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Uranium and thorium geochemistry in the Elberton batholith of the Southern Appalachians, USA

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ABSTRACT. U and Th data have been obtained by γ-ray spectrometry on samples from thirty quarry sites in the Elberton batholith, a large (500 km^2) late orogenic (320 Ma) mesozonal biotite granite in the Southern Piedmont, USA. The granite is enriched in the Th ($\bar{X} = 42$ ppm), but U contents ($\bar{X} = 3$ ppm) are close to the average abundance for granites (18 ppm Th; 4 ppm U). Th/U ratios vary widely throughout the batholith, ranging from 3 to 58, with an unusually high mean of 18 ± 10 (1). At some localities, lower Th/U ratios, high U contents of zircons (1500 ppm), and similarities to two-mica granites which have low Th/U ratios of ~ 1 indicate that the granite once had a much higher U content. Pegmatites are enriched in U (up to a factor of 8), but Th contents are low (by a factor of 3) compared with the granite suggesting loss of U from the granite by an early magmatic vapour-phase. Significant U loss may also have occurred as a result of groundwater leaching, possibly associated with uplift and weathering of the intrusion 200 Ma ago. The highest Th/U values occur in the upper portions of the batholith, consistent with the hypothesis of U loss by these processes. The U content is highly variable throughout the batholith but Th is more uniform, both regionally and at outcrop. The distribution of Th does not correlate with patterns shown using previously published, $^{18}O/^{16}O$, $^{87}Sr/^{86}Sr$, or trace element (Ba, Rb. Sr, Mn) data, which are thought to reflect inhomogeneity in the protolith of the granite although the possibility that at least some of the isotopic ratios were disturbed by late alteration processes cannot be eliminated.

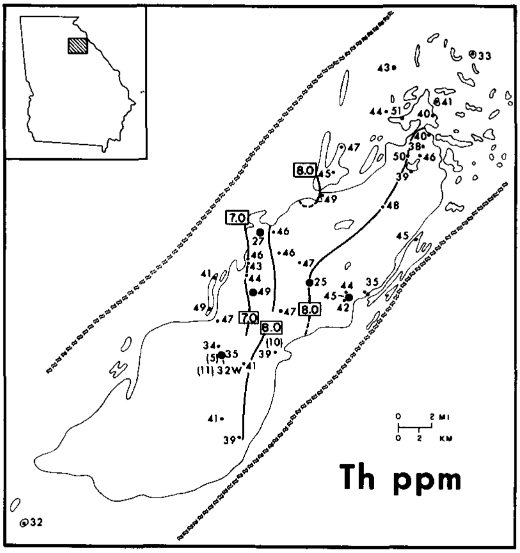
THE Elberton batholith is a large (500 km^2) late orogenic (320 Ma old) mesozonal granitic pluton in the Piedmont Province of the Southern Appalachians of the USA. The granite (see Stormer *et al.*, 1980) consists of a uniformly fine to medium grained light grey to locally pink rock with hypidiomorphic texture. It contains approximately equal amounts of alkali feldspar, plagioclase, and quartz; 4-7% biotite; and accessory ilmenite-hematite, magnetite, sphene, allanite, and zircon. Muscovite occurs rarely as a secondary subsolidus phase, and as a late primary phase in parts of the pluton. No major internal contacts are recognized in the batholith suggesting that it represents a single intrusive event (Whitney and Wenner, 1980).

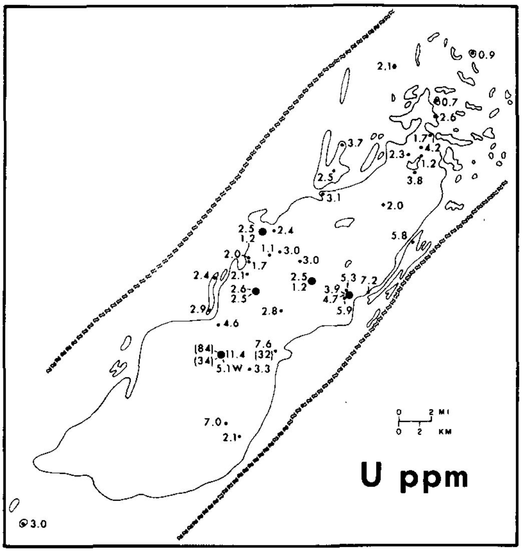
This study was carried out to determine how U and Th vary in a pluton characterized by a homogeneous distribution of major elements, and textural, and mineralogical characteristics; to compare the U and Th contents and the U/Th ratios of the pluton with other granites; to determine variations in the U and Th contents between the granite and late-stage pegmatites; and finally to assess whether any relationship could be identified between the U and Th data and variations in Rb, Sr, Ba, and Mn contents and $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ isotopic ratios. Comparison with the isotopic data enables variation of the U and Th contents in a granite pluton probably formed by partial anatexis of a compositionally variable protolith to be investigated.

Method of analysis

Approximately 1-2 kg samples of granite and up to 10 kg samples of pegmatite were selected from thirty 'fresh' unweathered outcrops in quarries. The samples were crushed to about 30 mesh, and 600 g aliquots were sealed in 600 ml Marinelli beakers for 21 days before analysis by γ-ray spectrometry. Measurements were made using an 18% Ge(Li) detector with a 4096 channel microprocessor controlled multichannel analyser. Calibrations were made with standards supplied by the US Geological Survey.

Ra-equivalent U (RaeU) is reported since the





FIGS. 1 and 2. FIG. 1 (*left*). Map of the Elberton granite batholith (after Whitney and Stormer, 1980) showing the distribution of Th concentrations in ppm. Sites where two samples were selected from different parts of the quarry are indicated by the enlarged points; at these sites, the Th concentrations are identical. Numbers in parentheses are data for pegmatites; one sample with suffix W is partially weathered. The major faults that border the batholith are the Towaliga–Hartwell Fault (north-west) and the Middleton–Lowndesville Fault (south-east). Contours with enclosed numbers are $\delta^{18}O$ values of 7 and 8 from Wenner (1980). FIG. 2. (*right*). Map showing the distribution of U concentrations in ppm (reported as RaeU). Sites where two samples were selected from different parts of the quarry are indicated by the enlarged points; where U concentrations differ for such samples, two numbers are given. Numbers in parentheses are data for pegmatites; one sample with suffix W is partially weathered.

technique measures ^{226}Ra; this can be used as a direct measure of U concentration only if secular equilibrium exists for the upper part of the ^{238}U decay series. Although RaeU and total U contents frequently differ in granites, several comparisons show that the maximum differences are less than 15–20% (e.g. Stuckless *et al.*, 1977). Assuming that the reported U contents of samples are within this range of the total concentrations then the tentative suggestions made here are valid. Duplicate analyses of samples indicate a mean precision of approximately 4% for U and 1.6% for Th.

Th *whole-rock data.* The Elberton pluton has a relatively wide range of Th, from 51 to 25 ppm with a mean of 42 ± 6 (1) ppm (fig. 1), which is approximately twice the average abundance of Th in granites ($SiO_2 > 70\%$) of 18 ppm (Rogers and Adams, 1969*a*). Th does not vary systematically in the granite although some sites have anomalously low Th contents. Much of the exposed pluton thus appears to be homogeneous for Th. At four localities, two samples from different parts of the same quarry have almost identical Th concentrations. At one site, a partially weathered sample in which feldspar is strongly altered has a slightly lower Th content (32 ppm) than an unweathered (35 ppm) sample suggesting that almost no Th migration has occurred as a result of weathering.

U *whole-rock data.* In contrast to Th, the mean U concentration of 3.1 ± 2 (1) ppm, is close to that of average granite of 4 ppm (Rogers and Adams, 1969*b*). The U content, however, varies throughout the intrusion from 0.7 to 11.4 ppm (fig. 2), in contrast to the distribution of Th. The U content varies considerably even for samples collected from different parts of the same quarry. Three sites display significant differences (of up to 70%) despite the fact that all samples appear fresh. Samples from one quarry, however, have the same U contents. The partially weathered sample in which the Th content appeared almost unaltered contains more than 50% less U (5.1 ppm) than the fresh sample (11.4 ppm U), collected nearby, consistent with U mobilization during near-surface weathering (e.g. Rogers and Adams, 1969*b*).

Whole-rock Th/U *ratios.* The Th/U ratios vary considerably throughout the intrusion ranging from 3 to 58 (fig. 3). The mean Th/U ratio of 18 ± 10 (1) is more than four times higher than the average of 3.5 to 4 for granites (Rogers and Adams, 1969*a*). The highest Th/U values occur at the north-east end of the pluton, where small outlying granite masses are in contact with country rock. In the centre of the pluton, Th/U ratios show a general decrease from north-west to south-east consistent with geological observations which indicate that the upper part of the batholith is exposed in the north-west with deeper levels of exposure in the south-east (Hess, 1979). The Th/U ratios are close to the average for granites at only one site.

Pegmatites. These occur sporadically throughout the batholith; they are abundant at some sites but are not found at others. Limited U and Th data suggest that the pegmatites are U-enriched and Th depleted compared to the granite. At one site in the south-central part of the batholith (fig. 2), an early pegmatite contains three times more U than the adjacent granite. At a second site, the U content is four times higher in late pegmatites than in the granite. The Th content of the pegmatites, however, is generally lower (sometimes by a factor of three) compared with the adjacent granite.

These data demonstrate the contrast in U and Th concentrations between pegmatites and granite. At a locality in the south-central part of the batholith where the U content is highest in the granite (11.4 ppm) and the Th/U ratio lowest ($\sim$ 3), polycrase (Ce,U,Th) $(Nb,Ti,Ta)_2O_6$ has been identified in several early formed U-enriched pegmatitic segregations (Stormer *et al.*, 1980).

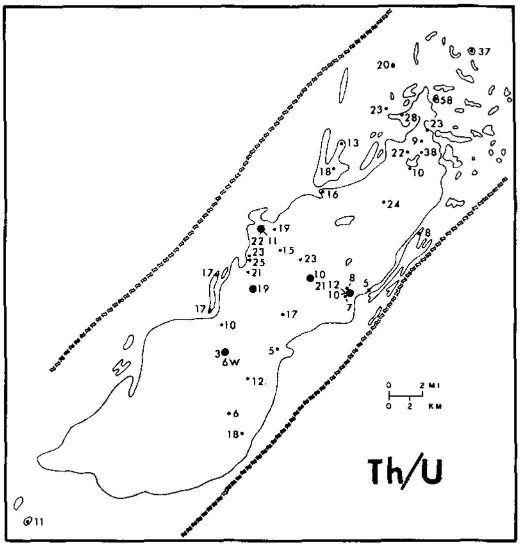


FIG. 3. Map of the Elberton batholith (after Whitney and Stormer, 1980) showing the distribution of Th/U values. Those sites with enlarged points represent two samples from different locations; where Th/U ratios differ for these samples, two values are given. One sample with a suffix W is partially weathered.

Discussion

The high Th/U ratios over most of the pluton suggest that U has been lost despite the apparent freshness of the samples (see also Stuckless and Nkomo, 1978). Some portions of the Elberton pluton contain muscovite in addition to biotite (Stormer *et al.*, 1980), although only in small quantities. Two-mica granites usually contain more leachable U than do hornblende or biotite granites in which U occurs predominantly in minerals that are resistant to leaching (e.g. Stuckless, 1980; Nash, 1979). Although no study of the mineralogical distribution of U and Th has been carried out it is probable that the Elberton granite may originally have had some U in a readily leachable form.

By analogy with observations on the Precambrian granites of Wyoming, the highly variable Th/U ratios (fig. 3) suggest that the Elberton granite may once have had considerably lower Th/U ratios (Stuckless, 1980). Pb isotope studies (e.g. Stuckless and Nkomo, 1978) are required to indicate whether or not significant quantities of U have been lost subsequent to emplacement of the intrusion. The enrichment of U in the pegmatites also indicates that a quantity of U was lost from the crystallizing magma in a volatile phase during formation of the pegmatites, as documented elsewhere; in some instances, U ore deposits occur in pegmatites (Rogers *et al.*, 1978).

In the Elberton granite U enrichment in the pegmatites is not associated with enrichment of Th, possibly reflecting the relatively high oxygen fugacity in the magma. Primary iron-titanium oxides provide a good indicator of oxygen fugacity (Buddington and Lindsley, 1964). In the Elberton pluton, the Fe-Ti oxides occur as ilmenite exsolution lamellae in hematite, hematite exsolution lamellae in ilmenite, and sparse, nearly pure magnetite (Ellwood *et al.*, 1980). This assemblage is consistent with the phase equilibria of the $Fe-Ti-O_2$ system during late-stage magmatism (Haggerty, 1971) in which conditions are oxidizing, and within one unit of the hematite-magnetite reaction. Hence most of the U may have occurred in the hexavalent rather than the tetravalent state and been transported by a volatile phase into pegmatites; the presence of a hematite-rich phase may thus be of value in identifying granites in which U has been removed by volatiles during late-stage crystallization.

It is difficult to estimate the original Th/U of the granite magma from the available data but the lowest Th/U ratio measured for the batholith is $\sim$ 3. However, the granite may once have had an even lower Th/U ratio which has been increased due to near-surface leaching. Zircons in a sample at one site (in which whole-rock samples contain 4.7 and 3.9 ppm U respectively, with Th concentrations of 45 ppm) are enriched in U, averaging around 1500 ppm providing additional evidence (Ross and Bickford, 1980; Silver, 1976; Ludwig *et al.*, 1980) that the Elberton pluton may have originally have had a greater U content. If the zircons crystallized earlier than pegmatite formation the high U content of the zircons may reflect the primary U concentration of the granitic magma. If it is assumed that the Th/U ratio was once almost uniform in the batholith, then the greatest loss of U occurred near to the top of the intrusion (fig. 3), either due to pegmatite formation, and/or during later near-surface leaching possibly coincident with uplift and exposure of the intrusion 200 Ma ago.

U and Th in metamorphic rocks at the contact with the granite at two sites show no significant U or Th enrichment. In one area, the U and Th contents of the adjacent gneissic country rock (7.2 and 14.5 ppm, respectively). At the same site, another sample of gneissic country rock is even lower in U and Th (3.1 and 15 ppm, respectively). At a second site, biotite schist has considerably lower U and Th contents (3.0 and 6 ppm, respectively) than the granite. These data suggest that no 'contact'-metasomatic U and Th enrichment of the country rock has occurred.

Correlation with $^{18}O/^{16}O$, $^{87}Sr/^{86}Sr$, and other trace element data

Comparison of the Th data with $^{18}O/^{16}O$ data from Whitney and Wenner (1980), $^{87}Sr/^{86}Sr$ data from Ellwood *et al.* (1980) and trace element (Rb, Sr, Ba, Mn) concentrations from Stormer *et al.* (1980) provide additional information on the controls of Th (and U) distribution. These data, when contoured, display systematic north-south variations, or 'stripes', in the granite that are interpreted as primary heterogeneities reflecting the variable protolith of the intrusion. Contours of the oxygen isotope data (fig. 1) provide an example of the 'stripes' across the batholith.

It has been suggested that the ^{18}O-depleted portions of the batholith were largely derived from primitive source materials, the ^{18}O-enriched areas representing formation from a high $^{18}O/^{16}O$ sedimentary protolith (Wenner, 1980). In view of the evidence of remobilization of U, the possibility of changes in the oxygen isotope ratios, due to late alteration processes, should be borne in mind, however. The Th data show no correlation with the isotopic or trace element patterns. In fig. 1, for example, the Th concentrations from the low-^{18}O regions (i.e. $\delta^{18}O \leqslant 7$) are almost identical to the ^{18}O-enriched ($\delta^{18}O \geqslant 8$) areas in the centre of the batholith indicating that the factors controlling the isotopic and other trace element distributions do not directly control the distribution of Th (or of U). Thus the distribution of Th cannot be related simply to variation in the protolith. The U data (fig. 2) and Th/U values (fig. 3) which are probably affected by low-temperature leaching, show no relationship to the isotopic element patterns.

Conclusions

The following tentative suggestions are made on the basis of these U and Th spectrometric data over the Elberton granite batholith.

1. The granite contains an average of 42 ppm Th, which is more than twice the Th content of average granite of 18 ppm.
2. The mean U content of 3 ppm is nearly the same as that of average granite of 4 ppm.
3. Th/U ratios vary throughout the intrusion, ranging from 3 to 58 with a mean of 18 ± 10 (1), which is exceptionally high compared to the Th/U ratios of average granite although several sites in the batholith have Th/U ratios of about 3, close to those for average granite.
4. Pegmatites are enriched in U (up to 8 times) but depleted in Th (by as much as one-third), compared with the granite, possibly indicating vapour-phase fractionation.
5. The U may have occurred as the hexavalent species during pegmatic formation, consistent with observations of the Fe–Ti oxide assemblages which suggest that the magma had high f_{O_2} at the time of crystallization.
6. The presence of a primary hematite-rich phase may be of value in identifying granites which had high oxygen fugacities during late stages of crystallization.
7. The highest Th/U ratios generally occur in the north-east and north-west of the batholith near to the roof zone. Across the central deeper part of the batholith Th/U ratios decrease north-west to south-east. Such a distribution is consistent with removal of U by pegmatite formation, and/or groundwater leaching. There is no evidence of metasomatic enrichment of U and Th in the country rock.
8. The Elberton batholith probably once had a higher U content than at present, as indicated by the Th/U ratio of 3, at one site and similarities to two-mica granites which have low primary Th/U values and high (1500 ppm) concentrations of U in zircons at one site.
9. The distribution of the Th does not follow that of previously published $^{18}O/^{16}O$, $^{87}Sr/^{86}Sr$, or trace element values indicating that the distri-

bution of Th (and presumably the primary U) was not related directly to that of the granite protolith.

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REFERENCES

Buddington, A. F., and Lindsley, D. H. (1964) *J. Petrol.* **5**, 310–57.

Ellwood, B. B., Whitney, J. A., Wenner, D. B., Mose, D., and Amerigian, C. (1980) *J. Geophys. Res.* **85**, 6521–33.

Haggerty, S. E. (1971) *Carnegie Inst. Washington Yearbk.* **70**, 165–76.

Hess, J. (1979) MS. thesis, University of Georgia, 193 pp.

Ludwig, K. R., Nash, J. T., and Naeser, C. W. (1980) *U.S.G.S. Open File Rept.* 80-236.

Nash, J. T. (1979) Ibid. 79-233, 1–39.

Rogers, J. J. W., and Adams, J. A. S. (1969*a*) In *Handbook of Geochemistry*, K. H. Wedepohl (ed.), Berlin, Springer-Verlag, **II-4.**

—— —— (1969*b*) Ibid. **II-5.**

—— Ragland, P. C., Nishimori, R. K., Greenberg, J. K., and Hauck, S. A. (1978), *Econ. Geol.* **73**, 1539–55.

Ross, C. R., II, and Bickford, M. E. (1980) In *Geological, Geochemical and Geophysical Studies of the Elberton Batholith, Eastern Georgia*, J. C. Stormer and J. A. Whitney (eds.), Guidebook 19, Georgia Dept. Nat. Resources, 52–62.

Silver, L. T. (1976) *Geol. Soc. Am. Abstracts with Programs*, 1107–8.

Stormer, J. C., Whitney, J. A., and Hess, J. R. (1980) In *Geological, Geochemical, and Geophysical Studies of the Elberton Batholith, Eastern Georgia*, J. C. Stormer and J. A. Whitney (eds.), Guidebook 19, Georgia Dept. Nat. Resources, 10–30.

Stuckless, J. S. (1980) *Am. Assoc. Petrol. Geol.* **64**, 789–90.

—— Millard, H. T., Jr., Bunker, C. M., Nkomo, I. T., Rosholt, J. N., Bush, C. A., Huffman, C., Jr., and Keil, R. L. (1977) *U.S.G.S. J. Res.* **5**, 83–91.

—— and Nkomo, I. T. (1978) *Econ. Geol.* **73**, 427–41.

Wenner, D. B. (1980) In *Geological, Geochemical and Geophysical Studies of the Elberton Batholith, Eastern Georgia*, J. C. Stormer and J. A. Whitney (eds.), Guidebook 19, Georgia Dept. Nat. Resources, 31–4.

Whitney, J. A., and Wenner, D. B. (1980) In *Excursions in Southeastern Geology*, R. W. Fry (ed.), Am. Geol. Inst. **2**, 351–78.

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