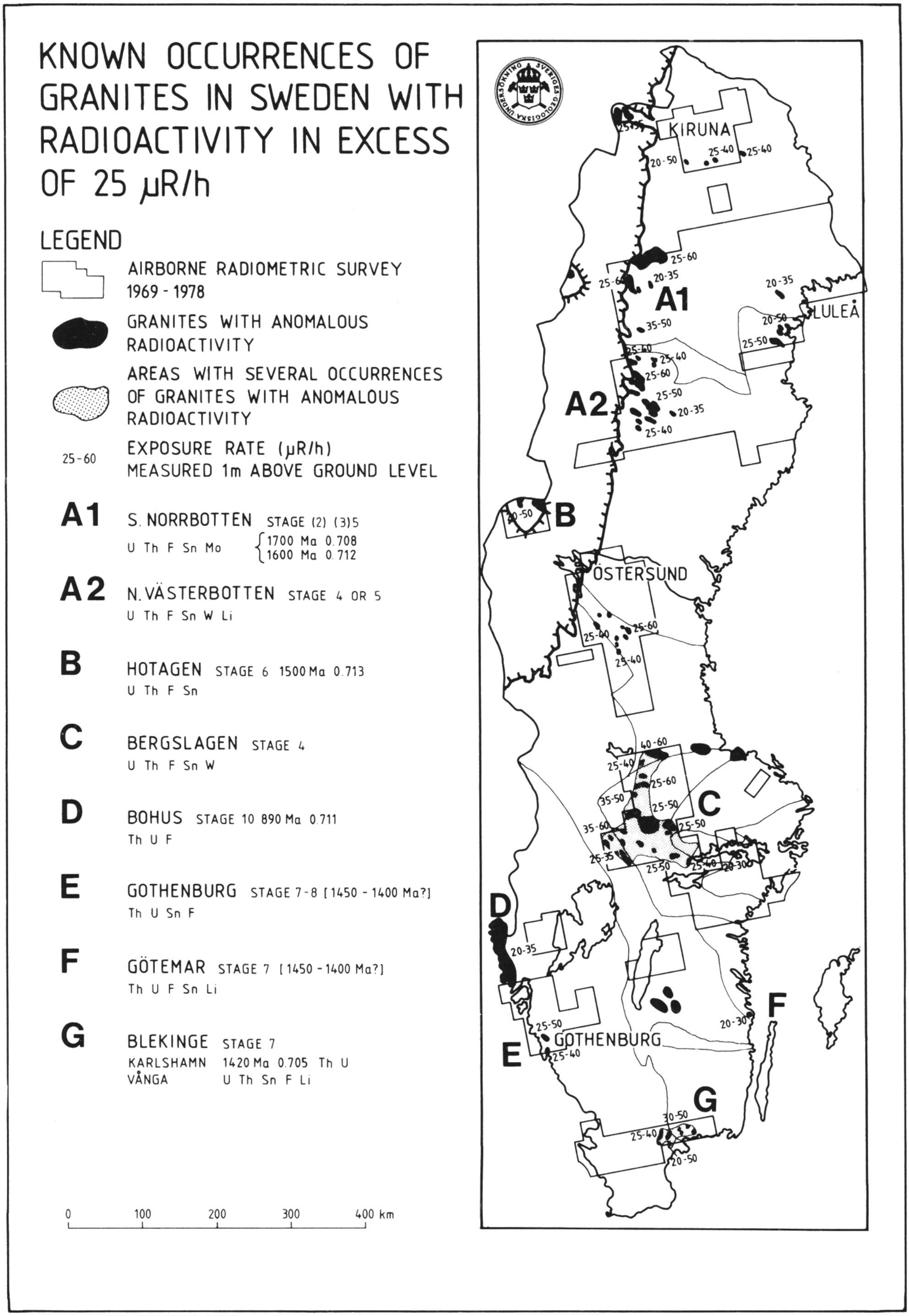

FIG. 1. Locations, ages, initial $^{87}Sr/^{86}Sr$ ratios, stages in Proterozoic evolution and geochemical associations of anomalously radioactive granitoids. Thin lines mark the geological boundaries in fig. 2*a*. Areas A–G are described in the text.

TABLE I. MAGMATIC EVOLUTION OF THE PROTEROZOIC OF SWEDEN

STAGE	DATES	EVENT	MAGMATIC RESPONSE	ROCKS OVER 25 μR/h
10	1000-850 Ma	Uplift	Granites (ss), flexure dykes	Bohus granite
9	1050 Ma	Continental collision & metamorphism		
	Rotation of Scandinavia relative to Greenland & N. America			
8	1220 Ma	Rifting	Basic dykes and sills Granites (ss) in SW Sweden	
7	1450-1400	Metamorphism Collision?	Granites (ss) I-type granitoid suites	Gothenburg, Götemar, Blekinge
6	1550 Ma	Rifting? Tension	Basic dyke swarms Alkali magmatism Rapakivi granites	
5 (north)	1750-1500 Ma	Andinotype	Granites (ss) I-type granitoids & volcanics	Hällnäs, Guorbevare, Björntjärn Dobblon volcanics
5 (south)	1750-1630 Ma	Andinotype	I-type granitoids & Volcanics	
4	1750 Ma	Hercynotype	Metamorphism, granites (ss)	Revsund type in area A2
3	1890 Ma	Andinotype	I-type granitoids	
2	over 1890 Ma	Andinotype	Calc. alkaline volcanics	Rhyolite in area A1
1	over 1890 Ma	Tension/Faulting	Greenstone belts	

Stage 5 magmatic activity suggests a new phase of 'andinotype' orogeny until about 1630 Ma in S. and C. Sweden or 1500 Ma in the former 'continental' area of northernmost Sweden. The stage 5 magmatic rocks in S. and C. Sweden (1750–1630 Ma) are derived from a low Rb–Sr source and do not generally show U enrichment, but the contemporary rocks of N. Sweden which are often derived from older crustal material can be considerably enriched in U, F, Mo, and Sn.

Tension-related magmatism, stage 6, around 1550 Ma (basic dyke swarms, alkaline complexes and gabbros) may relate to rifting prior to the independent evolution of SW Sweden and Blekinge. In SW Sweden the oldest known rocks are about 1700 Ma old and are calc-alkaline (stage 5). Stage 6, 1450–1400 Ma, was a period of extensive magmatism both in SW Sweden and in Blekinge and some of the alkali granites formed at this time are Th, U, F, and Sn enriched. At about 1220 Ma there was further granite intrusion in SW Sweden (stage 8) probably at a time of continental break-up in the initial phases of the Sveconorwegian orogeny. Rotation of Scandinavia in relation to north America and the subsequent collision resulted in a 'hercynotype' orogeny at about 1050 Ma (stage 9). During the subsequent uplift granites of stage 10 were intruded both in SW Sweden and in S. Norway. Many of these granites are U and Th enriched.

A. S. Norrbotten and N. Västerbotten. Magmatic rocks with abnormally high U contents occur in an area some 250 × 70 km, lying immediately east of the Caledonian front. The areas to the north and south have not yet been covered by airborne radiometric survey. The eastern boundary of the region marks a genuine decrease in the radioactivity of the bedrock as determined by airborne survey: the geological reason for this is not apparent.

The two subareas, A1 and A2 show distinct geological and geochemical differences. They are separated to the east by the Skellefte district, an important sulphide ore province. The three subareas represent, from north to south, a continental area, a volcanic arc, and a marine area (Table II).

A1. S. Norrbotten. The S. Norrbotten U province forms the southern margin of an area which was land during the early stages of Svecokarelian development. It comprises a series of belts of supracrustal rocks, mainly basic to acid volcanics (acid rocks predominating), intruded by various granitoids ranging in age from 1900 Ma to 1600 Ma. There are numerous epigenetic U mineralizations (fig. 2*b*), dated to around 1750 Ma, i.e. stage 4, described by Adamek and Wilson (1977, 1979), Guzman *et al.* (1980). These mineralizations are preferentially located in the volcanic belts. Many of the igneous rocks are also characterized by enhanced contents of U. Only the more radioactive granites (> 25 μR/h) are marked on fig. 1. The oldest Proterozoic rocks comprise a calc-alkaline volcanic suite older than 1890 Ma (stage 2). These volcanics are, in the Arvidsjaur area, slightly enriched in U and the most differentiated part, a rhyolitic tuff, contains 15–20 ppm U and 50 ppm Th. They are intruded by the Avaviken granite suite, (stage 3) with a preliminary U–Pb zircon age of 1850 $^{+13}_{-12}$ Ma and a very low initial $^{87}Sr/^{86}Sr$ ratio (Aftalion *et al.*, 1982). The Avaviken granite is the host rock to the Rävaberget epigenetic mineralization (1767$^{+6}_{-8}$ Ma) and is an excellent example of a primorogenic I-type intrusive suite ranging from quartz diorite to granite. Trace element studies demonstrate undisturbed fractional crystallization with linear increase of U from less than 1 ppm in the diorites to over 7 ppm in the most differentiated granites (P. Adamek, pers. comm.). The Th/U ratio is 1.9. The host rock of the Björklund U mineralization (1748$^{+42}_{-30}$ Ma) is a leucocratic alkali granite (alaskite) with 7 ppm U, Th/U 1.7 described in Adamek and Wilson (1979, pp. 359–60, fig. 3 and 4). The siting of both these granites seems to be related to a N–S regional fault zone.

Stage 4 carries deformation and metamorphism which varied in character and intensity over the region and was accompanied by the rise of well-differentiated granite diapirs at around 1750 Ma (e.g. Arvidsjaur, Adak, and possibly Bastusel). These do not show any U or Th enrichment: e.g. Arvidsjaur granite: 5.5 ppm U, 18.7 ppm Th (Müller, 1980); Bastusel diapir: 5.3 ppm U, 27 ppm Th in core, 3.9 ppm U, 27 ppm Th in the outer zone (D'Oliviera, 1979). The emplacement of the epigenetic U mineralization of the region (e.g. Pleutajokk 1738 ± 10 Ma with 6000 tonne U in good grade ore) dates from this period.

Magmatic activity continued in Norrbotten until about 1500 Ma (stage 5) (Welin *et al.*, 1971; Gulson, 1972), with the rise of well-differentiated light granite diapirs carrying very high U and Th contents associated with Mo and W mineralization (Hübner and Einarsson, 1982; Walser and Einarsson, 1982). The only radioactive intrusions actually dated are the Guorbavare granite (1590 ± 35 Ma, initial $^{87}Sr/^{86}Sr$ 0.712 ± 2) which lies directly west of the Pleutajokk U deposit, and the Hällnäs granite (*c.* 1700 ± 25 Ma, initial $^{87}Sr/^{86}Sr$ 0.708 ± 2), (Welin *et al.*, 1977). These granites have high Rb/Sr ratios and their high initial ratios may indicate that they were derived through the anatexis of Rb-rich crustal material. Alternatively their Sr systematics may have been disturbed or kept open by continued hydrothermal activity after intrusion. No other chemical data are available from these intrusions. The Björntjärn granite, with associated economic Mo deposit Allebuoda, is probably of the same generation and has been studied in detail by Armands and Drake (1978). Their data indicate 53 ppm U, 57 ppm Th, 20 ppm Sn, 10 ppm W, high Rb, and low Ba and Sr.

TABLE II. *Regional geological comparisons; N. Västerbotten, Skellefte district, S. Norrbotten*

	A1 S. Norrbotten	Skellefte district	A2 N. Västerbotten
Geology	S. part of Karelian continent prior to 1750 Ma. Continental supracrustals deposited prior to 1750 Ma Archaean basement	Volcanic arc with greywackes pelites, submarine volcanics andesites, dacites, rhyolites pyroclastics, and tuffs	Ocean basin or interarc/backarc basin prior to 1750 Ma. Marine sediments. No known Archaean
Geophysics[1]	Variable Bouguer field	Variable Bouguer field	Strong regional +ve Bouguer anomaly. Uniform low magnetic field
	Magnetic field variable but dominantly magnetic	Banded low magnetic anomalies	Thickest crust in Scandinavia[2]
Mineralization	Epigenetic uranium deposits of economic potential, e.g. Pleutajokk 6000 tonne U[3]	No uranium	Only one minor uranium mineralization
	Economic Mo deposits.[4] Important W mineralization. Minor Sn mineralization. Minor Zn, Pb, Ag, Au showings. Aitik Au–Cu mine	Cu–Zn–Pb–As–S–Ag–Au province with numerous mines	No Mo. Important W mineralization. Important Sn mineralization. Ni deposits to south-east
Geochemistry	Major areas with U, Mo, Sn, Be, and Ag anomalies in peat. Cu, Zn, As, Pb anomalies in restricted areas	Cu, Zn, Pb, As, Ag in peat	Major areas with Sn, W, As in heavy minerals. Cu, Pb, Zn, Ag in minor areas. U in peat

[1] Henkel, pers. comm. [2] Bungham *et al.*, 1980. [3] Gustafsson and Minell, 1977. [4] Hübner and Einarsson, 1982.

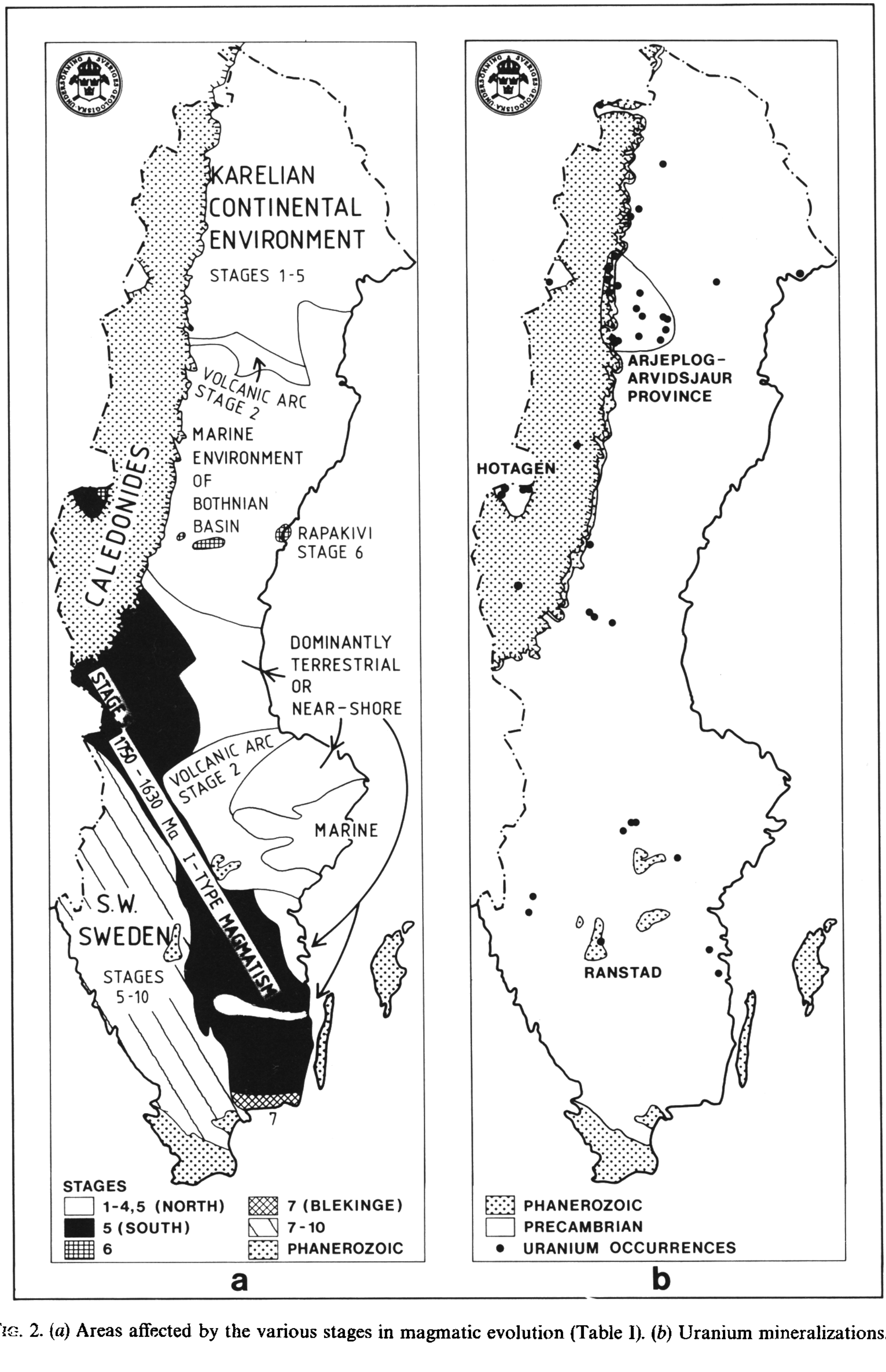

FIG. 2. (*a*) Areas affected by the various stages in magmatic evolution (Table I). (*b*) Uranium mineralizations.

An important post-metamorphic volcanic complex Dobblon (1690±75, initial $^{87}Sr/^{86}Sr$ 0.703±5) is generally slightly anomalous in U, Th, and Mo (8–17 ppm U, 30–40 ppm Th, 50 ppm Mo; Lindroos and Smellie, 1979; Smellie, 1982). Post-depositional enrichment during devitrification resulted in zones with 200–300 ppm U which contain over 4000 tonne U. The maximum U content is about 3000 ppm. In contrast, the youngest granite in S. Norrbotten in the Sorsele granite (1590±45 Ma, 0.708±2; Welin *et al.*, 1971) with U content slightly higher than normal (9 ppm U; Armands and Drake, 1978).

In summary, the S. Norrbotten province shows slight but significant enrichments over the clarke in early calc-alkaline I-type magmatic suites from 1900 Ma and older; important epigenetic U deposits formed at the peak of metamorphism (maximum hydrothermal activity) at around 1750 Ma, and conspicuously high contents of U and other elements occur in some of the late, crustally derived granite diapirs.

A2. N. Västerbotten. The U-enriched granites of N. Västerbotten are intruded into a series of metasediments of marine origin, formed in the north-west part of the Bothnian basin, a major marine area, representing either an ocean basin or an interarc-backarc basin prior to 1750 Ma (fig. 2*a*). This area now shows a uniformly low magnetic field and has a strong positive Bouguer anomaly suggesting that ocean floor might be present not far below the surface. On the other hand the seismic data suggests that this part of the Baltic shield has a very thick crust (Bungham *et al.*, 1980).

The U-enriched granites from the southern part of region A are assigned to the 'Revsund' granite group, representatives of which are the dominant intrusive type in the Bothnian basin of fig. 2*a*. As these granites post-date Svecokarelian metamorphism and deformation, they are regarded as 'post-orogenic' and have given ages around 1750 Ma (Welin *et al.*, 1971, 1977). However, some of the intrusions may be significantly younger and correlate with the late stage 5 granites of S. Norrbotten. The radioactive granites include coarse porphyritic granite (typical 'Revsund'), even-grained granite, and two-mica granite (Table III). While the U content is generally fairly high (10–18 ppm), the Th content is high in the coarse porphyritic granite, but low in the two-mica granite, which has a Th/U ratio of 0.7. The low Th/U ratio is similar to that found in the French two-mica granites (Cuney, pers. comm.). Five analyses from one of the granites indicate highly differentiated peraluminous granite with high SiO_2 and F, Table VI. Important Sn and W mineralization occurs in the vicinity (Hübner and Einarsson, 1982) and analyses by Armands and Drake show high Sn, W, Rb, and Li contents and high differentiation indexes. Earlier workers (e.g.

TABLE III. K, U, Th, *and* Th/U *determined by* SGU *using* in situ *gamma spectrometry*

Area	Granite	n	K%	s	U ppm	s	Th ppm	s	Th/U	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	68			12		41		3.3	(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	29	4.0	(0.3)	12	(5)	65	(14)	5.4	(4)
F	Karlshamn	8	4.6	(0.4)	8	(2)	42	(13)	5.6	(3)
F	Halen	6	5.0	(0.1)	27	(5)	80	(6)	2.9	(3)
F	Jämshög	2	5.0		19		90		4.7	(3)
F	Spinkemåla	4	5.1	(0.3)	18	(1)	58	(7)	3.3	(3)
F	Vånga	5	4.6	(0.3)	15	(5)	47	(5)	3.0	(3)

Sources: (1) Hålenius (pers. comm.); (2) Troëng (1982); (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.

Gavelin, 1955) favoured an S-type origin but more recent mapping supports a deep origin for this suite (see Wilson and Åkerblom, 1980; Wilson, 1980).

Any explanation of the origin of the N. Västerbotten-S. Norrbotten U province must take into account that it lies both on the north and south sides of a major palaeogeographical divide and that, in both the southern and northern parts, equivalent rocks to the east are not enriched in U. One possibility is that the whole province is related to a major mantle heterogeneity, with high U and F.

B. Hotagen. Two granite intrusions in the Precambrian Olden window, located in the Caledonides north of Östersund, have high contents of U (12 ppm) and Th (41 ppm), (Table III). Both show similar chemistry but the eastern granite has a large number of U mineralizations associated with it (fig. 2*b*). This granite has an area of about 16 × 8 km with the most radioactive part forming a circular outcrop area of about 8 km in diameter in the centre of the massif (Troëng, 1982). The granite has an age of about 1500 Ma, an initial $^{87}Sr/^{86}Sr$ ratio of 0.713 (Klingspor and Troëng, 1980), but in other geochemical characteristics (O isotopes, high F, Rb, low K/Rb, Sr, and Ba) appears to be a typical highly differentiated I-type granite.

Hotagen is the only area in which U mineralizations with economic potential are directly related to a U-rich granite. They occur in crush and breccia zones within the granite (Troëng and Wilson, 1981; Troëng, 1982), most notably Lilljuthatten, which contains over 2000 tonne U in high-grade ore and has been dated at 420 ± 5 Ma (Stuckless *et al.*, 1980). U 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. An alternative hypothesis is that pervasive crushing of the granite during Caledonian deformation (probably overthrusting) allowed the development of hydrothermal convection systems driven by radiogenic heat, as in the model proposed by Fehn *et al.* (1978). The granite is known to have a high proportion of leachable U; therefore, the mineralization is due to secondary processes and is not directly related to magmatism.

C. Bergslagen. Bergslagen is an important ore province with many economic deposits of base-metal sulphides, taconitic iron ores, Ag, Au, and W. It is Sweden's most important W province (Ohlsson, 1979; Hübner and Einarsson, 1982). The oldest rocks in Bergslagen are supracrustals belonging to stage 2 and have been interpreted as a volcanic arc system (Rickard, 1979; Löfgren, 1979; Loberg, 1980). They are intruded by a series of anatectic granites belonging to the Malingsbo, Fellingsbro and Enkullen groups, apparently coeval with the main Svecokarelian metamorphism and deformation prior to 1750 Ma (stage 4). These granites usually have high contents of U and Th, especially in their more differentiated parts.

The Bergslagen province is bounded to the west by a belt of younger granites, including the Dala and Filipstad granites (stage 5), some of which are enriched in U. The Malingsbo granite has a medium grain size and red to grey colour. Contacts with the acid volcanics of the country rock are diffuse, with numerous pegmatites. Xenoliths of country rock can be very common and vary considerably in degree of assimilation. Geophysical evidence suggests that the granite is up to 2 km thick (Werner, pers. comm. in Landström *et al.*, 1979). W and Sn mineralizations occur in the

Table IV. K, U, Th, Th/U and heat production values from Landström et al. 1979, 1980.

Area	Granite	n	K %	U ppm	Th ppm	Th/U	HP μWm^{-3}
C	Fellingsbro	20	4.3	8.2	33.4	4.5	4.8
C	Malingsbo	67	4.0	15.7	38.6	3.2	7.1
D	Bohus	69	4.3	9.7	44.3	4.7	6.0
G	Spinkemåla	7	4.6	6.8	42.8	8.1	5.2
G	Halen	9	4.4	23.7	61.1	2.7	10.7
G	Vånga	2	7.8	14	41.5	3.2	6.7

Analytical method: laboratory measurement, U-delayed neutron activation, Th-instrumental activation, K-atomic absorbtion.

HP: radiogenic heat production - the average value for granitic rocks is 2.8 μWm^{-3}.

vicinity of the Malingsbo granite (Ohlsson, 1979) and the Sn and W contents are enhanced (Armands and Drake, 1978). The high radioelement concentration (Tables III and IV; 16 ppm U, 39 ppm Th, 7% K) gives a heat production of twice the average for granitic rocks. This may have been an important factor in encouraging hydrothermal activity in the region, leading to the redistribution of, for example, W within the country rocks.

The Fellingsbro granite has been described by Lundegårdh *et al.* (1972) and Gorbatschev (1972). It is a coarse-grained rock with rectangular phenocrysts of microcline and contains numerous xenoliths of volcanic rock. According to Werner (pers. comm. in Landström *et al.*, 1979) the granite has a considerable root zone, probably 10 km deep and is associated with a marked positive gravity anomaly. Radioelement data appear in Tables III and IV.

Some members of the Filipstad and Dala granite groups also have anomalous U contents. They form part of a major belt of post-Svecokarelian stage 5 granites, with ages of 1750–1630 Ma, showing a wide range of SiO_2 contents and generally low initial $^{87}Sr/^{86}Sr$ ratios. They are I-type granitoids and a deep origin during an andinotype orogenic event is probable. Some of the Filipstad granites show higher initial ratios indicating a varying component of Rb-rich crustal material. The initial Sr composition of the actual U-enriched granites is not known, and there is no abundance data.

D. The Bohus granite. The Bohus granite occupies an area of about 20 × 90 km in SW Sweden but continues into SE Norway and thereby forms part of a major belt of Th- and U-rich granites about 300 km long (Killeen and Heier, 1975). The Bohus granite is a large, flat-lying, sheet-like body probably comprising many separate intrusions (Asklund, 1947; Lind, 1966) within a metasedimentary gneiss environment. Pegmatite veins and schlieren are common and the contact with the gneisses is marked by a major zone of pegmatites. The time of intrusion (890 ± 37, initial $^{87}Sr/^{86}Sr$ 0.711 ± 3; Skiöld, 1976) is coeval with mineral dates from SW Sweden indicating that it was intruded at a time of uplift (stage 10). Granite magma genesis may be through anatexis upon release of pressure (cf. Pitcher, 1979, p. 644). The granite has a restricted range of SiO_2, is peraluminous (Asklund, 1947) and is an excellent example of an S-type granite. In comparison with other U-rich granites the differentiation index is lower (84) and Sn and W are not anomalous. Although all types of Bohus granite are anomalous with respect to Th and U (Table IV), there are considerable variations between the different petrographic types.

E. Gothenburg. A highly radioactive alkali granite probably belonging to the Åmål II unit of Gorbatschev (1975): (stage 7) occurs near Gothenburg. Other Åmål granites are dated to around 1400 Ma. The alkali granite forms a number of thin sheet-like intrusions (Samuelsson, 1980: fig. 1, unit 7). It is rich in U and Th (Table III), has high SiO_2, is slightly peraluminous and has high F, Zr, and Sn, but low K/Rb, Sr, and Ba contents.

F. The Götemar granite. The Götemar granite is an isolated single massif with a diameter of 5 km on the south-east coast of Sweden. Dating of the granite is under revision and it is likely that it is of comparable age to the Blekinge granites: 1450–1400 Ma (Åberg pers. comm.). The whole granite has enhanced Th and U (Table II) and is a highly differentiated leucocratic alkali granite with high F (0.4%), Li, Be, Rb, Mo, and low K/Rb, Ba, and Sr (Kresten and Chyssler, 1976; Armands and Drake, 1978). It has the composition of an eutectic melt at 2 kb H_2O pressure corresponding to an intrusion depth of 7–8 km but is thought by Kresten and Chyssler to be shallower. This could be the result of the high F content affecting the position of the eutectic minimum (Manning, 1980).

G. Blekinge. A 50 × 20 km zone contains a number of radioactive granites probably belonging to stage 7 (Table I). These include the large Karlshamn and smaller Jämshög, Vånga, Spinkemåla and Halen granites to the west. The only reliable dating is from the Karlshamn granite (1422 ± 31 Ma, initial $^{87}Sr/^{86}Sr$ 0.7046 ± 6, Springer, 1980). The Karlshamn granite is calc-alkaline and extreme differentiates in the western part are Th and U enriched (Table III). The eastern half, studied by Springer is less radioactive (4.0 ppm U, 17 ppm Th, Th/U 4.2, measured by laboratory γ-spectrometry). A slightly younger leucocratic intrusion in the eastern part has 5.3 ppm U, 38 ppm Th, Th/U 7.1.

The smaller Blekinge intrusions are thought by Wiklander (1974) and Lundqvist (1979) to be related to the Karlshamn granite but show distinctly different geochemical and geophysical characteristics (Table VI). While samples of the Karlshamn granite show the range of densities and the strong magnetic field typical of calc-alkaline intrusives (I-type granitoids), samples of the other granites have low densities and low or weak magnetic characteristics (Herbert Henkel, pers. comm.). In contrast to the Karlshamn granite the differentiation indexes are high, Rb is high and Ba and Sr are low (Kornfält, pers. comm.). These bodies may represent high-level plumasitic differentiates from a deeper concealed granite. U and Th contents are much higher than in the Karlshamn granite (Tables III and IV). The Vånga granite has been studied by Lundegårdh (1978) who considered that it has been strongly affected by a period of migmatization. It is described as a red microcline granite and has high SiO_2, F and is slightly peraluminous.

Geochemistry

Available major element analyses are presented in Table VI. U, Th, and K values are compiled in Tables III and IV. In addition, major and trace element analyses of over 700 Swedish granites are presented in Armands and Drake (1978). The chemical characteristics of granites with more than 10 ppm U can be summarized as follows:

Major elements. The majority of samples show high SiO_2 and high differentiation index, varying from 84 to 99, with the majority over 88. Analyses cluster over the low-temperature minima of the quartz-feldspar cotectic of the Q-Ab-Or normative diagram in a distribution similar to 507 granitic rocks (Luth *et al.*, 1964). The granites are generally peraluminous: mol $Al_2O_3/(K_2O+Na_2O+CaO)$ is usually greater than 1.0. Simplified variation diagrams for the various granites are given in fig. 3. Plots of TiO_2, MgO and CaO distinguish three groups: (1) Vånga granite (low CaO, MgO and TiO_2), (2) Götemar granite and (3) Fellingsbro, Hotagen, Revsund, 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.

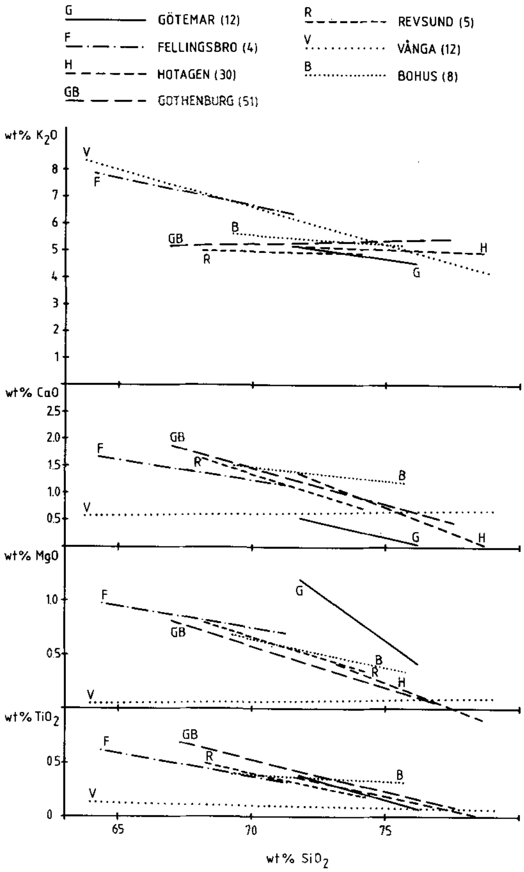

FIG. 3. Simplified variation diagrams. The lines are the best fit through the data. Number of samples indicated after granite name.

Juniper and Kleeman (1979) have summarized earlier work on the composition of Sn-bearing granites and showed that in New England, those granites which produce Sn mineralizations can be distinguished on three diagrams: SiO_2-($CaO+MgO+FeO$)-($Na_2O+K_2O+Al_2O_3$), ($Na+K$)-Fe-Mg and Ca-Na-K. Published analyses of Swedish granites have been plotted on these diagrams by Torbjörn Carlsson (University of Luleå) who suggests that U-enriched granites tend to lie in specific fields, e.g. fig. 4. Results from 5 U-rich and 3 average granites are compared in Table V. These plots confirm that the U-rich granites are alkali-rich leucocratic granites with relatively low Ca. Several granites of similar character plot in the U field without showing enrichment in U (or Sn); for example, the Bastusel granite with less than 5 ppm U. The Ragunda Rapakivi granite analyses plot well within the Sn field: this granite is associated with minor Sn mineralization.

Trace elements. The granites generally show high Rb, low Sr, Ba, and K/Rb. Armands and Drake (1978) have studied both the major and trace element compositions of a large number of Swedish granites and have confirmed the usefulness of ratios adopted by Russian workers, e.g. Ba/Rb, Li/K, K/Rb (Tauson and Kozlov, 1973) in characterizing specialized granites. They also demonstrated that Li and Sn are high in many of the U-rich granites and that W is high in some of them. Similar results are reported from the younger granites of Nigeria by Olade (1980) and Imeokparia (1980). Fluorite is a common accessory mineral and the F content can be as high as 0.5%.

U *and* Th. The U and Th values in Tables III and IV were compiled from independent investigations sampling different parts of these granites. The majority of the granites with over 25μR/h radioactivity have 10-20 ppm U and up to 80 ppm Th. On a Th-U plot (fig. 5) many fall near the Th/U = 3.5 line. Those with low Th/U ratios have higher standard deviations. U dominance is seen in the S. Norrbotten-N. Västerbotten province (A1, A2) and Th dominance in the S. Swedish granites

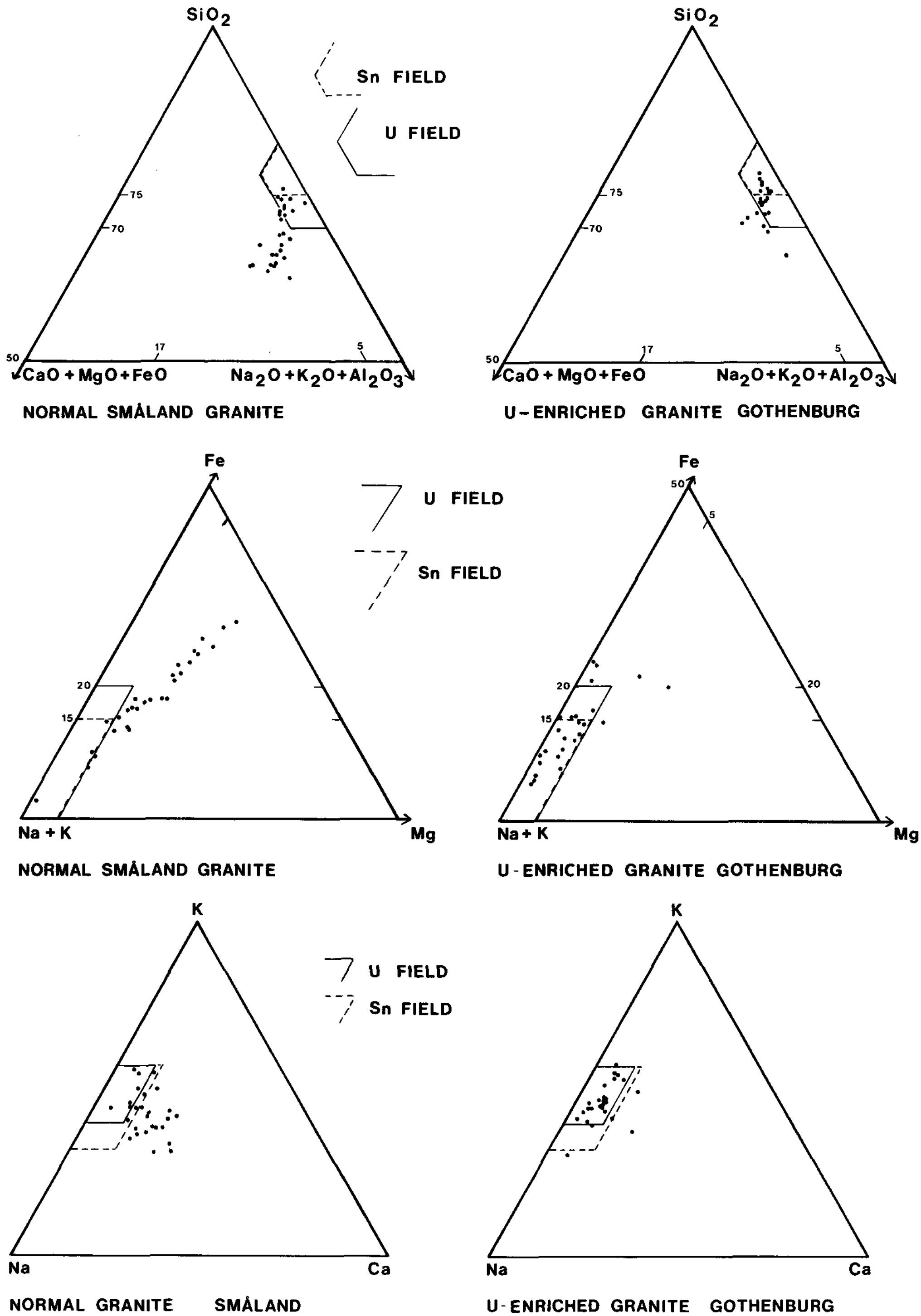

FIG. 4. Major element data on the U-enriched granite from Gothenburg contrasted with that from a normal granite. Småland granite data from Gorbatschev *et al.* (1976). Fields for Sn granites after Juniper and Kleeman (1979), for U granites by T. Carlsson (pers. comm.).

TABLE V. *Major element plots of uraniferous and non-uraniferous granites*

Area	Granite	n	% of analyses falling in uranium field (fig. 4)			Sum out of 300
			$\frac{SiO_2}{CaO+MgO+FeO}$ / $Na_2O+K_2O+Al_2O_3$	$\frac{Na+K}{Fe}$ / Mg	$\frac{Ca}{Na}$ / K	
Uraniferous granites						
B	Hotagen	30	100	90	93	283
D	Bohus	8	75	62	12	150
E	Gothenburg	21	90	90	67	247
F	Götemar	12	100	33	92	225
G	Vånga	9	81	100	100	281
Granites without known uranium enrichment						
	Jörn	15	33	27	20	80
	Perthite	25	32	32	20	92
	Småland	33	30	12	18	60

TABLE VI. *Average compositions of uranium-enriched granites*

Area granite n	A2 Revsund 5	B Hotagen 35	C Fellingsbro 4	D Bohus 8	E Gothenburg 51	F Götemar 12	G Vånga 12	G Karlshamn 40
SiO_2	72	75.2	69	73	73	75	74	65
TiO_2	0.27	0.16	0.43	0.4	0.4	0.2	0.2	0.9
Al_2O_3	15	13.0	15	13	13	14	14	16
Fe_2O_3	2.6	0.4	3.5*	1.4	1.0	0.4	0.8	1.7
FeO	—	1.1	—	1.3	1.7	0.6	1.2	2.5
MnO	0.04	0.04	0.07	0.34	0.05	0.05	0.04	0.11
MgO	0.47	0.18	0.8	0.48	0.38	0.75	0.16	1.01
CaO	0.82	0.6	1.3	1.5	1.1	0.25	0.8	3.13
Na_2O	3.5	3.7	2.9	2.6	3.2	3.9	3.5	3.4
K_2O	5.5	5.1	6.9	5.3	5.3	4.8	5.5	5.1
H_2O^+	—	0.4	—	0.6	0.6	0.4	0.4	
H_2O^-	—	0.1	—	0.2	0.2	0.1	0.2	
P_2O_5	—	0.10	—	0.1	0.1	0.03	0.05	0.38
CO_2	—	0.04	—	—	0.05	0.05	0.05	
F	—	0.17	—	—	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	0.16
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, 1982	SGU	Asklund, 1947	SGU	Kresten and Chyssler, 1976	Lundegårdh, 1978	Springer, 1979

* Total Fe as Fe_2O_3

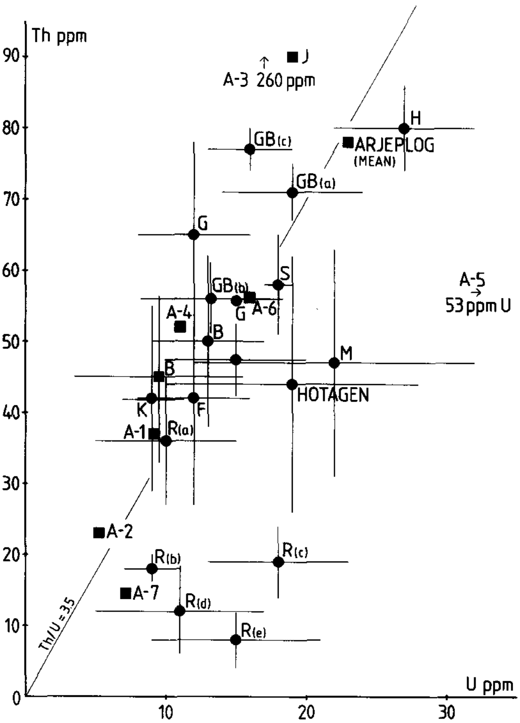

FIG. 5. Average U and Th contents. Circles indicate *in situ* gamma spectrometric data, squares represent neutron activation data from Armands and Drake (1978). Error bars represent standard deviations. A 1-5: Arjeplog (Armands and Drake 1978); B, Bohus; F, Fellingsbro; G, Götemar; GB, Gothenburg; H, Hallen; J, Jämshög; K, Karlshamn; M, Malingsbo; R, Revsund; S, Spinkemåla.

(Bohus, Gothenburg, Götemar, Karlshamn, and Jämshög).

Sr *isotopes*. Available initial $^{87}Sr/^{86}Sr$ ratios are quoted in fig. 1 for granites with more than 10 ppm U. All the well-differentiated granites have high values indicative of a dominantly crustal source, or extensive late-stage alteration. There is little evidence for late-stage interaction with wet sediments: the host rocks of the granites are often volcanic sequences or metamorphic rocks. However many of these granites have very high Rb/Sr ratios, e.g. the Hotagen granite, with Rb/Sr up to 25 (Klingspor and Troëng, 1980). Reactivation of the Sr isotope system in a high-Rb/Sr granite only a short time after intrusion is sufficient to raise the initial ratio considerably. Granites with high radioelement contents can be expected to take several million years to cool because of the radiogenic heat. The hydrothermal systems in these granites would remain active for a longer period and might open or disturb the Rb-Sr systems. This may be the explanation for the fact that U-rich granites commonly have high initial $^{87}Sr/^{86}Sr$ ratios, especially in comparison with non-enriched members of the same suite.

Conclusions

1. U-rich igneous rocks in Sweden range in age from over 1900 Ma to 900 Ma. There is no obvious age pattern in their distribution.
2. U-rich granites were intruded into rocks of continental, marine, and volcanic arc environments. They seem therefore to be independent of palaeogeography.
3. U-rich granites show no apparent relationship to the distribution of Archaean basement.
4. Granites with over 10 ppm U are highly differentiated leucocratic alkali granites with initial $^{87}Sr/^{86}Sr$ ratios over 0.708. This suggests that there is a considerable crustal component involved in their genesis. Their affinities are more with the Hercynian granites of France (Moreau, 1976) than with the U-enriched, more juvenile granites of Scotland (Plant *et al.*, 1980). I-type granitoid suites can be slightly enriched in their most differentiated members.
5. Most of the granites have fluorite as an accessory mineral; Sn and W are enriched in several; and Sn, W or Mo deposits and mineralization are associated with several in S. Norrbotten, N. Västerbotten and Bergslagen. The radiogenic heat may be of considerable importance in encouraging hydrothermal processes. Existing radiometric surveys should be of great use to the Sn, W, and Mo prospector.
6. Despite radioactive granites covering large areas in N. Västerbotten, Bohus, Bergslagen, Gothenburg, and Blekinge no U mineralization worth follow-up have been discovered in these regions.
7. U mineralization in the S. Norrbotten and Hotagen areas is believed to be related to metamorphogenic hydrothermal processes in areas of enhanced U background.
8. The high initial $^{87}Sr/^{86}Sr$ ratios commonly observed in U-enriched granites may be the result of the extra radiogenic heat keeping the Sr-isotope system open for a longer than normal period. As U-enriched granites commonly have high Rb/Sr ratios this could have a dramatic effect in increasing the initial $^{87}Sr/^{86}Sr$ ratio.

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