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Identification of uraniferous granitoids in the USA using stream sediment geochemical data

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ABSTRACT. Trace element variations in stream sediments from an area of 76 000 km^2 in central Colorado are used to identify uraniferous granitoids on the basis of whole rock geochemical criteria developed to distinguish barren from metalliferous granitoids in Britain. These criteria (which include enhanced Ba, Be, Cs, Cs/Ba, K, La/Eu, Li, Lu/Eu, Nb, Rb, Rb/K, low Sr and Mg, and *RE* patterns with marked negative Eu anomalies) are used to formulate an index based on the Pikes Peak batholith of the Front Range as a type uranium source rock.

Uraniferous granitoids in Colorado, which are associated with sedimentary basins containing major uranium mineralization, are identified using this index which may be applicable to the interpretation of stream sediments from elsewhere. The use of stream sediment geochemistry as an exploration method for similar uranium source rocks, which may indicate potential uranium provinces, is thus possible.

THE National Uranium Resource Evaluation (NURE) programme of the United States Department of Energy (DOE) which commenced in 1973 includes airborne radiometric and magnetic surveys, hydro-geochemical and stream sediment reconnaissance (HSSR) and surface and subsurface geological investigations. Koch *et al.* (1980) have studied resource appraisal methods using HSSR data from the Los Alamos Scientific Laboratory (LASL) for four adjoining 1° × 2° National Topographic Map Series (NTMS) quadrangles in Colorado (fig. 1). These data form the basis for this investigation.

Studies in Britain (Simpson *et al.*, 1979, and Plant *et al.*, 1980) have developed a model for magmatic and subsequent deuteric and hydrothermal enrichment of U and Sn in granitoids, and identified exploration criteria for such intrusions using whole-rock geochemical, geophysical, and geological information. In this paper the application of these criteria to the recognition of uraniferous granitoids (which could contain vein-type U deposits, or which could have provided a source for sedimentary uranium deposits) is demonstrated, based on an index developed for the LASL HSSR data.

Recognition of mineralized granites

Studies of the content and distribution of uranium in granitoids ranging in age from 750 to 250 Ma in the Caledonian and Hercynian provinces of Britain suggest that mineralization results from uranium redistribution in uraniferous granites (Watson and Plant, 1979; Simpson *et al.*, 1979; Plant *et al.*, 1980) and fission track studies indicate that the high uranium content of the granites away from mineralization is due to its occurrence in resistate primary minerals. Mineralization is attributed to reaction between granites and shales or low-temperature metapelites and/or epizonal water, uranium being released by dissolution of primary accessory minerals, such as zircon. Hence, *metalliferous* granitoids containing high concentrations of uranium and other metals in

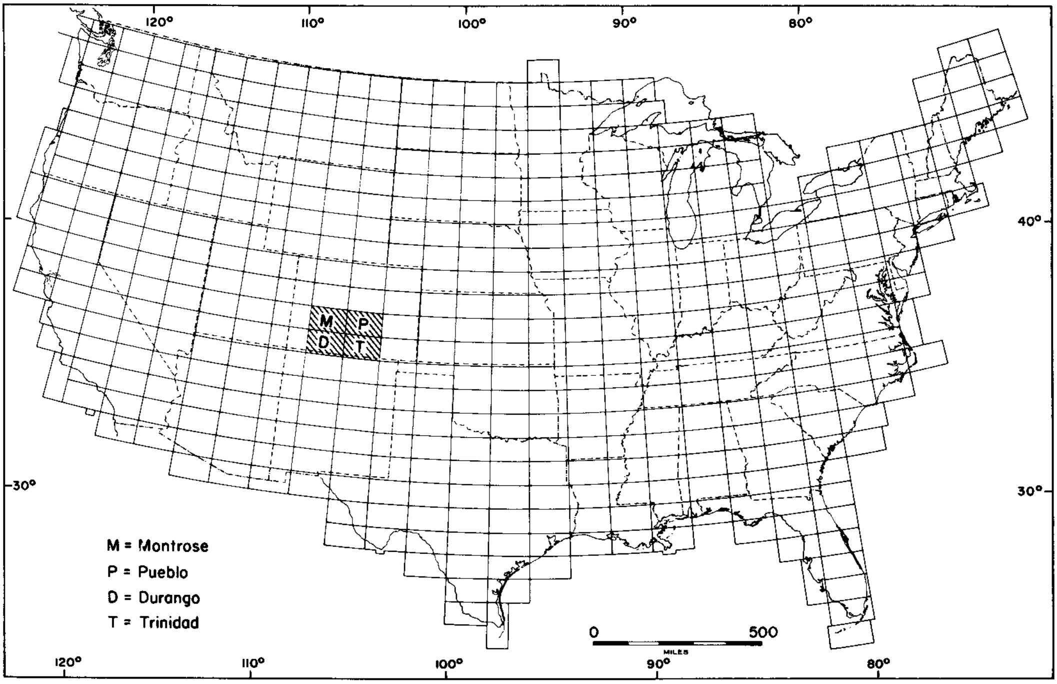


FIG. 1. Index map locating the four NTMS quadrangles studied.

primary minerals are distinguished from *mineralized* granitoids, in which metals have been redistributed and occur in ore minerals. Much of the literature on granites is concerned with major element geochemistry, or petrographical and mineralogical aspects, and recent surveys (Nishimori *et al.*, 1977; Castor *et al.*, 1977; Murphy *et al.*, 1978) confirm the general lack of whole-rock trace element data in relation to uranium geochemistry in granitoids and associated rocks.

Simpson *et al.* (1979) and Plant *et al.* (1980) have shown that British metalliferous intrusions with high mean contents of uranium also have increased whole-rock levels of Th, Rb, K, Sn, Nb, Y, Cs, Ta, Li, Be, and F; low Ba, Sr, and Zr; high Rb/Sr, U/Th, Cs/K, and K/Ba ratios; low K/Rb and Sr/Y ratios; and have chondrite-normalized *RE* patterns that are light-*RE* enriched with marked negative Eu anomalies. Many intrusions also have large negative Bouger gravity anomalies and, in the high-grade metamorphic terrain of Scotland, broad large-amplitude ring-shaped magnetic anomalies centred on the granitoid. Geologically, they tend to have a post-tectonic setting at a high structural level, being emplaced after regional cooling of the crust; a low-pressure thermal aureole; and isotopic compositions indicative of a 'juvenile' source. Many of them probably crystallized near to the surface, under conditions of low partial pressure of water. Petrographic criteria thought to be indicative of high-temperature water-rock interaction in the British mineralized granitoids (Simpson *et al.*, 1979; Plant *et al.*, 1980) are given in Table I.

Bolivar (in press) has indicated that data from the HSSR programme, although unlikely to identify ore bodies, will help to identify geochemical provinces favourable for detailed follow-up. The geochemical criteria developed to identify different suites of granite in Britain distinguish mineralized and metalliferous intrusions on the one hand from barren granitoids on the other. Thus, uraniferous granites containing high levels of uranium in primary accessory minerals are identified in addition to uranium mineralization. The criteria are most applicable, therefore, to the delineation of areas for follow-up and are particularly suited to the identification of uranium provinces associated with granite source rocks. Since although uranium may occur in accessory minerals at the present level of erosion, such intrusions may represent the eroded root zones of mineralized plutonic/volcanic complexes, the uranium having been leached out during erosion and concentrated in adjacent sedimentary basins to form ore deposits (for example, Bowden *et al.*, this volume). Moreover, metamictization of uraniferous accessory minerals, which is

TABLE I. *Comparison of geological and geophysical characteristics of metalliferous granitoids of the British Isles with Pikes Peak batholith*

	Metalliferous (a–c)	Pikes Peak (d–g)
Petrographic changes		
Two-mica granite; musc. replacing bte.	Yes	Yes
Feldspars to sericite/kaolinite	Yes	Yes
Ferromagnesians to chlorite/epidote, etc.	Yes	Yes
Hematization of ferromagnesians	Yes	Yes
Tourmalinization	Yes	Yes
Greisenization	Yes	Yes
Accessory minerals		
Fluorite	Yes	Yes
Topaz	Yes	Yes
Beryl	Yes	Yes
Cassiterite	Yes	Yes
Columbite-tantalite	Yes	Yes
Uraninite, uranothorite, etc.	Yes	Yes
Thorite	Yes	Yes
Xenotime	Yes	Yes
Monazite	Yes	Yes
Apatite	Yes	Yes
Geophysical		
Strong negative Bouguer anomaly	Yes	?
Filtered magnetic anomaly	Yes	?
Zone of high heat flow	Yes	Probably (*h*)
Setting		
High-level setting	Yes	Yes
Sharp contacts with cold 'wet' country rocks	Yes	Yes

(*a*) Plant *et al.* (1980)
(*b*) Brown *et al.* (1980)
(*c*) Tischendorf (1977)
(*d*) Gross and Heinrich (1965, 1966)
(*e*) Barker *et al.* (1975)
(*f*) Carpenter *et al.* (1979)
(*g*) Hutchinson (1976)
(*h*) Blackwell (1978); Lachenbruch (1978).

likely to be particularly important in old Precambrian intrusions, would also provide large volume sources of uranium for leaching. It is nevertheless possible, using statistical procedures, to distinguish uranium occurring in resistate minerals from that associated with mineralization, and the application of such methods to HSSR data is briefly discussed.

The Pike's Peak Index, which is used in this paper, is based on the whole-rock geochemical criteria used to distinguish different suites of British granites and was developed for the purpose of identifying uraniferous granites using regional stream sediment survey data. Such elements as Zr, Hf, Th, and the *RE* elements will mostly be contained in resistate heavy minerals with particularly variable contents in stream sediments. An index based on as many criteria as possible will therefore be more stable than one based on a single criterion such as Th since all of the terms will be subject to random error. This is particularly so since the index is based on crossing single thresholds rather than on a polynomial function. The present empirical index provided a good base for the exploratory study but will be refined on the basis of continuing work. In particular, a more generally applicable index should be developed since such elements as Th, Hf, and the *RE* are not routinely determined in most stream sediment surveys.

Study area

The study area consists of the Pueblo, Montrose, Durango, and Trinidad NTMS quadrangles in southern Colorado (fig. 1). Geological maps at the scale of the 1:250 000 quadrangles, multi-element HSSR data, and uranium occurrence data are available for the area which contains major uranium deposits including the Hanson deposit with reserves of 30 000 000 lb U_3O_8 and the Pitch mine with reserves of 1 740 000 lb U_3O_8.

Geology

The principal structural-geomorphic units in Colorado and the study area are shown in fig. 2. The eastern part of the area, including about half of the Pueblo and a third of the Trinidad quadrangle, is in the High Plains area of the Great Plains geologic province. To the west are mountain ranges separated by broad valleys, including South Park and the San Luis Valley. A small part of the Colorado Plateau lies in the north east. Fig. 2 also shows the Colorado Mineral Belt which according to Tweto (1968) contains most of the metal mining districts of Colorado.

The geology of the study area is summarized in fig. 3—see also Weiner and Haun (1960) and Epis and Weiner (1976). In the High Plains, the rocks are horizontal or gently dipping sediments ranging in age from Cretaceous to Recent, except for small areas of older Mesozoic rocks. Westwards, the sediments of the Colorado Front Range are Cambrian to Recent and lie uncomfortably on the Precambrian basement of the Rockies. To the west, Palaeozoic and Mesozoic rocks in the Sangre de Cristo Mountains and the Sawatch Range give way to the Cainozoic rocks of the San Luis Valley and the mainly flat lying volcanics of the San Juan Mountains.

Sketch maps, geological summaries and references to detailed geological accounts for the four quadrangles are given by Shannon (1978), Broxton *et al.* (1979), Dawson and Weaver (1979), and Morris *et al.* (1978). 1:250 000 scale geological maps have been compiled by Johnson (1969), Scott *et al.* (1978), Steven *et al.* (1974), and Tweto *et al.* (1976).

HSSR data

The HSSR data consisting of the following number of sample sites for each quadrangle (Pueblo, 1058; Montrose, 1857; Durango, 1604;

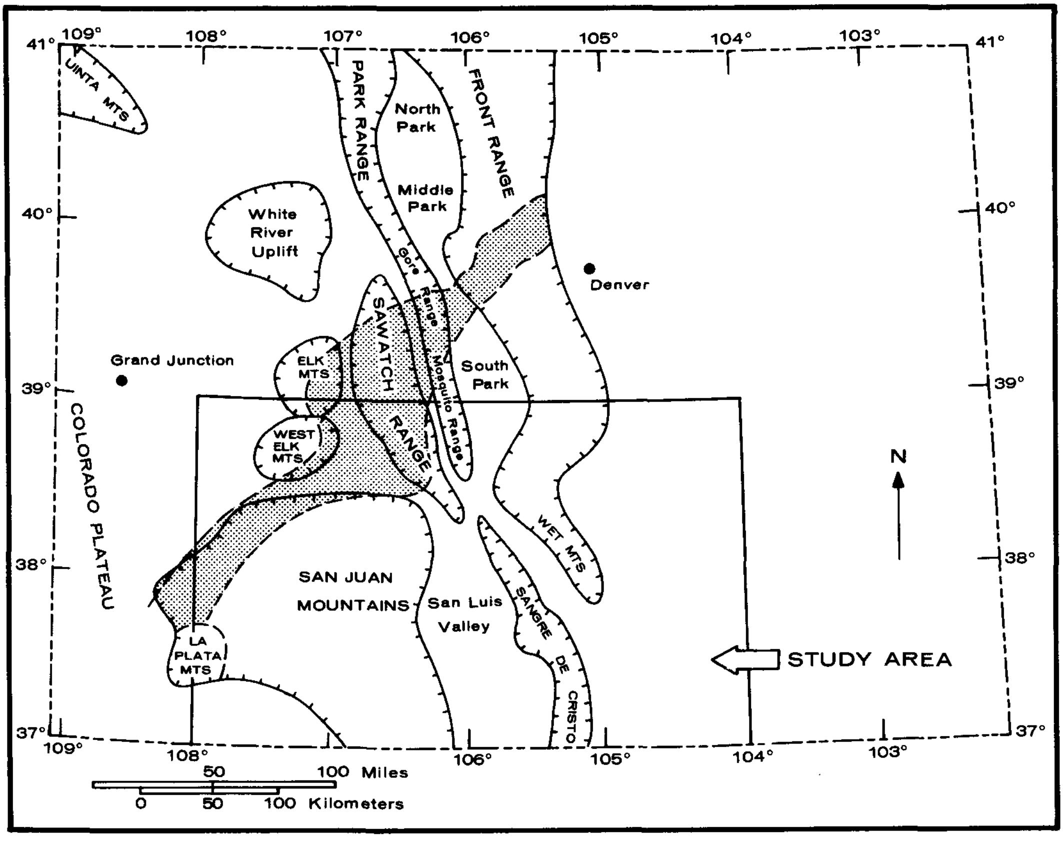


FIG. 2. Principal structural-geomorphic units in the mountain province of Colorado and location of the Colorado Mineral Belt (shown stippled). After Tweto (1968).

Trinidad, 1240; total, 5759) were obtained from LASL on magnetic tape, and are listed in reports for individual quadrangles (Shannon, 1978; and Morris *et al.*, 1978). A few samples, for which analytical or other data were not available, are omitted. Stream sediment samples derived from granitoid rocks form a subset of the data.

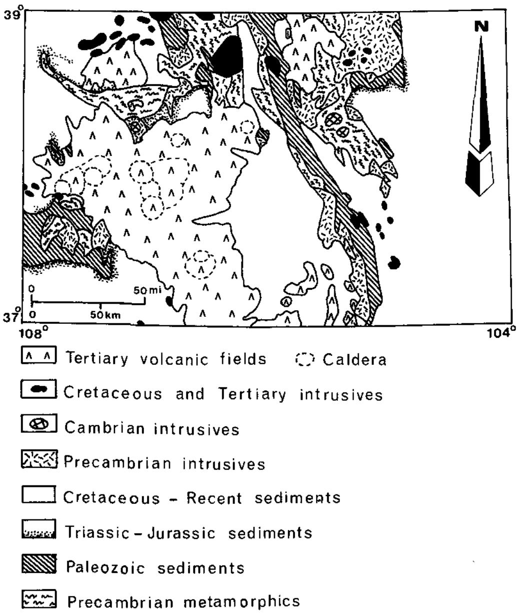


FIG. 3. Sketch map showing principal geological units in the study area (after King and Beikman, 1974).

The field and analytical procedures used are described by Broxton *et al.* (1979). Where possible water samples and approximately 25 g of active stream sediment were collected at an average sampling density of 1 per 10 km^2. After drying, samples were sieved to obtain the size fraction less than 100 mesh. Sediment samples were analysed for uranium by the delayed-neutron method and a computer-controlled energy dispersive X-ray fluorescence system was used to determine Ag, Bi, Cd, Cu, Nb, Ni, Pb, Sn, and W. Be and Li were determined by arc-source emission spectrography and Al, Au, Ba, Ca, Ce, Cl, Co, Cr, Cs, Dy, Eu, Fe, Hf, K, La, Lu, Mg, Mn, Na, Rb, Sb, Sc, Sm, Sr, Ta, Tb, Th, Ti, V, Yb, and Zn by instrumental neutron activation analysis. Approximate limits of detection are given in Table II.

Airborne radiometric and magnetic surveys of the area are reported in geoMetrics (1979*a*, 1979*b*), Texas Instruments (1980), and Western Geophysical (1979).

TABLE II. *Detection limits for selected elements in stream sediments (Bolivar, in press)*

Element	Analytical method*	Nominal detection limit (ppm or %)
Ba	NAA	400
Be	ASES	1
Cs	NAA	2
Eu	NAA	0.5
Hf	NAA	1
K%	NAA	0.3%
La	NAA	4
Li	ASES	1
Lu	NAA	0.2
Mg%	NAA	0.3%
Nb	XRF	20
Rb	NAA	25
Sr	NAA	300
Th	NAA	0.8
U	DNC	0.02

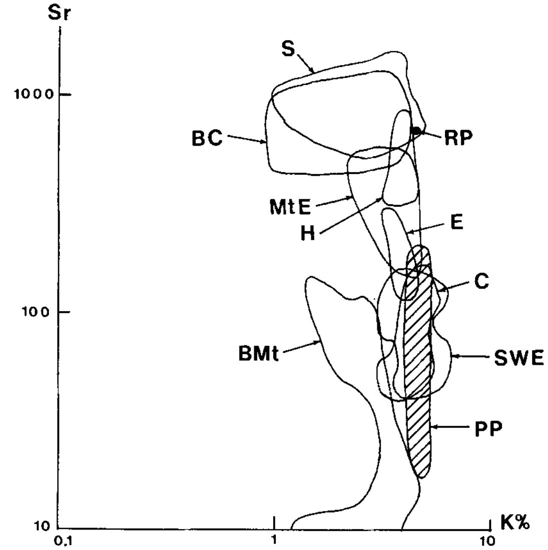
*NAA = Neutron activation analysis;
ASES = Arc-source emission spectroscopy;
XRF = X-ray fluorescence;
DNC = Delayed neutron counting.

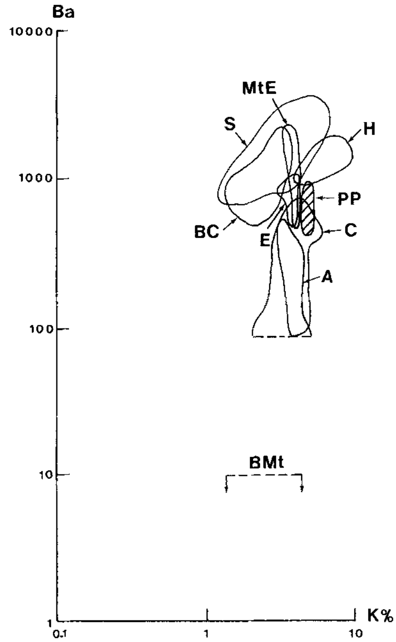
Pike's Peak batholith

General setting. The 1040 Ma (Hedge, 1970) Pike's Peak batholith has been extensively studied (for example, Gross and Heinrich, 1966; Barker *et al.*, 1976; Hawley and Wobus, 1977; and Carpenter *et al.*, 1979). It has many features in common with the metalliferous granitoids of Britain (Table I) and occurs in the HSSR resource appraisal study area of Koch *et al.* (in press). It lies to the south of the Front Range, and the southern half of the batholith and associated minor sodic and potassic plutons of Lake George and Mount Rosa outcrop in the Pueblo quadrangle.

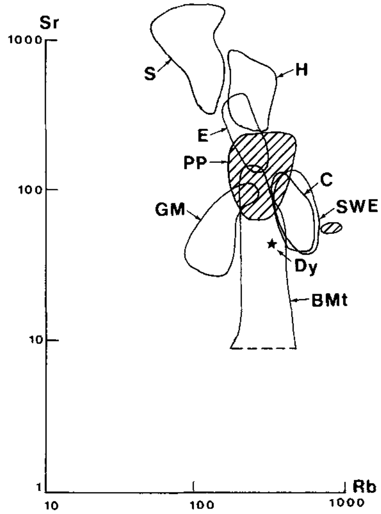
Barker *et al.* (1975) estimate crystallization at 1.5 kbar (5 km depth) and about 700 °C. Hawley and Wobus (1977) suggest from its associated metamorphic assemblage that maximum P-T conditions were about 6 kbar and 700 °C, that water was available, and that the system was locally open to carbon dioxide. Criteria supporting extensive deuteric/hydrothermal alteration include the presence of biotite and late muscovite, alteration of feldspars and ferromagnesians, greisenization and the occurrence of accessory fluorite, topaz, and beryl.

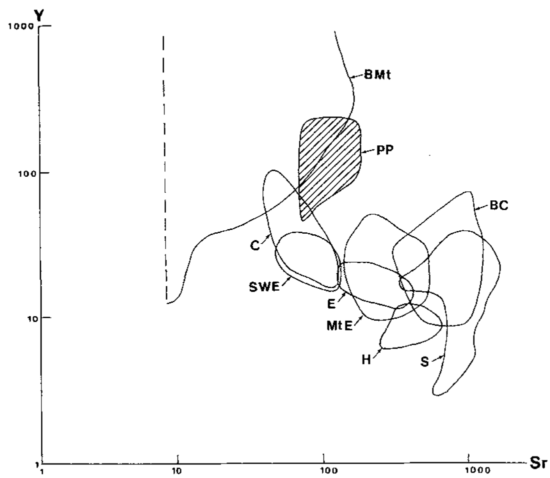
Strong magnetic patterns are associated with the batholith (geoMetrics, 1979*a*), but interpretation of regional gravity data is uncertain (Qureshy,





FIGS. 4 and 5. FIG. 4 (*left*). Whole-rock Sr ppm-K% variation of Pikes Peak batholith in relation to other selected granitoids. Key for figs. 4–7: A, granitoids from Kanuti-Hodzana and Porcupine River areas, Alaska (Stablein, 1980); BC, Boulder Creek granodiorite, Colorado (Gable, 1980); BMt, Bokan Mountain granite, Alaska (Thompson *et al.*, 1980); C, Cairngorm granite, Scotland (Plant *et al.*, 1980); Dy, bostonite dyke, Front Range, Colorado (Simmons and Hedge 1978); E, Elberton granite, Georgia (Hess, 1979); GM, Granite Mountains, Wyoming (Stuckless *et al.*, 1977; Stuckless, 1978); H, Helmsdale granite, Scotland (Plant *et al.*, 1980); MtE, Mount Ethel granite, Colorado (Snyder and Hedge, 1978); PP, Pikes Peak batholith, Colorado (Hawley and Wobus, 1976, 1977); RP, Rosalie Peak granite (Bryant and Hedge, 1978); S, Scottish 'barren' granites (Plant *et al.*, 1980); SWE, Southwest England batholith (P. Simpson, pers. comm., 1980). FIG. 5 (*right*). Whole-rock Ba ppm-K% variation of Pikes Peak batholith in relation to other selected granitoids.





FIGS. 6 and 7. FIG. 6 (*left*). Whole-rock Sr ppm-Rb ppm variation of Pikes Peak batholith in relation to other selected granitoids. FIG. 7 (*right*). Whole-rock Y ppm-Sr ppm variation of Pikes Peak batholith in relation to other selected granitoids. Key as fig. 4.

1958, 1962), although Barker *et al.* (1975) suggest that a positive gravity anomaly is consistent with reaction-melting and accumulation of olivine and pyroxene in the lower crust.

TABLE III. *Comparison of whole-rock geochemistry of granitoids of British Isles with Pikes Peak batholith (ppm except for K and F per cent)*

	Normal (a, b)	Metalliferous (a, b)	Pikes Peak (c–e)
Ba	700–4000	10–800	300–1000
Be	0–3	1–19	3–9
F	0.1 (f)	0.1–0.4 (f)	0.3–0.6
K	1–7	3–7	4–6
Li	5–40	20–600	16–140
Nb	?	20–30	40–150
Rb	50–200	200–1000	320–800
Sr	150–2000	40–150	70–150
Sn	0–5	5–25 (g)	4–18
Th	1–10	10–60	12–110 (h)
U	1–5	5–60	2–10 (h)
Y	2–40	2–100	70–200
Eu anomaly	No	Yes	Yes
Enhanced *HREs*	No	Yes	Yes

(*a*) Plant *et al.* (1980)
(*b*) Brown *et al.* (1980)
(*c*) Carpenter *et al.* (1979)
(*d*) Hawley and Wobus (1977)
(*e*) Barker *et al.* (1976)
(*f*) Tischendorf (1977)
(*g*) Wilson (1972)
(*h*) New data: Th(NAA) and U(DNC), 25 detn.

Whole-rock geochemistry. Whole-rock chemical data for the batholith are compared with data for barren and metalliferous granitoids of Britain in Table III and it is apparent that Pike's Peak granite is similar to the metalliferous suite. More detailed comparisons can be made on the basis of element pairs used to distinguish the different suites of British granitoids (figs. 4–7). In these diagrams the field of 'barren' granitoids is clearly separated from the metalliferous suite represented by the Cairngorm (Sn–Nb–Pb–Zn–Li–F) and Cornubian (Sn–W–Cu–As–Zn–Pb–U–Mo) granite batholiths. The Helmsdale granite, Scotland, is regarded as 'intermediate' since the elevated levels of uranium and other elements are thought to be mainly due to post-magmatic fault controlled mineralization (Watson and Plant, 1979). Data are also plotted for some North American granitoids including the Boulder Creek granodiorite, Colorado (Gable, 1980); Bokan Mountain granite, Alaska (Thompson *et al.*, 1980); Elberton granite, Georgia (Hess, 1979; Wenner *et al.*, this conference*); Granite Mountains, Wyoming (Stuckless *et al.*, 1977; Stuckless, 1978); and the Mount Ethel granite, Colorado (Snyder, 1979).

Clearly, the general trends for different suites of British granites may be identified in these data. Moreover, significant uranium mineralization has been noted from the Mount Ethel granite (Nelson-Moore *et al.*, 1978), the Granite Mountains (Stuckless *et al.*, 1977), and Bokan Mountain (Thompson *et al.*, 1980). An increase in Th content with increasing differentiation is shown by its systematic relationship to the magnitude of the negative Eu anomaly in chondrite-normalized *RE* plots (fig. 8) which has been attributed to separation of plagioclase feldspar. The trend for uranium is similar but more scattered, probably because of surface redistribution of uranium.

Stream sediment geochemistry. Stream sediment samples from the Pike's Peak pluton reflect whole-rock geochemistry, although the absolute and relative concentration differ in stream sediments. Levels of selected elements in stream sediments derived from the Pike's Peak and San Isabel batholiths are compared with those for all granites from the study area in Table IV. Many of the whole-rock trends identifying metalliferous granitoids in Britain† can be identified in the Pike's Peak stream-sediment data, while those from the San Isabel pluton appear to be typical of the barren type of granite. An important characteristic of the Pike's Peak stream sediment data is the marked negative Eu anomaly in the chondrite-normalized *RE* distribution pattern (fig. 9), reflecting the whole-rock geochemistry of the pluton (Barker *et al.*, 1979). In addition, the whole rock patterns show heavy REE enhancement (cf. Cairngorm), which is also shown by the Lu/Eu ratio in the stream sediments (fig. 10A). A few stream sediments from the Montrose and Durango quadrangles have high *RE* concentrations (fig. 10A), but they are not so pronounced as those of the Pike's Peak area. While most of the granite-derived sediments in the study area do not show Eu anomalies, some from the Montrose and Durango quadrangles show a similar trend to that of the Pike's Peak samples (fig. 10B), although to a lesser extent. This trend is accompanied everywhere by increased U contents.

Be and Nb are enhanced in samples from Pike's Peak compared with those from the San Isabel granite (fig. 11A), and except for a few samples from the Montrose quadrangle, Nb is at background levels in stream sediment samples derived from other granites. The Pike's Peak pluton is also distinguished by enhanced Cs/Ba and Rb/K ratios

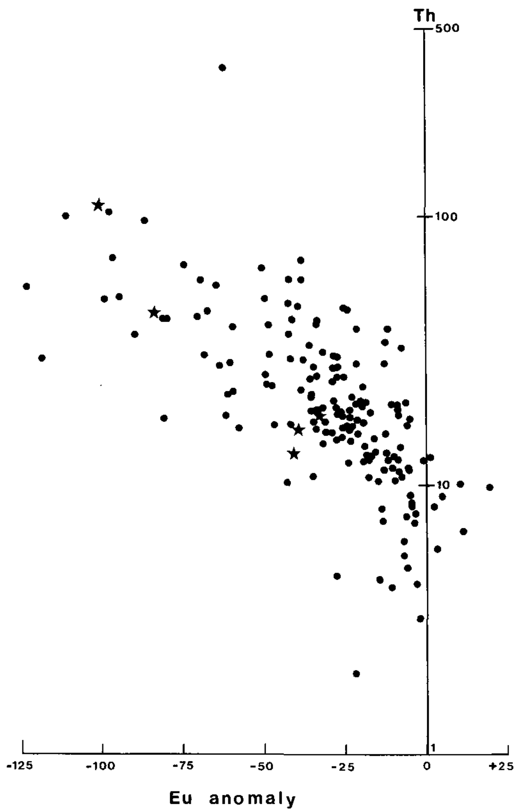
* To be published in the next volume.

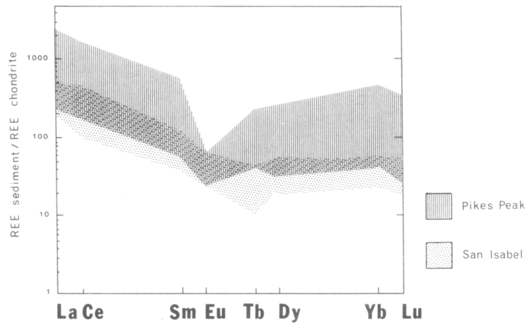
† Sr data were not available for the LASL stream sediments.

TABLE IV. *Concentration levels for selected elements in stream sediments over granites*

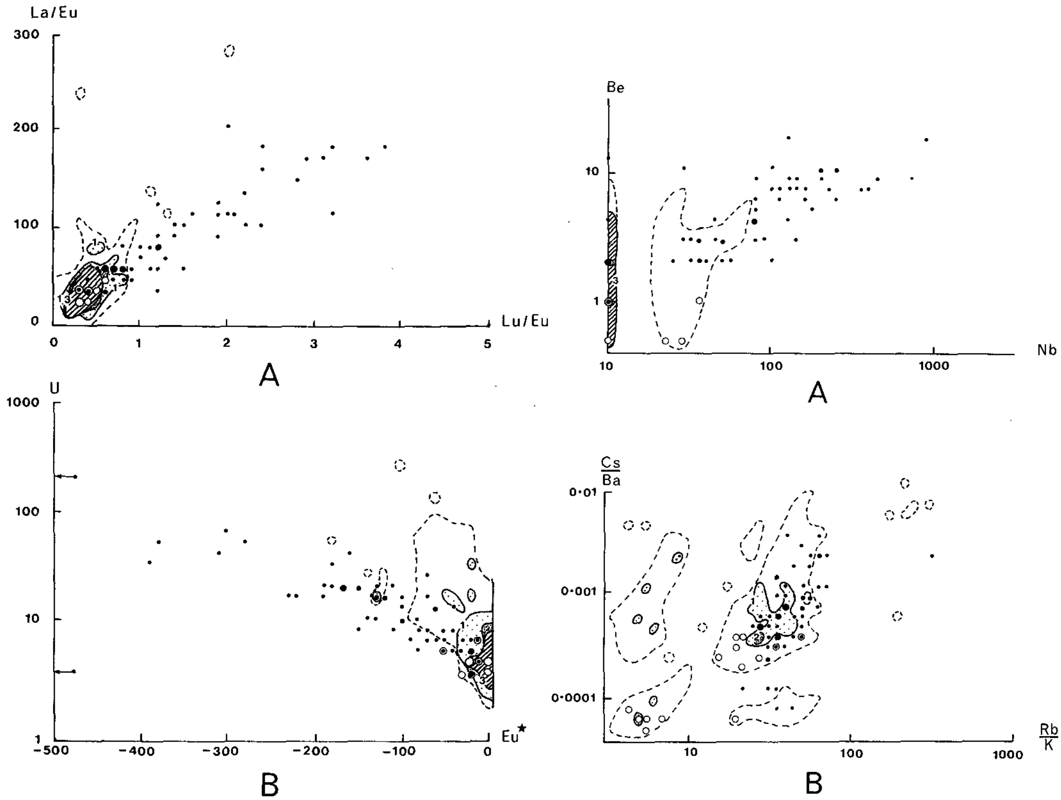
	Pueblo				Durango		Trinidad		Montrose	
	Pikes Peak (60)		San Isabel (14)		(68)		(42)		(153)	
	x̄	s	x̄	s	x̄	s	x̄	s	x̄	s
Ba	594	266	898	103	482	189	743	152	630	219
Be	5.7	4.1	1.0	0.5	2.9	1.2	3.1	0.6	2.3	1.1
Cs	3.7	1.7	1.7	1.2	11	7	2.2	1.8	4.1	2.7
Eu	2.9	1.2	3.0	0.8	2.1	0.5	2.9	1.0	2.1	1.4
Hf	89	102	26	11	18	17	20	14	28	33
K%	2.3	0.9	1.9	0.2	1.8	0.8	2.1	0.4	1.8	0.5
La	265	211	94	31	51	26	80	93	114	263
Li	39	25	21	6	53	31	41	16	41	20
Lu	4.3	3.6	1.1	0.4	0.7	0.5	0.8	0.4	1.0	0.6
Mg%	0.4	0.5	1.4	0.6	1.8	1.1	1.7	0.4	1.7	0.9
Nb	116	139	14	8	10	0	11	3	13	10
Rb	96	32	34	21	64	53	33	35	52	31
Sr	100	0	197	195	137	119	127	84	127	114
Th	74	66	13	3	17	16	11	3	35	83
U	21	30	5	1	9	11	12	36	14	17
Eu anom.	Strong		None		Weak		None		Moderate	

x̄ = Mean; s = standard deviation } ppm or per cent.





FIGS. 8 and 9. FIG. 8 (*left*). Whole-rock Th ppm as a function of chondrite-normalized Eu anomaly in granitoids. Data from Lenthall (1972), Stablein (1980), McLennan and Taylor (1980), and Harris and Marriner (1980) shown as dots. New data from Pikes Peak batholith shown as stars. FIG. 9 (*above*). Fields of chondrite-normalized *RE* distributions for stream sediments derived from the Pikes Peak (60) and San Isabel (14) plutons, Pueblo quadrangle.



FIGS. 10 and 11. FIG. 10 (*left*). Comparison of 60 Pikes Peak (solid dot) and 14 San Isabel (open circle) stream sediments with all 227 granitoid-derived stream sediments excluding Pikes Peak, contoured at 0, 1, 2 and 3 per cent frequency. Dot size proportional to 1, 2, 3, and 5+ coincident samples. FIG. 11 (*right*). Comparison of 60 Pikes Peak and 14 San Isabel stream sediments with all 227 granitoid derived sediments excluding Pikes Peak; symbols etc. as fig. 10.

compared with San Isabel (fig. 11B), although there is overlap with the field occupied by most of the samples. High ratios of the elements also occur in a few samples from the Durango and Montrose quadrangles.

We hypothesize that a significant proportion of uranium in the stream sediments occurs in resistate minerals, for example, monazite, allanite, xenotime, as indicated by the correlation between U and Hf* ($r = 0.812$) for the Pike's Peak samples (fig. 12). Hence, regressing U on the rare earth elements will account for much of the uranium in these minerals, and residual uranium (total minus regression predicted uranium) can then be used to identify uranium mineralization (Koch *et al.*, 1980). Table V shows correlation coefficients for uranium and residual uranium with selected elements for stream sediments derived from the San Isabel and Pike's Peak granites. The *RE*-based regression ($R^2 = 0.917$) removes correlation of residual uranium with all other elements, including Hf* except for a moderate residual correlation with Li; the high Li samples are close to the Mount Rosa intrusion.

The Th content is high relative to U in the Pike's Peak samples compared with other granite-derived samples (fig. 13) consistent with data from granites of the Granite Mountains district, Wyoming (Stuckless, 1978, 1979; Stuckless *et al.*, 1977), probably reflecting the greater mobility of U compared to Th in the surface or near-surface environment. The high Th/U ratio also supports the concept of uraniferous granite as a potential source for the formation of uranium deposits in nearby sedimentary basins.

*Used as an indicator for Zr content which was not determined.

TABLE V. *Correlation of uranium and residual uranium from regression on REEs with other selected elements for 74 samples of Pikes Peak and San Isabel granites*

	Uranium	Residual uranium
Ba	−0.669	−0.163
Be	0.715	0.023
Cs	0.126	0.109
Eu	0.430	−0.030
Hf	0.812	−0.103
K	0.009	−0.290
La	0.898	0.005
Li	0.864	0.406
Lu	0.932	−0.011
Mg	−0.422	0.035
Nb	0.821	−0.060
Rb	0.497	−0.086
Sr	−0.165	−0.045
Th	0.936	0.092
U	1.000	0.283

Implications for recognition of Pike's-Peak-type batholiths from HSSR data

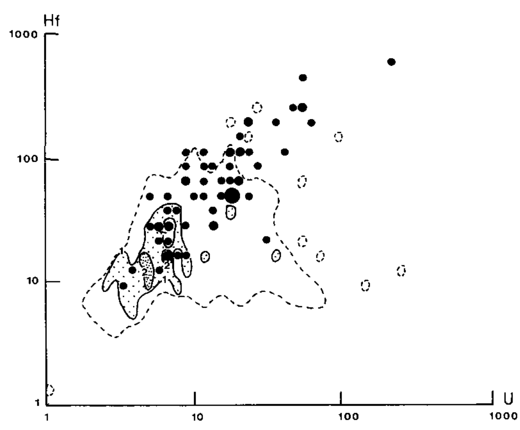
Examination of 277 stream sediment samples from other granites in the study area (Table IV; Figs. 10–13) suggests that similar granites to Pike's Peak occur but whole-rock data are generally lacking. The whole-rock geochemistry of the granitoids of the Spanish Peaks complex (Jahn *et al.*, 1979), and the Tertiary stocks of the Colorado mineral belt (Simmons and Hedge, 1978), have been studied with emphasis on *RE* distribution patterns but only three specimens resemble the metalliferous granitoid trend. Ninety stream sediments from the granodiorite, quartz monzonite, and quartz diorite suite of the Pueblo quadrangle, however, show similar geochemical trends to those of Pike's Peak while stream sediments derived from intermediate extrusive and metamorphic rocks of the study area and from rhyolites of the Durango area show no similar trend.

Test of method: study area

In order to test the extent to which stream sediments draining granites of the Pike's Peak type could be recognized, an empirical 'Pike's Peak Index' (PPI) was developed based on differences observed between stream sediments from the Pike's Peak and San Isabel batholiths for several element pairs plotted on scatter diagrams. Each criterion met (Table VI) is given a score, these are summed and the total multiplied by four to yield a maximum PPI of 100.

Initial screening of the 337 granite-derived samples, using a lower PPI cut-off of 50, detected 58 samples (out of a possible 60) over the Pike's Peak batholith of which 93 per cent scored between 72 and 96 (mean 86, std. dev. 10). Only one sample (out of 14) with a PPI of 52 was detected over the San Isabel pluton. Discrimination between the data used to establish the index was therefore good.

The PPI shows a strong correlation with log U and log Th for granite-derived sediments (0.603 and 0.771 respectively, n = 337), and also for sediments from other acid and intermediate intrusive rocks (0.543 and 0.823, n = 123). The over-all trends are identical, and the data are combined in fig. 14. Correlation with untransformed U and Th is less pronounced in both sets of data (0.325 and 0.335, n = 337; 0.308 and 0.723, n = 123).



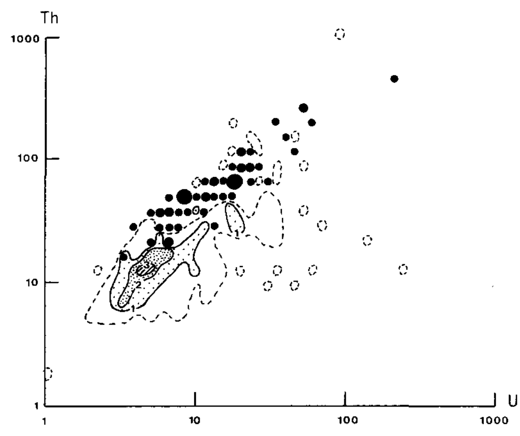


FIG. 12 (*left*) and FIG. 13 (*right*). Comparison of 60 Pikes Peak stream sediments with all 227 other granitoid-derived sediments. Symbols etc. as fig. 10.

TABLE VI. *Pikes Peak Index (PPI) for stream sediment data*

Criterion	Score
Ba < 912	1
Be > 1.7	2
Cs > 2.5	1
Cs/Ba > 0.0036	2
*Eu anomaly < −30	3
K > 2.3%	1
La/Eu > 34	3
Li > 30	1
Lu/Eu > 0.48	3
Mg < 1%	1
Nb > 25	2
Rb > 68	1
Rb/K > 28.2	2
Sr < 250	1
*Y(est.) > 63	1
Total	25 × 4 = 100 maximum possible

All trace element values in ppm.
* Chondrite-normalized.

The spatial distribution of PPI values greater than fifty identified several intrusions (fig. 15). Screening the *entire* data set for each quadrangle showed only a small number of false anomalies. Such samples usually have PPIs below sixty, and rarely occur in groups. In several cases, sediments on the periphery of granitoids and designated as draining other formations gave a high PPI value, reflecting granitoids detritus. This occurs, for example, east of the Pike's Peak batholith, particularly over the Palaeocene Dawson Formation and Quaternary Nussbaum Alluvium and eolian sands.

The range of PPI values over granitoid and other rock types in the Pueblo, Montrose, and Durango quadrangles are given in Tables VII–IX. It is clear that PPIs > 50 generally identify uraniferous granites, many of which are associated with uranium (or other element) mineralization while less uraniferous source rocks including alkaline complexes with high primary Th/U ratios are screened out. The index failed to identify the hydrothermally altered fluorite-enriched Baker's Bridge and Ten Mile Granites in the Durango triangle, however. In the case of the Trinidad quadrangle only a few PPIs exceeding 50 occur while areas mapped as alaskite granite have PPI values below 50. These areas are continuous with areas mapped as 'metamorphic' in the Pueblo sheets, however, suggesting the alaskites may be gneiss. Moreover, the northward extension of the 'alaskite granites' into the Pueblo quadrangle forms the 'barren' San Isabel Granite.

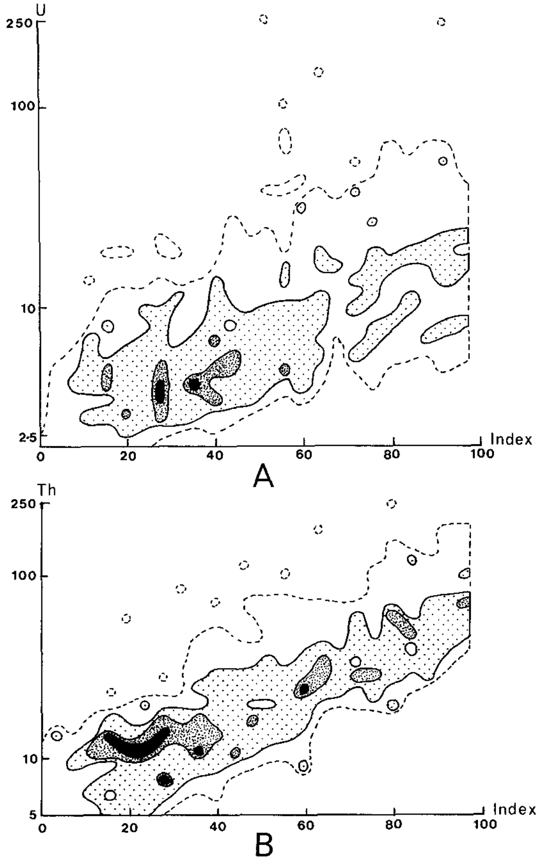


FIG. 14. Correlation of Pikes Peak Index with uranium (A) and thorium (B) in all 460 stream sediments draining acid and intermediate intrusions. Contoured at 0, 0.5, 1, and 2 per cent frequency.

Test method: other areas

A preliminary investigation of the application of the Pike's Peak index was also carried out for the Mount Ethel pluton, Colorado and the Alaska Range plutons for which LASL HSSR data are available. The Mount Ethel pluton (*c*.1400 Ma, Snyder and Hedge, 1976), comprises granodiorite, quartz monzonite and leucogranite. Fluorite is an abundant accessory in the rocks of the area, and the granitoids show many of the features of water–rock interaction listed in Table I. Behrendt *et al.* (1969) reported a −25 mgal Bouguer gravity anomaly and a zone of 'relatively smooth' magnetic anomalies of up to 100 γ.

Economic uranium mineralization occurs at several localities (fig. 16) within the area of the pluton. PPI values for the Mount Ethel and older (*c*.1700–1800 Ma, Snyder, 1979) Buffalo Pass

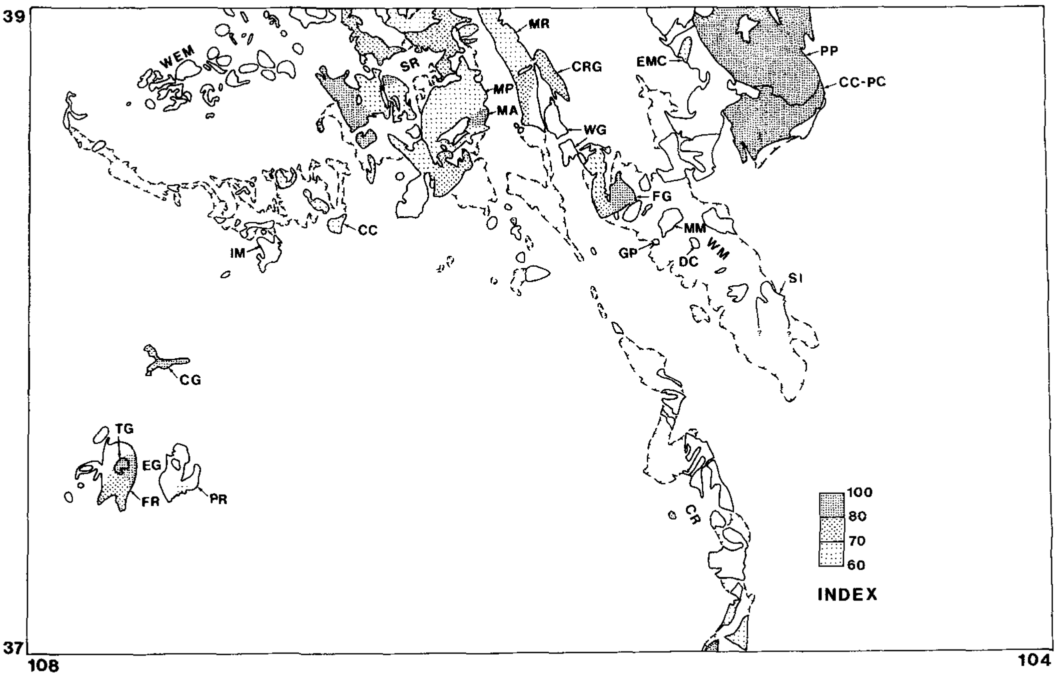


FIG. 15. Classification of all intrusive rocks in the study area on the basis of Pikes Peak Index values for stream sediments. Boundaries of intrusives shown by solid line, Precambrian metamorphic rocks by broken line. Geology after Johnson (1959), Scott *et al.* (1978), Steven *et al.* (1974), and Tweto *et al.* (1976). Key to abbreviations: CC, Cochetopa Canyon granite (Montrose); CC–PC, Cripple Creek–Phantom Canyon gneiss and migmatite (Pueblo); CG, Cateract Gulch granite (Durango); CR, Culebra Range (Trinidad); CRG, Castle Rock Gulch granodiorite (Pueblo); DC, Democrat Creek complex (Pueblo); EG, Eolus granite (Durango); EMC, Eleven Mile Canyon quartz monzonite (Pueblo); FG, Fernleaf Gulch granodiorite (Pueblo); FR, Florida River batholith (Durango); GP, Gem Park complex (Pueblo); IM, Iron Mountain complex (Montrose); MA, Mount Antero granite (Montrose); MM, McClure Mountain complex (Pueblo); MP, Mount Princeton batholith (Montrose); MR, Mosquito Range (Montrose); PP, Pikes Peak batholith (Pueblo); PR, Pine River batholith (Durango); SI, San Isabel granite (Pueblo); SR, Sawatch Range (Montrose); TG, Trimble granite (Durango); WEM, West Elk Mountains (Montrose); WG, Whitehorn granodiorite (Pueblo).

pluton are shown in fig. 16. The highest values occur mainly in the older core of the Mount Ethel pluton in the area of most important uranium mineralization (*c.*1700–1800 Ma) while no mineralization has been reported from the *c.*1700–1800 Ma Buffalo Pass pluton which is associated with low PPI values (fig. 16).

Beyth and McInteer (1980) have evaluated the potential for U mineralization of seven early Tertiary plutons in northern Alaska using multivariate statistical analysis based on the criteria of Simpson *et al.* (1979). PPI values calculated in this paper are entirely consistent with the results of Beyth and McInteer (1980); the plutons with the highest PPIs (Cathedral, Kahiltna, Ruth, and Tonzona) all have Sn mineralization although detailed follow-up for uranium has not yet been undertaken.

Conclusions

The 'Pike's Peak Index' applied to LASL stream-sediment data successfully identifies uraniferous granitoids of Precambrian and Tertiary age, while screening out alkaline rocks with high primary Th/U ratios and other rock types unlikely to provide a source of uranium; a similar approach could be applied to regional geochemical data elsewhere to identify potential uranium-mineralized granitoids. Further work is required to refine the index described in this preliminary evaluation, particularly as some elements (e.g. *RE* and Th) are not determined in many stream sediment surveys. Such an index is preferred for screening regional geochemical data to any single criterion such as Th since it is more stable.

The concept of uraniferous batholiths as im-

TABLE VII. *Granitoid rocks and Pikes Peak Index (PPI) for Pueblo quadrangle*

Rock formation	Age	Evidence of uranium enrichment/mineralization	PPI range
PPIs > 50			
Pike's Peak	1040 Ma	deuteric/hydrothermal alteration (see Table I)	70-96
Cripple Creek granite gneiss/migmatite	*c.*1700 Ma	minor uranium production from carnotite deposit in adjacent Dakota Sandstone	> 70
Salida granodiorite	1700-1690 Ma	minor uranium production (Cotopaxi). Uraninite/fluorite in associated metasediments (1)	> 70
Castle Rock Gulch granodiorite	Precambrian	monazite and euxenite in pegmatites (1)	50-60
Eleven mile Canyon and adjacent quartz monzonites	1460 Ma	strong residual uranium anomalies	50-60
PPIs < 50			
San Isabel	Precambrian	—	< 50
Precambrian intrusives NW of Canyon City and in the Wet Mountain	Precambrian	—	< 50
Alkalic igneous rocks and associated Th-rich carbonatites (high primary Th/U ratios)	Cambrian	—	< 50
Whitehorn granodiorite	Cretaceous	—	< 50

For references see Table IX.

TABLE VIII. *Granitoid rocks and Pikes Peak Index (PPI) for Montrose quadrangle*

Rock formation	Age		Evidence of uranium enrichment/mineralization	PPI range
PPIs > 50				
Granitoids of the Mosquito Range	Precambrian		monazite-, euxenite-enriched pegmatites (1)	> 50, 60-90 between Brown's Canyon and Buffalo Peaks
Granitoids of the Sawatch Range	Precambrian		associated with minor uranium in Palaeozoic inlier. Granites contain accessory fluorite tourmaline and beryl (1)	> 70
Granitoids near Los Ochos and at Stubbs Gulch	Precambrian		uranium deposits in adjacent sediments (which post-date Tertiary faulting) (1)	60-70
*Mount Princeton granitoid	36 Ma	intrudes against 1650 Ma granitoids (4)	associated with W-Mo mineralization (5)	60-70
Mount Pomeroy quartz monzonite	*c.*36 Ma			60-70
Mount Antero granite (intruded into Mount Princeton)	31 Ma		high residual uranium values; extensive mineralization with brannerite, beryl, molybdenite, hubnerite, wolframite, topaz, fluorite, and tourmaline in pegmatites. Hydrothermal alteration with zeolite, chlorite, illite, epidote, calcite, and fluorite over 64 km^2 (6)	> 90
PPIs < 50				
Powder horn granite	*c.*1700 Ma		—	< 50
Iron Hills alkaline (2) complex (Th, *RE*-enriched, low U)	570 Ma		—	< 50
Small granitoid stocks	70-65 Ma		—	< 50
West Elk and Sawatch Range granodiorite and quartz monzonites	*c.*36-30 Ma (3)		—	< 50 (but poor sample coverage)

* Associated with deep negative Bouger gravity low −310 mgal (residual anomaly −10 mgal) and also with the −30 to −50 NW-trending residual anomaly over the Colorado mineral belt attributed to Major Laramide/middle Tertiary batholith at depth (7). The rhyolitic Wall Mountain Tuff 36-35 which cover approximately 10400 km^2 may have originated from an associated caldera (8).

For references see Table IX.

TABLE IX. *Granitoid rocks and Pikes Peak Index (PPI) for Durango quadrangle*

Rock formation	Age	Evidence of uranium enrichment/mineralization	PPI range
PPIs > 50			
Trumble granite	1350 (9)	extensive hydrothermal alteration (9, 11)	70-90
Florida River granite		extensive hydrothermal alteration (9, 11)	70-90
Eolus granite	1454 (10)	10 sq. miles uraninite mineralization with fluorite in hydrothermally altered granite (1)	70-90
Cateract Gulch granite and margins	1350 Ma		50-90
Lake City	28 Ma	minor uranium mineralization (1) and (Au-Ag-Pb-Zn-Cu) mineralization (12)	50-90
Uncompagre Caldera (partly on Montrose quadrangle)	c.28 Ma		
PPIs < 50			
Eolus granite (east of Emerald Lake)	1454 Ma	—	< 50
Baker's Bridge Granite	1612 Ma	signs of hydrothermal alteration and fluorite in granite (9)	< 50
Ten Mile Granite	1724 Ma		

References for Tables VII-IX
(1) Nelson-Moore *et al.*, 1978
(2) Armbrustmacher, 1980
(3) Tweto, 1975
(4) Wetherill and Bickford, 1965
(5) Dings and Robertson, 1957
(6) Sharp, 1970
(7) Tweto and Case, 1972
(8) Scott and Taylor, 1975
(9) Bickford *et al.*, 1969
(10) Hutchinson, 1976
(11) Barker, 1969
(12) Steven *et al.*, 1974

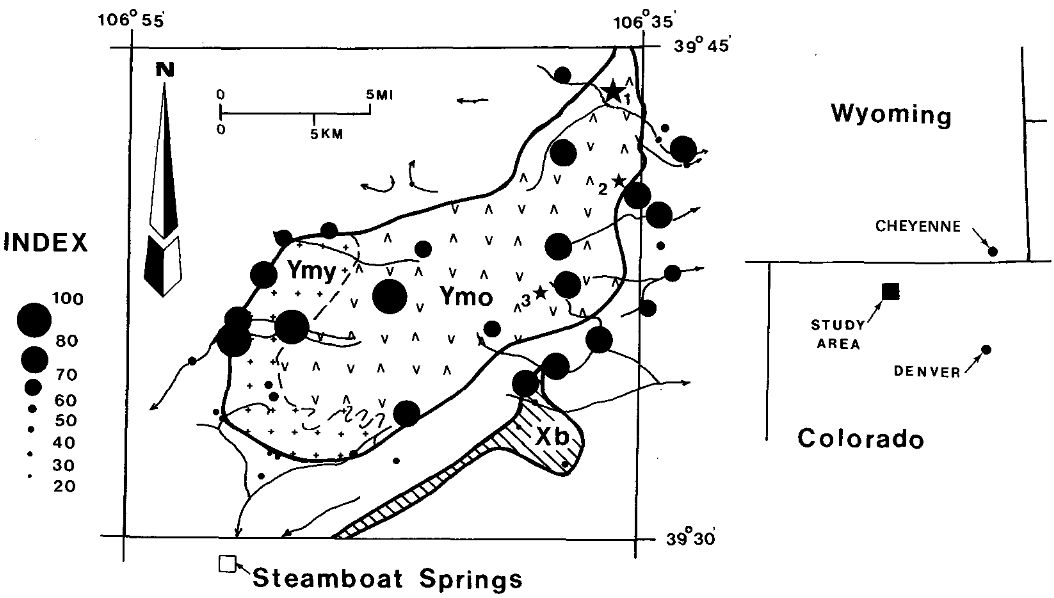


FIG. 16. Pikes Peak Index for stream sediments draining the Mount Ethel and Buffalo Pass plutons, Craig quadrangle, Colorado. Ymy = younger Precambrian rocks of Mount Ethel pluton; Ymo = older Precambrian rocks of Mount Ethel pluton. Geology after Snyder (1979) and stream sediment sample locations after Bolivar and Hill (1979). Localities with uranium mineralization after Nelson-Moore *et al.* (1978): (1) Pedad Claims, (2) Crystal Mine, (3) pegmatite vein.

portant source rocks for sedimentary uranium deposits indicated by detailed studies in Wyoming in relation to the Granite Mountains (Rosholt and Bartel, 1969; Seeland, 1978*a*, 1978*b*; Stuckless, 1978, 1979) probably applies elsewhere in the Rocky Mountains and adjacent regions; (Dahlkamp, 1980; Rose and Wright, 1980; Ragland and Rogers, 1980; Silver *et al.*, 1980). The use of stream-sediment data in the reconnaissance phase of exploration programmes elsewhere may focus attention on regions containing similar uraniferous granites, thereby helping to identify uranium provinces worthy of more detailed exploration.

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