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Uranium content, distribution, and migration in the Glendessarry syenite, Inverness-shire

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ABSTRACT. The distribution of uranium in a suite of variably deformed and metamorphosed rocks from the leucocratic member of the Glendessarry syenite has been determined using the fission track method. The uranium content of the magma increased during crystallization and uranium was concentrated in accessory minerals such as monazite, zircon, sphene, allanite, apatite, and micro-inclusions of a Zr- and Ti-rich phase. Contamination of the magma by pelitic metasediment enhanced the uranium content and monazite and zircon formed instead of sphene, allanite, and apatite.

Evidence of subsolidus uranium mobility in late stage magmatic or metamorphic fluids is presented here and shows: (*a*) Intracrystalline redistribution of uranium, especially in grains of sphene. (*b*) Intergranular mobility in a fluid phase, which affected the uraniferous accessory minerals in several ways.

STUDIES of the behaviour of uranium during high-grade metamorphism have recently gained importance and large-ion lithophile element depletion in some granulite-facies terrains is relatively well established (e.g. Lambert and Heier, 1967); however, the processes responsible for uranium mobility are still under discussion (Collerson and Fryer, 1978; Fyfe, 1973). The interest in high-grade metamorphic terrains in genetic studies of ore-forming processes concerns their role as a source region for upper crustal uranium deposits (e.g. Kostov, 1977), and their influence on the formation and subsequent evolution of U-provinces.

The Glendessarry syenite is suitable for detailed studies for the following reasons: (*a*) It is a product of deep-seated processes. (*b*) Intrusion occurred at a low crustal level. (*c*) Amphibolite-facies metamorphism contemporaneous with intrusion affected the complex to varying degrees. (*d*) Uranium is concentrated in a limited number of accessory minerals, some of which commonly occur in the lower crust.

A comparative investigation of metamorphosed and non-metamorphosed phases of the complex was undertaken in relation to studies of uraniferous accessory minerals. Johnstone *et al.* (1969) described the regional setting of the syenite (fig. 1) and its emplacement in high-grade psammitic and pelitic Moinian metasediments. Lambert *et al.* (1964) established the magmatic origin and syn- or slightly pretectonic timing of the intrusion and Van Breeman *et al.* (1979) reported a U-Pb isotopic age of 456 ± 5 Ma and proposed a mantle origin. A detailed petrological study was carried out by Richardson (1968), who ascribed mineralogical changes (summarized in Table I) to an influx of H_2-rich, reducing fluids from sediments during amphibolite-facies deformation.

A suite of twelve samples of the leucosyenite was selected to represent different stages of metamorphism/deformation. Polished thin sections were used for induced fission track analysis of ^{235}U (Bowie *et al.*, 1973) with a neutron dose of $5 \times 10^{16} n\ cm^{-2}$, undertaken at the HERALD reactor AWRE, Aldermaston. Lexan polycarbonate plastic is the preferred detector because of its low uranium content; the detector discs were etched in 6*N* NaOH at 75 °C for four minutes. Rock powders were analysed by the delayed neutron method (Bowie *et al.*, 1973).

Results

General

Most of the uranium is located in accessory minerals, which in decreasing order of U content are: Zr/Ti rich inclusions in perthite; monazite-

TABLE I. *Summary of relevant mineralogical changes in the syenite due to amphibolite facies-metamorphism. After Richardson (1968)*

Original Mineralogy	Effects of metamorphism
Alkali feldspar phenocrysts	Granular orthoclase and sodic plagioclase
Pyroxene-biotite intergrowths	Hydration to ultimately pyroxene-free, hornblende-biotite associations
Accessory calcite	Calcite absent
Euhedral sphene	Recrystallization and loss of crystal outlines
Coarse-grained igneous texture	Development of well-defined fabric and diminution of grain size

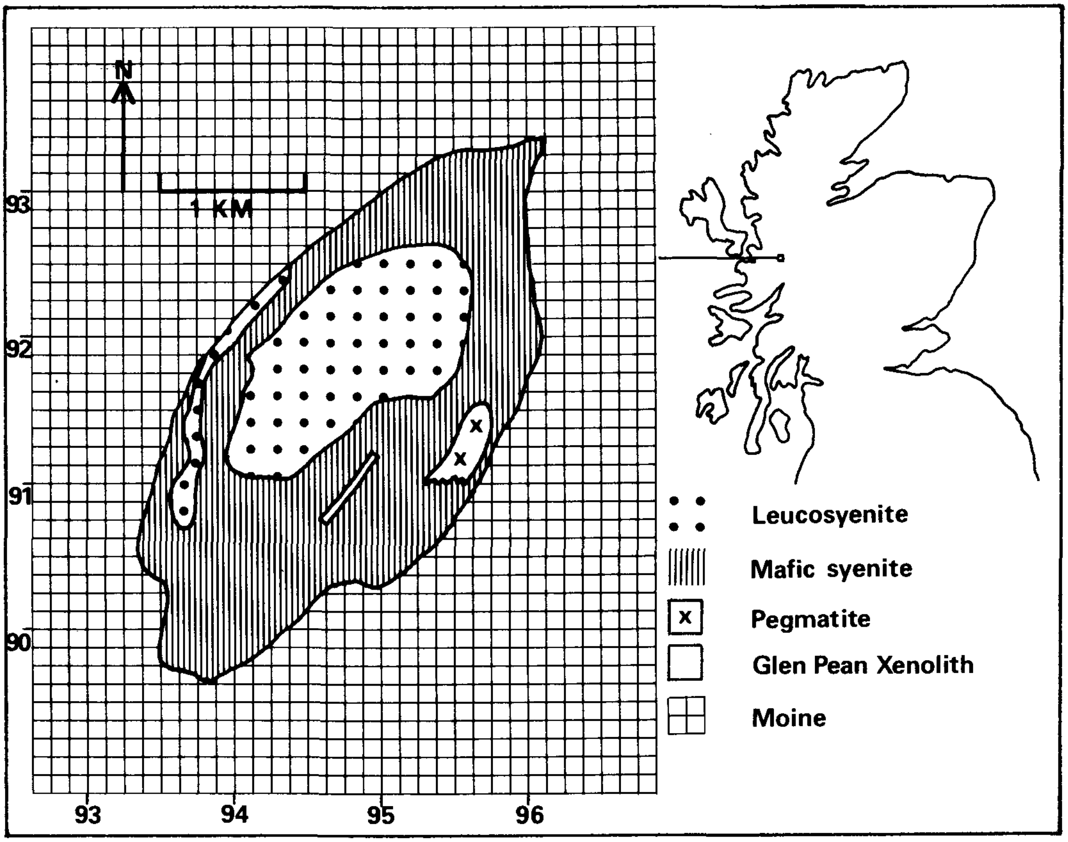

FIG. 1. Geological map of the Glendessarry syenite, Inverness-shire.

zircon; sphene–allanite; and apatite, which is in general agreement with previously published data (Rogers and Adams, 1969). Uranium is not significantly associated with the primary rock-forming minerals or absorbed on grain boundaries.

The primary uranium distribution

All the leucocratic rocks at Glendessarry exhibit some metamorphic/deformation effects. However, samples from the centre of the leucosyenite mass show least post-magmatic recrystallization and the distribution of uranium in relict euhedral minerals from this phase is thought to be relatively unmodified by secondary processes. In these rocks uranium is associated with the Zr/Ti rich inclusions, zircon, sphene, allanite, and apatite. Its distribution in the latter three principal uraniferous minerals is shown in fig. 2*A*. Most sphene and apatite crystals have uniform fission track distributions, but the track density varies between crystals. Since other sphene grains show an increase in uranium concentration towards the edges (fig. 2*B*), those uniform crystals with greater abundance are considered to have formed later indicating increased uranium concentration in the residual magma, as recorded by other workers (e.g. Bohse *et al.*, 1974). Both uniform and regularly zoned U distributions indicate solid solution of uranium within the crystal lattice.

In a vein intruded into the Glen Pean Xenolith (fig. 1), zircon occurs with monazite and together they contain a high proportion of the whole-rock uranium (fig. 2*C*) of 7.8 ppm. This rock, composed of perthite associated with biotite, muscovite, and quartz, with minor pyrite indicative of more reducing conditions of crystallization than the leucosyenites in which primary hematite formed (Richardson, 1968), may be the product of contamination of the magma by country-rock metasediment.

Secondary uranium redistribution

Redistribution of uranium within the syenites, sometimes directly related to the hornblende-rich, foliated members of the suite, is interpreted below

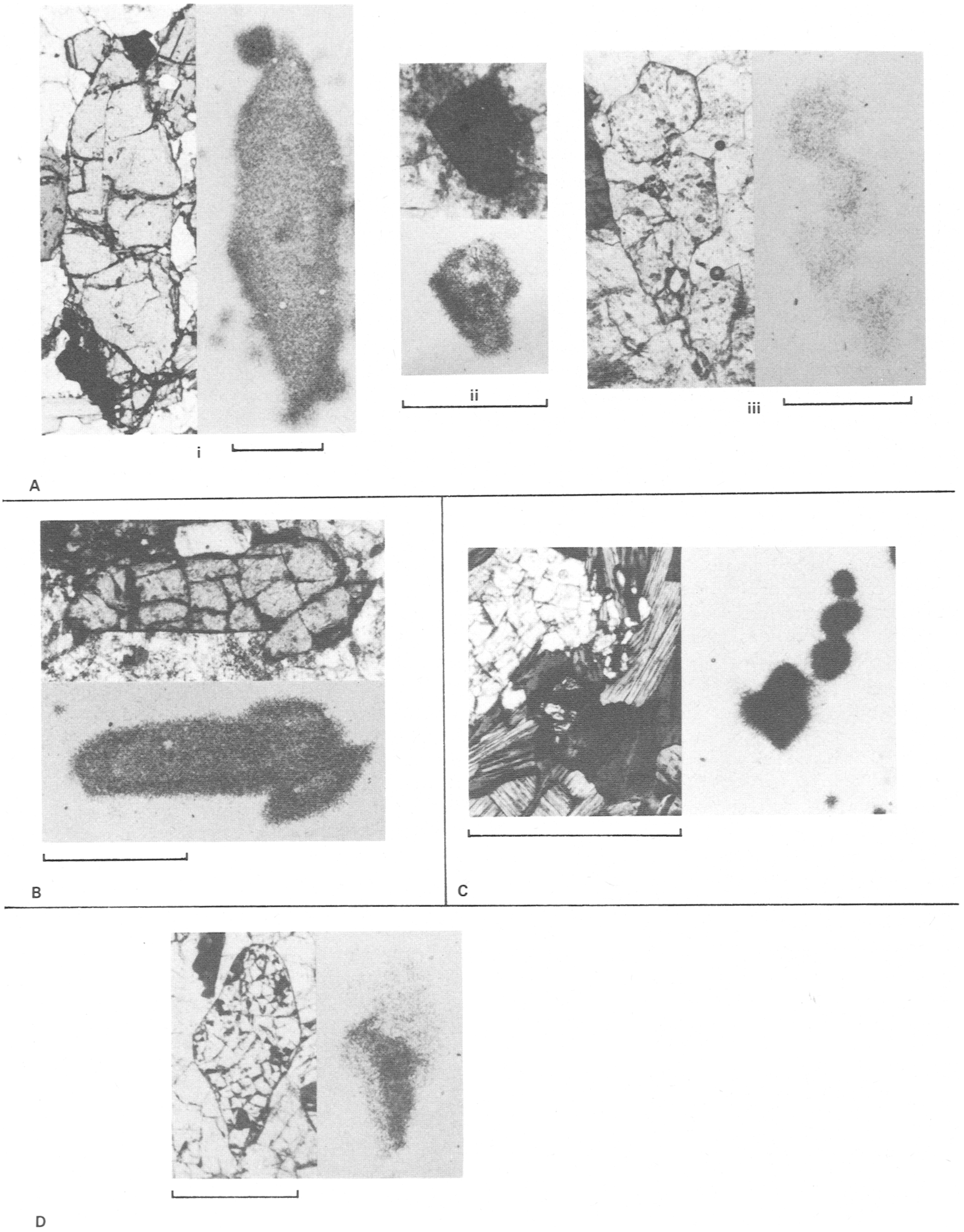

FIG. 2. Photomicrograph–Lexan plastic overlay pairs showing: *A*. i. Sphene, ii. Allanite, iii. Apatite. *B*. Sphene with regular zoning of uranium. *C*. Uraniferous accessories in syenitic vein intruded into the Glen Pean xenolith–zircon and monazite in biotite associated with feldspar. *D*. Apatite grain with an irregular, U-rich core. Scale bar = 0.5 mm.

in the light of three possibilities (cf. Clark *et al.*, 1979). (i) New mineral growth associated with addition of U. (ii) U addition or loss with no new mineral growth. (iii) Internal U mobility and concentration.

The uranium-bearing accessory minerals are described below in relation to uranium redistribution:

Apatite. A cluster of apatite, sphene, allanite, and biotite crystals in alkali feldspar is shown in fig. 3*A*. The corresponding fission track distribution contains linear areas with lower track density (relative to the host apatites) which correspond to intergrain boundaries. Other apatites are irregularly zoned (fig. 2*D*) with uranium-poor rims—the inverse of the expected magmatic trend. The simplest interpretation of both these features involves uranium scavenging by an intergranular fluid phase.

Sphene. Large (up to 1 cm), euhedral grains of sphene respond to deformation by loss of their crystal outlines and diminution of grain size, associated with recrystallization and rotation into concordance with the developing fabric. Some grains thus affected possess zones with high uranium concentration as indicated by the variable track density (fig. 3*B*). Isochemical recrystallization accompanied by internal uranium mobility may have been accompanied by addition of uranium from an intergranular fluid. The development of a heterogeneous uranium distribution in sphene associated with an elevated whole-rock uranium content (Table II) suggests that such late addition of uranium may be responsible for the variation shown.

Sphene in recrystallized samples forms overgrowths on iron oxide as a result of its interaction with plagioclase feldspar. Since neither precursor is uraniferous and the overgrowths are significantly enriched in uranium (fig. 3*C*), the presence of a subsolidus fluid phase capable of uranium transport may again be inferred.

Allanite. In the least deformed members of the suite, allanite is rare but has a euhedral habit sometimes associated with strong colour zoning. It is more abundant in the hornblende-rich leucosyenite where secondary allanite is usually more uraniferous than its primary analogue, and may also have an inhomogeneous uranium distribution (fig. 3*D*). Allanite also occurs as reaction rims on apatite, probably related to the circulation of uranium and *RE*-bearing fluids within the syenite.

TABLE II. *Relationship of whole-rock uranium content to its occurrence in sphene*

Field no.	U (ppm)	Uranium distribution in sphene grains
42774	1.3	uniform or regular zonation (magmatic)
42778	1.5	
42780	1.1	
42781	1.8	
45660	1.3	
45670	1.5	
48474	1.2	
42791	1.9	zones of high uranium content in one or more grains
45662	1.9	
45671	2.4	
45672	2.8	

Discussion

Although the uranium content of these rocks is concentrated in the accessory magmatic minerals, there is substantial evidence for its transport during sub-solidus fluid migration. The uraniferous phases reacted to this process in different ways: for example, uranium was leached from apatite although there is evidence for its concentration in sphene; most allanite is secondary, fixing formerly mobile uranium, but zircon has embayments (Van Breeman *et al.*, 1979) indicative of corrosion and uranium release. Such varying responses may be due to fundamental differences resulting from the physico-chemical nature of the minerals themselves, or to chemical evolution of the fluid. Although Richardson (1968) documented the interaction of the syenite with H_2-rich, reducing country-rock fluids, late-stage magmatic fluids may also have been involved, particularly in view of the syntectonic nature of the syenites. Redistributive processes may be similar to the incipient stages of the model proposed by Simpson *et al.* (1979) and Plant *et al.* (1980) for the formation of mineralized granites (*s.l.*) from their metalliferous precursors.

Questions raised by this study include: (i) The extent to which processes demonstrated by fission track radiography result directly from amphibolite-facies metamorphism. (ii) The source of the secondary uranium and its possible transport by an intergranular fluid phase. (iii) The chemical composition of the fluid and speciation of the uranium. (iv) The extent to which the development of high uranium zones in sphene was an iso-chemical process.

Conclusions

Features of the primary uranium distribution are preserved in the least-deformed syenites, and these suggest that the magmatic uranium content increased during crystallization. Most of the uranium present in these rocks is concentrated in six minor or accessory minerals: Zr/Ti-rich inclusions, monazite, zircon, sphene, allanite, and apatite. Metasediment contamination at the magmatic stage produced a different suite of urani-

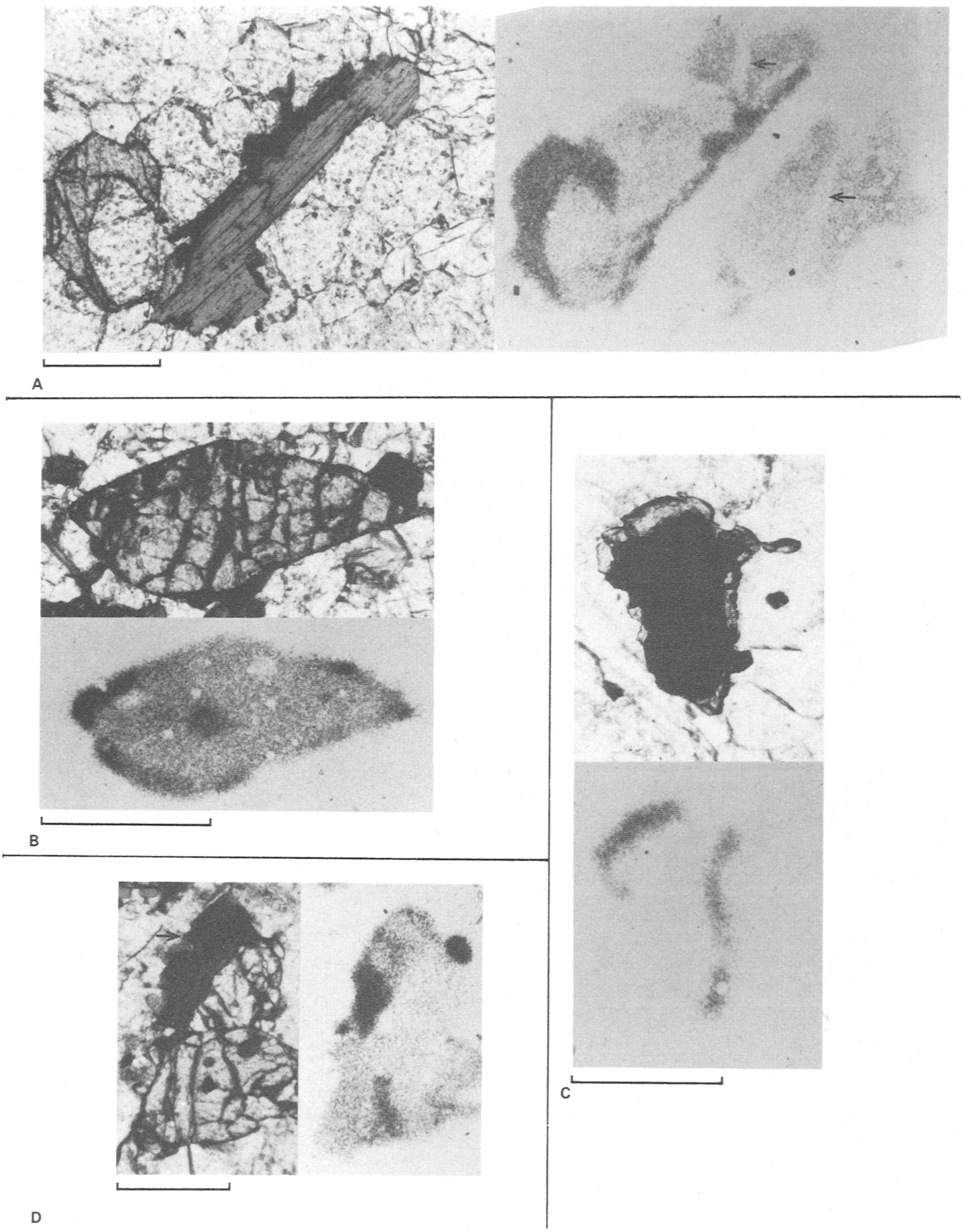

FIG. 3. Photomicrograph–Lexan plastic overlay pairs showing: *A*. Areas of low fission track density (arrowed) associated with grain boundaries in apatite. *B*. High fission track density indicating local uranium concentrations in sphene. *C*. Secondary, U-bearing sphene reaction rims on iron oxide phase enclosed in feldspar. *D*. Allanite (arrowed) with variable track density associated with apatite. Sphene in lower half of the photograph and U-rich zircon (top right) are also present. Scale bar = 0.5 mm.

ferous accessories and a higher whole-rock uranium content. Secondary uranium mobility has occurred on at least two scales: (*a*) Intracrystalline movement of uranium which produced zones of high uranium content and general variation in uranium distribution. (*b*) Uranium movement in solution causing depletion of uranium in apatite and precipitation of secondary uranium bearing mineral phases, such as allanite.

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