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Uranium-rich granites in the Olden window, Sweden

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ABSTRACT. U-enriched granites occur in a Precambrian window in the Caledonides of central Sweden and intrude an extensive supracrustal formation dominated by acid terrestrial volcanics. During the Caledonian orogeny, thrusting, foliation, mylonites, and mesoscopic folds developed in the Precambrian rocks under low-grade metamorphic conditions. Ground and airborne γ-spectrometry indicate U-enrichment mainly in the northern part of the window where two uraniferous granites have been intruded. Several small U vein-type mineralizations are associated with one of the granites. The largest occurrence of the mineralization might be economic, and a Rb-Sr age determination has established a minimum age of 1500 Ma on the associated granite which is highly evolved.

URANIFEROUS granites in the Olden window are being investigated as part of a regional U prospecting programme carried out by the Geological Survey of Sweden (SGU). The Olden window, in the Central Scandinavian Caledonides, is one of the anticlines along the Swedish-Norwegian border where the Precambrian basement of the Caledonian alltochthon is exposed (fig. 1). Geological mapping of the Precambrian basement, which is composed mostly of acid to intermediate volcanics, micrograrites, and biotite granites, is almost complete and a regional geochemical study of the rocks is in progress. The granites, some of which are anomalously high in U and Th and contain important occurrences of vein-type U-mineralization, have been investigated in more detail. This paper briefly describes the geology of the area and more detailed studies on the granites, with particular reference to the Olden intrusion and the genesis of U mineralization, are presented.

Geological setting

The geological evolution of the Olden window has been discussed by Troëng and Wilson (in press) and is summarized in Table I. More than half of the *c.*1400 km^2 area of the Olden window in Sweden comprises terrestrial volcanic supracrustals (fig. 2). These rocks are considered to be the oldest and range from rhyolitic to dacitic in composition with the former predominant. Small occurrences of sulphide mineralization are probably associated with the volcanic activity.

The volcanics are associated with fine-grained, porphyritic microgranites which may represent the hypabyssal equivalents of the supracrustals formed during the same event. The association is reminiscent of the Precambrian Subjotnian lithologies south-east of the Caledonian front in central Sweden (Lundqvist 1968).

Three medium- to coarse-grained granites, the Olden, Björkvattnet and Lappluvan intrusions are emplaced into volcanics in the north-eastern, north-western, and south-eastern parts of the window respectively, and are associated locally with small occurrences of sulphide mineralization. A Rb-Sr whole-rock age determination on seven samples from the Olden granite gives only scattered data points but they lie about a 1500 Ma line with

TABLE I. Geological evolution of the Olden Window

Time		Stratigraphy		Deformation	Metallogeny
PALEOZOIC			METAMORPHISM	D_5 Subvertical fracturing	U
				D_4 (?) Doming of Olden Window	
		Greywacke		D_3 Post-nappe crenulation folding	
				D_2 Overthrusting	
		Limestone		D_1 Pre-nappe folding	
		Black shale			
		Quartzite			Zn, Pb
PRECAMBRIAN	? 1200 Ma	Intrusion of mafic dykes			
	c. 1500 Ma	Intrusion of granites			Pb, As, Cu, Zn
		Extrusion of volcanic sequence			Pb, Cu

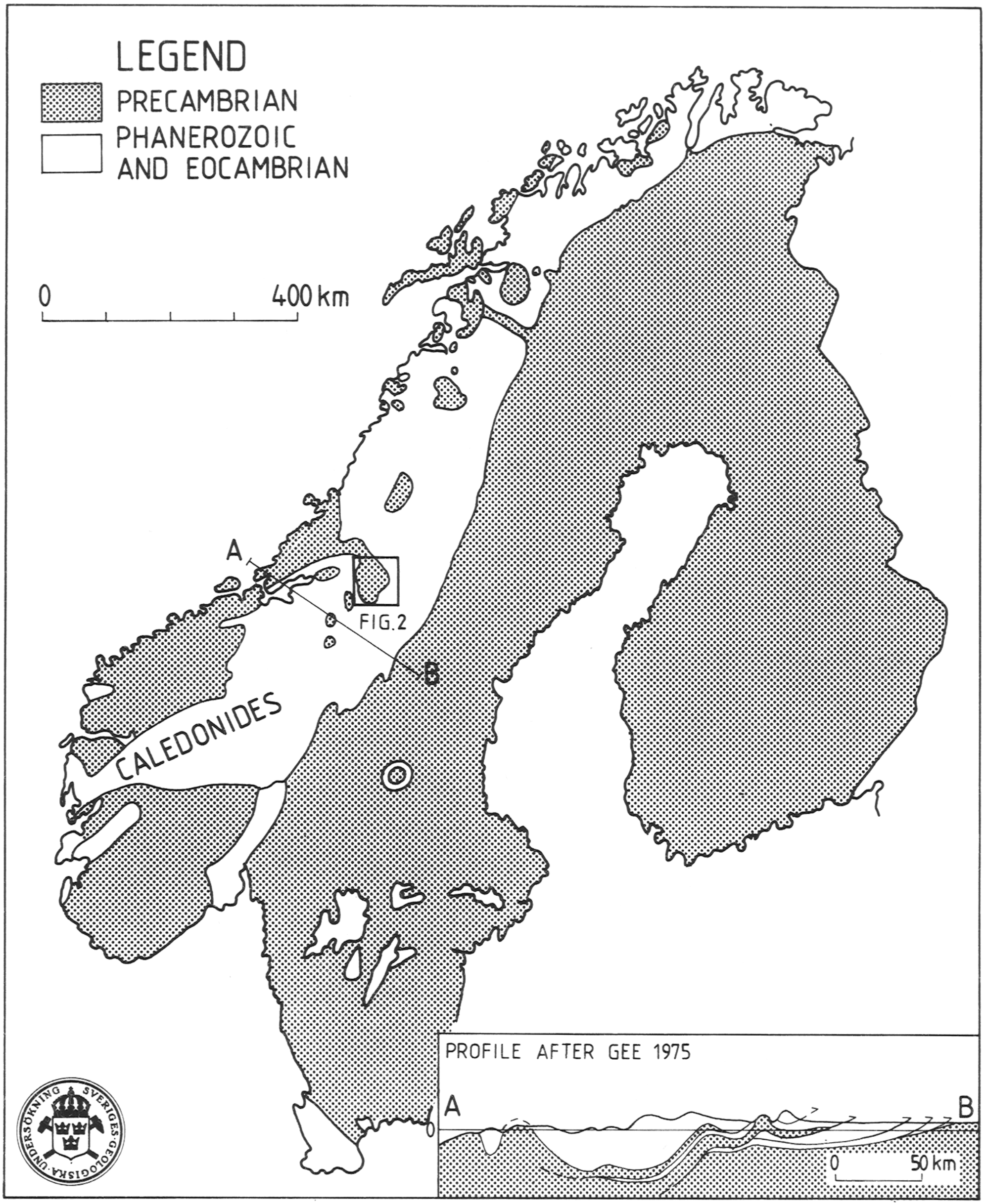

FIG. 1. Sketch map of Scandinavia showing the location of the Olden and other basement windows within the Caledonides.

an initial $^{87}Sr/^{86}Sr$ ratio of 0.7134 ± 0.0012 (Klingspor and Troëng, 1980). Intrusion of basic dolerite dykes and lopolithic bodies followed consolidation of the granitic intrusions and before deposition of late Precambrian sediments.

A sequence of quartzite, black shale, limestone, and greywacke was deposited from the late Precambrian to Ordovician. Primary sedimentary contacts delineated by thin conglomeratic horizons are preserved locally along the eastern contact of the Olden window (Walser 1980, Asklund 1960) but only one outlier of the Caledonian cover sequence is found in the window. Small occurrences of sulphide mineralization in the basal quartzite locally penetrate the upper part of the granitic basement.

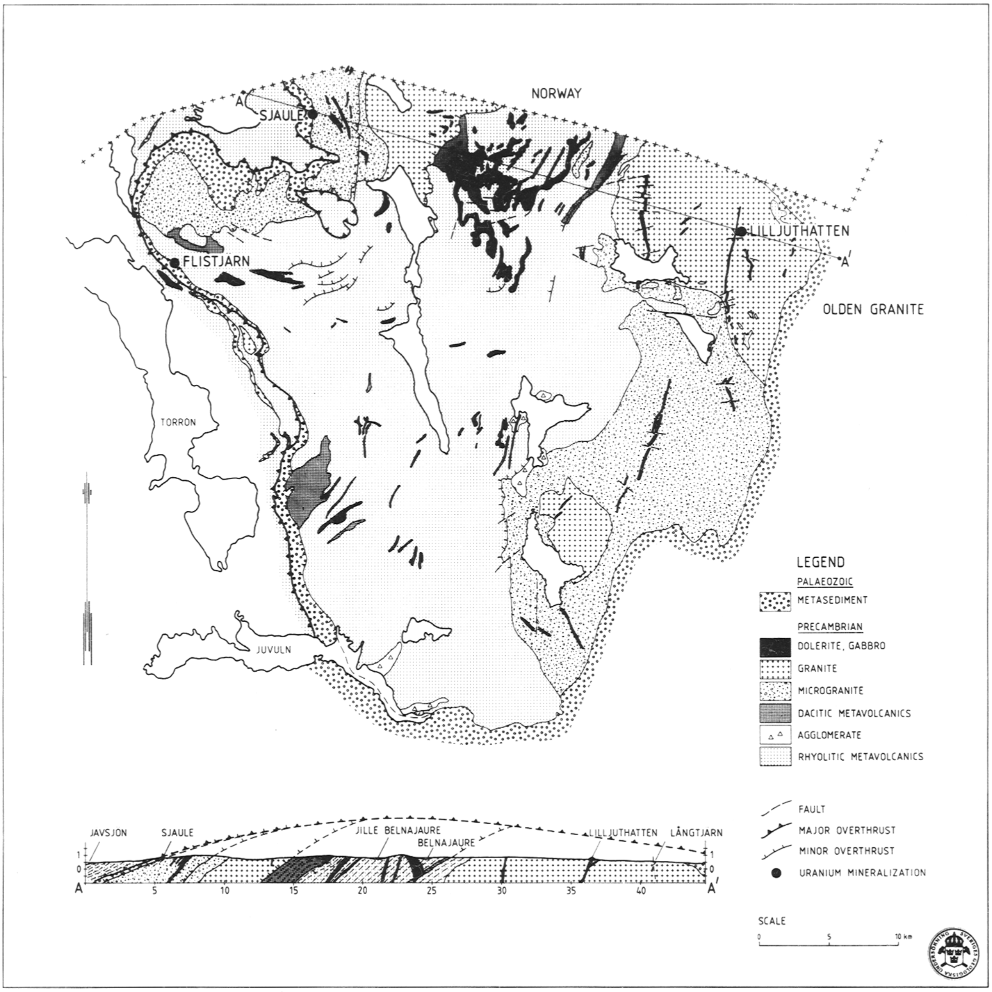

FIG. 2. Geological map of the Olden window.

The first episode of deformation occurred in the Precambrian or as a Caledonian pre-thrusting event. Thrusting towards the east began in Silurian times associated with folding, mylonitization, and the development of a regional schistosity mainly in the volcanic rocks. Later deformation refolded earlier structures, affecting both the basement and Palaeozoic rocks and gentle doming of the Olden window occurred.

The last deformational episode was characterized by the formation of subvertical fracture zones and faults, some of which are associated with epigenetic uranium mineralization.

The Caledonian metamorphism reached greenschist facies in the basement. Occasionally garnets have formed in volcanic rocks and granites and also as very small, euhedral, post-tectonic crystals in the Caledonian mylonites. A garnet-biotite geothermometry study indicated a metamorphic temperature of around 350 °C (Harrisson, 1979).

The Olden granite

Petrography. Some petrographic aspects of the Olden granite have been described previously (Troëng and Wilson, in press; Klingspor and Troëng, 1980). In summary, it is a coarse- to medium-grained, commonly porphyritic rock with almost equal amounts of quartz, plagioclase, and K-feldspar. The mafic minerals, which seldom exceed 6% of volume, are mostly biotite with subordinate chlorite, epidote, sphene, and allanite.

The granite is cut by numerous fracture zones and joints and locally a weak gneissose texture is developed. In thin section the feldspars are commonly fractured and the quartz is partly to completely recrystallized.

A simplified mineral paragenesis of the complex is given in fig. 3. A magmatic, a metamorphic, and a hydrothermal stage are distinguished. Stage I is characterized by the crystallization of the main rock-forming minerals. The perthitic K-feldspars are large (generally ranging in size from 1 to 15 mm), often optically zoned and with inclusions of quartz and plagioclase. The optical zonation and distribution of quartz and feldspar inclusions is parallel to the crystallographic orientation of the perthites. Other common inclusions are biotite and chlorite. The quartz and plagioclase inclusions indicate that the K-feldspar crystallized later than primary plagioclase and quartz. Furthermore K-feldspar has sometimes nucleated on primary plagioclase or replaces it. These textures may be due to K-feldspar growth in stage II.

Plagioclase (generally 1 mm to 6 mm in size and An_5 to An_{15} in composition) has minor quartz inclusions. Optical zoning is usually reflected by a partly sericitized core within a relatively unaltered rim. The occurrence of euhedral to subhedral plagioclase grains of smaller size and with less sericitization than the primary varieties suggesting more than one generation of plagioclase. In addition, growth of secondary plagioclase is observed. Quartz growth occurred during all three stages of the paragenetic sequence.

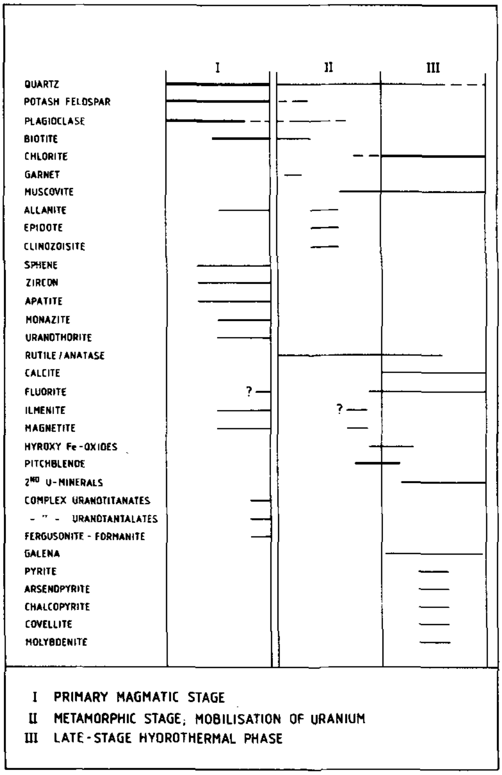

FIG. 3. Paragenetic table showing the crystallization sequence in the Olden granite. Bar thicknesses represent relative mineral abundances.

The primary distribution of mafic and accessory minerals is difficult to interpret since they were strongly affected by the metamorphic stage. The mafic constituents are present as interstitial aggregates within the dominant feldspar–quartz rock fabric. Primary biotite, preserved as unaltered cores in partial pseudomorphs, often contains sphene, zircon, apatite, allanite, magnetite, and ilmenite inclusions. The zircons are often optically zoned suggesting U-enriched rims. Monazite, uranothorite, fergusonite–formanite series, and complex uranotitanates and uranotantalates, the composition of which are not precisely known, occur within aggregates of recrystallized mafic minerals. The uranothorite is occasionally observed in sphene crystals associated with a radial fracture network caused during metamictization.

Late-stage magmatic fluids probably gave rise to such phases as chlorite, epidote, and fluorite.

During prograde metamorphism (stage II) occasional garnets have formed in sericite-rich intergranular patches or fractures within the larger K-feldspars. Quartz continued to be mobilized and, as discussed above, additional generations of plagioclase and possibly K-feldspar formed, producing complex hybrid textures and compositions. The primary biotite has partly recrystallized to fine-grained scaly aggregates of dark brown iron-rich biotite associated with allanite, epidote-clinozoisite, sphene, and magnetite. Sphene and allanite frequently occur in cleavage planes of primary biotite as well as in recrystallized clusters of other mafic minerals. Sphene and allanite occur together as lamellar intergrowths and in replacement textures.

During the later stages of metamorphism the biotite has preferentially broken down to muscovite with subsidiary magnetite and ilmenite. Subsequently, sporadic alteration of sphene and ilmenite has given rise to tiny aggregates of rutile or anatase, or both, and the magnetite has been partly oxidized to hematite. Towards the end of stage II, U-bearing oxidizing solutions penetrated the granite along crush zones and fractures. The crush zones, filled with recrystallized biotite and alteration products, like chlorite and sericite, provided a reducing environment for U precipitation mostly as pitchblende.

The late-stage hydrothermal episode (stage III) is characterized by mobilization of quartz, and the development of chlorite, muscovite (mostly as sericite), fluorite, and small amounts of calcite in fractures in K-feldspar and plagioclase. Fe, U, and radiogenic Pb have been mobilized from the mineralized zones and occur respectively as hydroxy Fe-oxides, galena and uranium secondaries which include beta-uranophane, uranophane, boltwoodite and vandendriesscheite (R. Löfvendahl in press). Fluorite, as a later phase, is associated with several minor U occurrences in the Olden granite but only exceptionally within the most important mineralization, Lilljuthatten. Minor amounts of sulphides occur sporadically in the granite.

TABLE II. Compositional ranges of 35 samples from the Olden Granite.

Constituent	Mean	Standard deviation	Compositional range
SiO_2	75.2	2.2	67.9 - 78.6
TiO_2	0.16	0.9,	0.00 - 0.36
Al_2O_3	13.0	0.9	11.7 - 16.2
Fe_2O_3	0.4	0.3	0.0 - 1.6
FeO	1.1	0.4	0.4 - 2.0
MnO	0.04	0.02	0.0 - 0.06
CaO	0.6	0.4	0.0 - 1.6
MgO	0.18	0.18	0.0 - 0.71
Na_2O	3.7	0.4	3.1 - 4.8
K_2O	5.1	0.4	4.4 - 6.7
H_2O+	0.4	0.1	0.1 - 0.6
H_2O-	0.1	0.06	0.0 - 0.3
P_2O_5	0.10	0.2	0.0 - 0.44
CO_2	0.04	0.03	0.0 - 0.13
F	0.17	0.13	0.02 - 0.48
S	0.02		
BaO	0.04	0.02	0.0 - 0.08

Classification. Thirty-five samples of the Olden granite have been analysed for major elements (Table II) and seven representative samples have been modally analysed. The minor variation in the composition of the granite is reflected by the low standard deviations. The chemistry of the granite, especially the contents of silica, alkalis, fluorine, and the low barium content, is consistent with an alkali granitic composition (Nockolds *et al.*, 1978). The majority of samples have An/Or ratios below 0.11 (average 0.05) which correspond closest to the field of an alkali feldspar granite (Streckeisen, 1976) consistent with the amount of normative quartz, the sum of alkalis and differentiation index values.

In contrast, the modal analyses are consistent with a monzogranite composition (Streckeisen, 1967). The results differ, however, from those reported by Troëng and Wilson (in press), where the percentage of K-feldspar was estimated to be substantially more (fig. 4). The perthitic nature of the K-feldspars, their metamorphic alteration and the absence of quantitative chemical analyses of the feldspars, makes identification difficult. These difficulties were partly resolved by etching with sodium cobaltinitrate (after Reid, 1969) but the

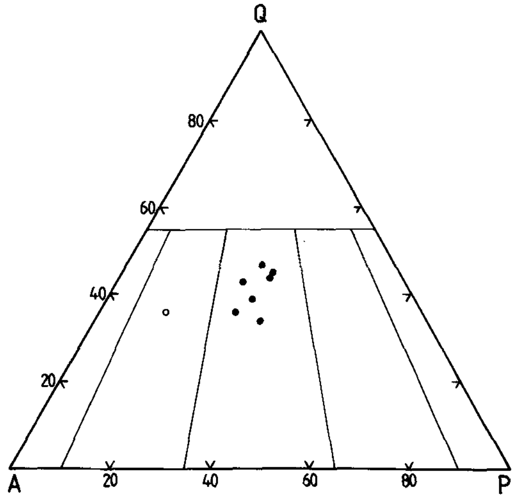

FIG. 4. Modal classification of seven samples from the Olden granite following Streckeisen (1967). Open circle represents the average modal analyses from Troëng and Wilson (in press).

discrepancy between modal and normative classification remains.

This is probably explained by the formation of secondary albite with a low anorthite component during the metamorphic stage. The secondary albite, without analyses is difficult to distinguish from the primary variety and consequently plotted samples will be displaced towards the P corner of the Q-A-P diagram (fig. 4).

Whole-rock geochemistry. Chemical parameters indicate that the Olden granite is derived from a highly evolved magma source. Rb, Sr and K/Rb ratio averages have been calculated from seven samples used for age determinations (Klingspor and Troëng, 1980). Compared to the granite averages reported by Taylor (1964), the Olden values for Rb (413 ppm), Sr (65 ppm), and K/Rb (107), indicate that Rb is significantly enriched and Sr impoverished. The high Rb content in relation to K and Sr suggests that the granite is highly differentiated, consistent with the high differentiation index (Thornton and Tuttle, 1960) ranging between 86 and 99 (average of 94 ± 3) and the *REE* pattern (fig. 5) which has large negative Eu anomalies suggesting partial melting of an evolved source with plagioclase as a residual phase (J. S. Stuckless, pers. comm.). The anomalously high contents of such incompatible elements as U and Th also indicate a high degree of evolution. A plot of alumina saturation (Shand, 1951) shows that the samples fall along the metaluminous–peraluminous dividing line with only a slight tendency to fall into the peraluminous field. A plot on the Q-Ab-Or ternary diagram (fig. 6) shows a composition which is closer to granite than to alumina-oversaturated granite (Luth *et al.*, 1974). The lack of a strong peraluminous tendency is more commonly associated granites derived from an igneous (I-type) than from a sedimentary source (S-type) (Chappel and White, 1974; White and Chappel, 1977). Other parameters that support an I-type origin include the generally high Fe-oxidation ratios, normative corundum values which average 0.9 wt. %, the high sodium content, and preliminary oxygen isotope data (J. S. Stuckless, pers. comm.).

However, the granite has a high initial $^{87}Sr/^{86}Sr$ ratio (0.7134) and a high and restricted SiO_2 content supporting a sedimentary origin. Thus according to the classification of Chappel and White (1974) the Olden granite has characteristics which support both an I- and a S-type origin.

Distribution of U, Th, *and* K

An airborne γ-spectrometer survey using the method described by Lindén and Åkerblom (1976) has been carried out over the Olden window and the relative distribution of U (in arbitrary units) is shown in fig. 7. The high concentrations of U in the two northern granites are clearly shown, while the southern granite shows no U enrichment. There is a general increase of U towards the northern half of the Olden window. The granites are not distinguished from the metavolcanics on the Th/U distribution map.

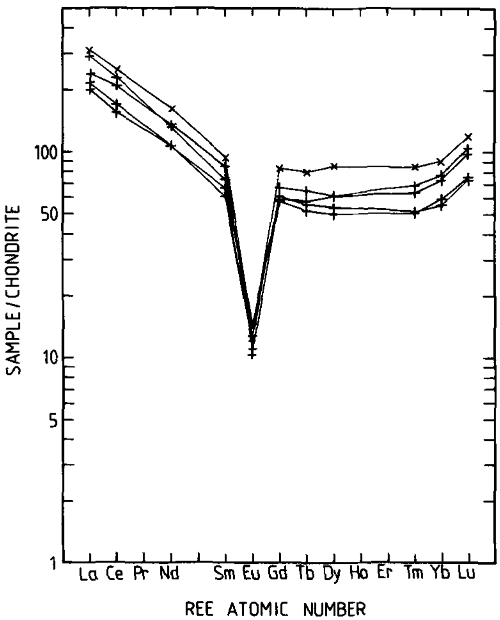

FIG. 5. Chondrite-normalized *REE* patterns for five unmineralized samples of the Olden granite.

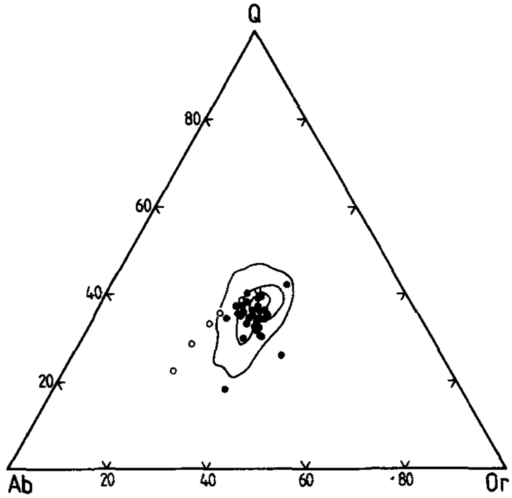

FIG. 6. Ternary plot of normative quartz, albite, and orthoclase for thirty-five samples of the Olden granite. Open circles represent the minimum melt composition for the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O for pressures of 0.5, 1.0, 2.0, 3.0 (Tuttle and Bowen, 1958) and of 5.0, 10.0 kb (Luth *et al.*, 1964). The contours represent granites after Luth *et al.* (1964).

The airborne survey has been followed up by ground spectrometry and the distribution of U and Th within and around the three granites is illustrated in figs. 8-10. As discussed above the variation in potassium is small in the Olden granite and accordingly the distribution of potassium shows no significant trends in the Olden or the two other granites, consistent with geochemical and mineralogical observations on the Olden granite.

Olden granite. The correlation between U and Th in the southern part of the Olden granite is good (fig. 8). However, within the most anomalous area to the east, Th is more evenly distributed than U, possibly because of the greater mobility of the latter. Areas of highest U and Th are generally associated with the coarsest granite.

Average U and Th contents determined from 68 spectrometer measurements are 12.5 ppm eU and 41.4 ppm Th respectively with a eU/Th ratio of 0.30. A radiographic and mineralogical study of the U- and Th-bearing minerals in the granites and volcanics is in progress and the following minerals have been qualitatively identified in the Olden granite: allanite, monazite-cheralite series, uranothorite, thorite-huttonite-thorogummite series, fergusonite-formanite series, zircon, weakly active epidote, and a complex series of uraniferous niobates-tantalates-titanates.

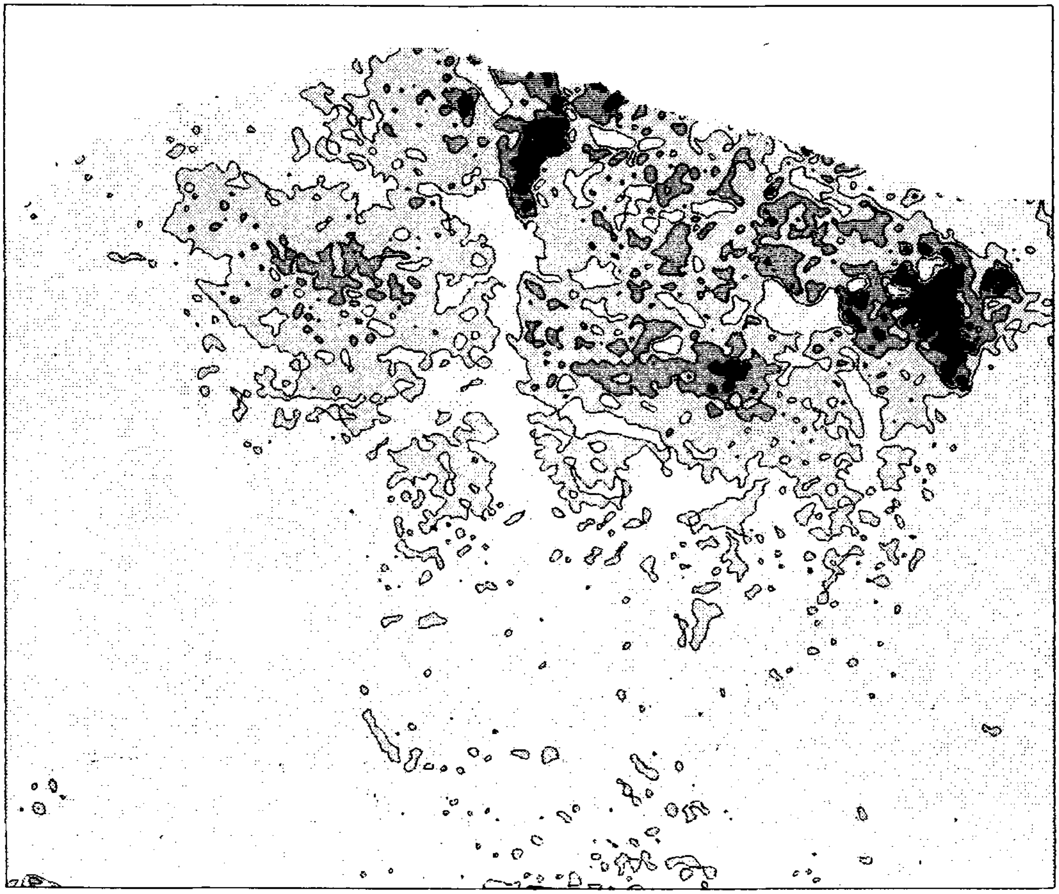

FIG. 7. Relative distribution of U from airborne spectrometry measurements over the Olden window. Darker areas represent higher U contents.

Björkvattnet granite. In the Björkvattnet granite, which is similar to the Olden granite, the areas of highest U and Th are associated with the coarsest granite (fig. 9). The high U and Th areas appear to cross the boundary between granite and volcanics (fig. 9) but this is a feature of the computer program used to 'smooth' the data.

Average U and Th contents determined from 27 spectrometer measurements are 19.0 ppm eU and 45.4 ppm Th with a eU/Th ratio of 0.42 U- and Th-bearing minerals in this granite include allanite, uranothorite, thorite-huttonite-thorogummite series, zircon, and weakly active epidote.

Lappluvan granite. The Lappluvan granite is not significantly enriched in U or Th and there are no significant distribution patterns (fig. 10). U and Th averages 5.3 ppm eU and 22.2 ppm Th with a eU/Th ratio of 0.26 from seventeen measured points. Allanite and zircon are so far the only U- and Th-bearing minerals identified.

Uranium mineralization

One important and several minor uranium deposits occur in the north-eastern and north-western part of the Olden window. To the north-east mineralization is associated with altered crush zones and joints in the central part of the Olden granite, whilst in the north-west the host rocks are mainly meta-volcanics. According to Troëng and Wilson (in press) the two most important occurrences of mineralization in the north-west, Sjaule and Flistjärn (fig. 2), are characterized by colloform pitchblende infilling sub-vertical north-east trending joints. The mineralized structures extend from the Precambrian basement into the thin pile of allochthonous Caledonian units, indicating a post-thrusting age for the mineralization.

The largest U deposit in the Olden granite, Lilljuthatten, is presently being investigated by drilling and preliminary results indicate some 1800

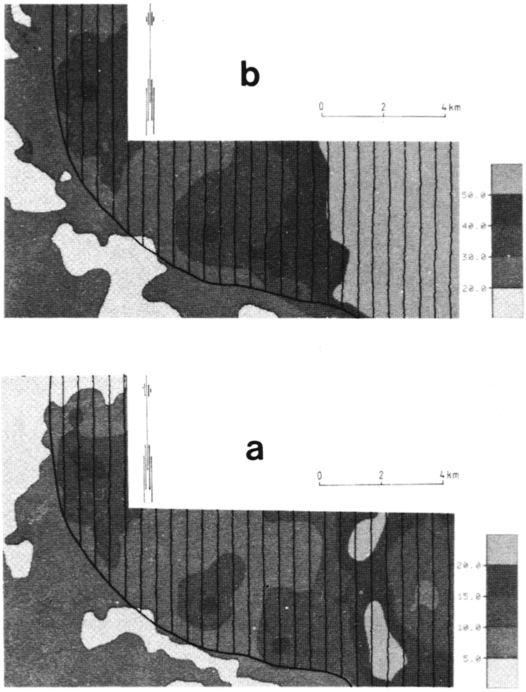

FIG. 8. U (a) and Th (b) distributions within the southern part of the Olden granite. Ruled area marks the granite and values are in ppm.

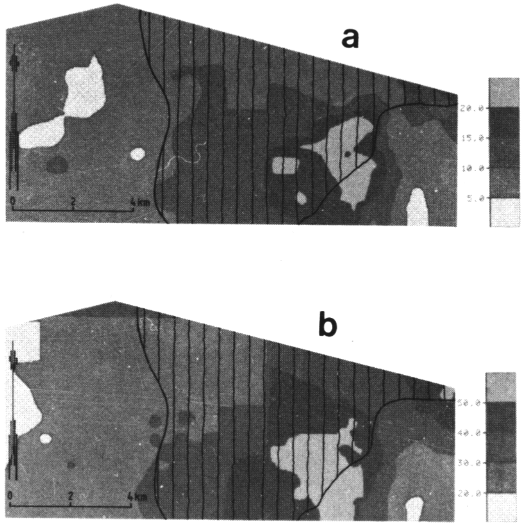

FIG. 9. U (a) and Th (b) distributions within the Björkvattnet granite. Ruled area marks the granite and values are in ppm.

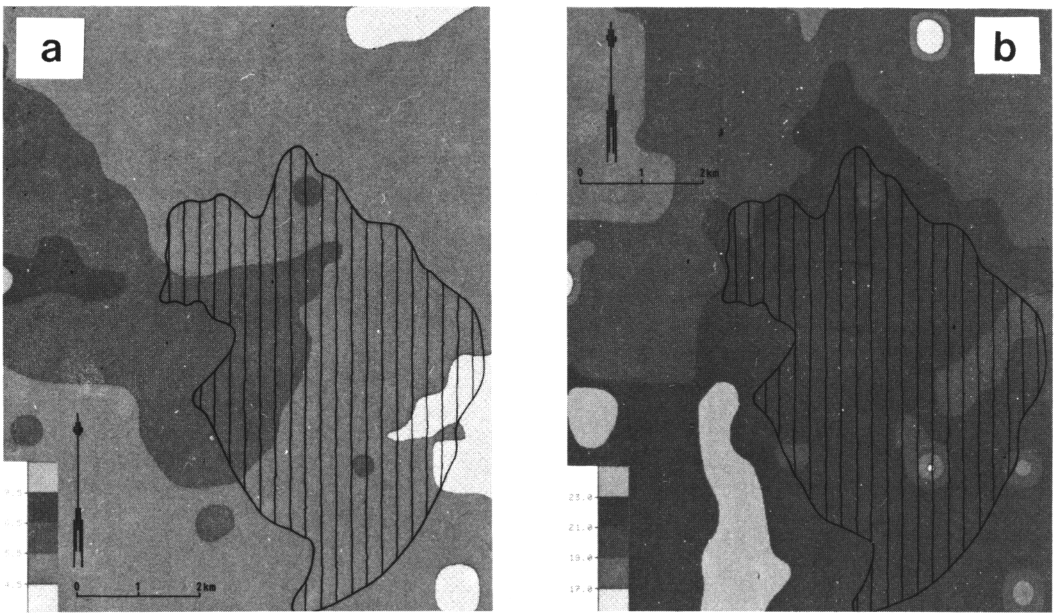

FIG. 10. U (a) and Th (b) distributions within the Lappluvan granite. Ruled area marks the granite and values are in ppm.

tonnes U of high grade ore. The U, dominantly in the form of pitchblende, is structurally controlled by NE trending, subvertical, mafic-enriched fracture zones close to an approximately N-S striking dolerite dyke. The most extensive part of the mineralization is found to the north-east of the dyke but smaller occurrences are present both within the dyke and on its south-western side. The depth of the known deposit does not exceed 90 m from the surface.

Preliminary investigations of the geochemical variations in the granite approaching the mineralized fracture zones have been carried out. Samples from two drill cores through the mineralized body were analysed for major and trace elements. Results from one of the drill cores are summarized in fig. 11. Unfortunately the high U content in the fractures interferes with the trace element analyses for the mineralized zones and these have not therefore been included. The U distribution is positively correlated with K, Al, Fe, Mg (fig. 11), and P (not shown in diagram); Si shows a negative correlation. Na behaves similarly to Si (Troëng and Wilson, in press) although not evident from these drill cores. The variations are best explained by examining the mineralogy of the mineralized zones. As discussed above, the fracture zones were probably rich in biotite, chlorite, and sericite prior to the introduction of the U-bearing solutions.

Permeation of the fracture zones by U-rich oxidizing solutions, and precipitation of the U by these minerals would be reflected by a positive correlation of U with K, Al, Fe, and Mg. The oxidation ratio might also be expected to increase over the mineralization, and this seems to be the case for the profiles examined.

Isotope studies

Rb–Sr whole-rock analyses of the Olden granite have been carried out by Klingspor and Troëng (1980) and Stuckless *et al.* (1980). The latter study gives an approximate age of 1540 Ma although two samples near the Lilljuthatten ore zone have been reset to much younger apparent ages. Isotope systematics of the Th–Pb and U–Pb systems are complex, but U–Pb data for a few samples suggest a host-rock age of approximately 1500 Ma (Stuckless *et al.*, 1980).

Analyses of five mineralized and five unmineralized samples from drill core cutting the Lilljuthatten mineralization, give an apparent Pb-Pb age of 420 ± 5 Ma (errors at 95% confidence level) (J. S. Stuckless, pers. comm.). This supports the geological observations that the Lilljuthatten mineralization was formed from U leached from the Olden granite by hydrothermal fluids during the Caledonian.

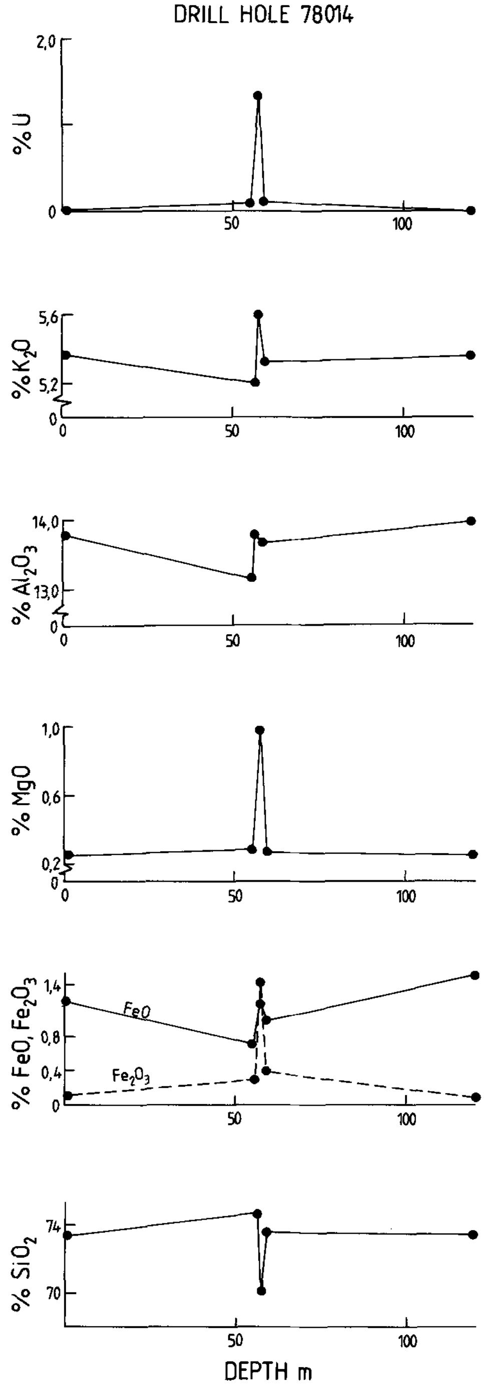

FIG. 11. Variations of some major elements in drill core 78014 over a mineralized fracture zone.

Genetic implications

The two granites with high U and Th contents intruded about 1500 Ma ago might be regionally correlated either with the Rapakivi granites of central Sweden or the I-type granitoids of the 1500-1750 Ma episode (Wilson and Åkerblom, 1982). The Olden granite exhibits most of the geochemical characteristics typical of other U-enriched granites in Sweden including high SiO_2, high $^{87}Sr/^{86}Sr$ ratios, high differentiation indices, high alkali contents, high F and Rb, and low Ca, Ba, and Sr (Wilson and Åkerblom, 1982).

Both granites contain anomalously high U and Th in the coarsest portions which probably represent late-stage differentiates. Comparison of the two granites shows the Olden granite to have a slightly lower U content than the Björkvattnet granite. The primary magmatic distribution of U may be attributed to variations in oxygen fugacity (Saha *et al.*, 1970) and a high oxygen fugacity would tend to leach U, resulting in variations in the granite. However, the lower U content (and the lower eU/Th ratios; the Th content is approximately the same in both granites) within the Olden granite is probably best explained by the concentration of the U into mineralized zones which do not occur in the Björkvattnet granite. This is supported by the findings of Saunders (1979) who has identified characteristics of potential U provinces using aerial gamma-ray spectrometer surveys which include a high mean eU and low mean eU/Th and eU/K ratios. The former is considered to indicate conditions potentially favourable for the geochemical concentration of U, whilst the latter indicates that U concentration has occurred previously.

It is not known if the difference in the degree of mineralization between the Olden and Björkvattnet granite is due to varying degrees of U leachability, which depend on uranium mineralogy, the availability of solutions capable of dissolving and transporting (probably as complexes), channels for fluid migration and conditions for the precipitation of uranium. A recent investigation (L. Nilsson, pers. comm.) has shown that U was easily and effectively leached from the Olden granite. Thus the Olden granite appears to have been a favourable source for U. In contrast the U in the Björkvattnet granite mostly occurs in such minerals as uranothorite, which are equally common in the Olden granite. It is suggested that the brittle deformation of the Olden granite, which contrasted with the more plastic deformation of the Björkvattnet granite, was a critical factor in the behaviour of uranium.

The solutions responsible for the mobilization and concentration of U into the existing deposits in the Olden granite, are thought to have been oxidizing carbonate- and fluorine-rich and formed as a result of the rise in temperature during and after the Caledonian thrusting or, alternatively, that radiogenic heat has been responsible for the development of hydrothermal convection systems. Cataclasis of the Olden granite would have created a permeable system for solutions to circulate according to the model proposed by Fehn *et al.* (1978).

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