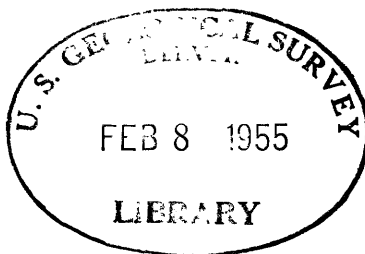# UNITED STATES GEOLOGICAL SURVEY

TEI-247

RADIOACTIVE TERTIARY PORPHYRIES IN THE CENTRAL CITY DISTRICT, COLORADO, AND THEIR BEARING UPON PITCHBLENDE DEPOSITION

By
George Phair

August 1952

This preliminary report is released without editorial and
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and nomenclature, to make the information available to
interested organizations and to stimulate the search for
uranium deposits.

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GEOLOGY AND MINERALOGY

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UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

RADIOACTIVE TERTIARY PORPHYRIES IN THE CENTRAL CITY DISTRICT,

COLORADO, AND THEIR BEARING UPON PITCHBLENDE DEPOSITION *

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Trace Elements Investigations Report 247

* This report concerns work done on behalf of the Division
of Raw Materials of the U. S. Atomic Energy Commission

RADIOACTIVE TERTIARY PORPHYRIES IN THE CENTRAL CITY DISTRICT,

COLORADO, AND THEIR BEARING UPON PITCHBLENDE DEPOSITION

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ABSTRACT

Results of analyses of 117 samples indicated that the Tertiary
porphyry sequence in the middle part of the Front Range ranks among
the most radioactive igneous series in the world, according to the
present literature. With the intrusion of nonporphyritic, lime-poor,
quartz bostonite dikes in the western half of the Central City dis-
trict, the magmatic enrichment in both uranium and thorium reached a
peak of more than 20 fold over the best available averages for granitic
rocks.

The sequence of events in the Central City district is thought to
be as follows: (1) intrusion of slightly to moderately radioactive
monzonite throughout the eastern half of the district, (2) intrusion
of excessively radioactive, nonporphyritic varieties of quartz bostonite
in the western half of the district north of what was to become the area
of pitchblende deposition, (3) intrusion of the highly radioactive quartz
bostonite porphyry dikes with which 15 of the 17 known occurrences of
pitchblende are now associated (within 500 feet), (4) deposition of

pitchblende as a local and unusual variant in the regional pyritic-
gold ore deposition near, but not in, the quartz bostonite porphyry
dikes. The implication of the field and chemical evidence is that
uranium-rich solutions given off by a cooling quartz bostonite mass
at depth became further enriched by leaching uranium from the quartz
bostonite channelways while en route to higher levels. Zircon, the
probable host for much of the uranium and part of the thorium in the
rocks, separated in reduced amounts from the youngest quartz boston-
ite liquids--a change which, in effect, tended to throw uranium into
the residual liquid. Possible mechanisms by which uranium became con-
centrated with respect to thorium in the derived aqueous solutions
are considered. In this connection the late magmatic introduction of
fluorite and of ferric oxides may be of special significance.

INTRODUCTION

About half of the writer's time in the field and laboratory since
June of 1949 has been spent upon a study of the relationships between
the pitchblende deposits and the Tertiary porphyries in the middle part
of the Front Range mineral belt. Since the early work of Ball, Spurr,
and Garrey (1908), who first showed this belt of ore deposits to be
coextensive with a belt of porphyry intrusion 90 miles long, the region
has been widely accepted as a text-book illustration of the close
genetic connection linking ore deposits and igneous intrusives. Recent-
ly Lovering and Goddard (1950) have summarized the regional evidence
linking specific ores with specific members of the porphyry sequence.

The immediate objectives of this study were to find out: (1)
whether or not the pitchblende deposition was related to a particular
member, or members of the porphyry series, and (2) if so, whether or
not such porphyry or porphyries had distinctive uranium contents.

It was hoped that the results would be of help in blocking out
favorable areas in the middle and northern parts of the Front Range
mineral belt for detailed uranium reconnaissance. Insofar as the present
study goes, both of the above objectives have been realized and the
results are positive. It remains for future investigations to determine
to what extent uranium deposits and the particular type of porphyry
are coextensive in parts of the Front Range outside of the relatively
small area covered by this report.

Because most of this nation's past production of high-grade pitch-
blende has come from mines on Quartz Hill in the Central City district

about 35 miles due west of Denver, our detailed studies have been concentrated in and around that district. For the purposes of this report we have included in the Central City district the northern half of the Idaho Springs district as outlined by Bastin and Hill (1917). These detailed investigations have been supplemented by a reconnaissance sampling of the porphyries in adjacent parts of the Georgetown Quadrangle. These studies represent a part of the U. S. Geological Survey's program of uranium reconnaissance in the Front Range carried on under sponsorship of the U. S. Atomic Energy Commission.

As early as 1916 Alsdorf inferred a genetic relationship between the pitchblende deposits in the Central City district and a type of porphyry, mapped by Bastin and Hill (1917) as bostonite. Alsdorf based his argument largely upon local space relationships. As geologist and operator of the main pitchblende-producing mines he had had an unrivaled opportunity to observe space relationships underground. Since Alsdorf's time most of these mines have been inaccessible. Upon the basis of regional evidence Bastin and Hill (1917) argued against a genetic association between pitchblende and bostonite. Later Hill (1944) reiterated his earlier views in a confidential report for the Union Mines Development Co. In their Front Range summary (1950) Lovering and Goddard re-examined the existing evidence and stated, "It is possible that the uranium-bearing solutions are related to a deep bostonite magma apexing in a narrow northerly zone at depth and that these fluids first followed fissures or dikes transverse to the east-northeasterly veins in which the ore has been found."

The writer was concerned with the intrusives as possible sources for the uranium in the veins and was able to devote full attention to the dikes, leaving the details of the actual deposits to the field geologists

responsible for their evaluation. In this connection thanks are due

Messrs. King, Granger, Armstrong, Moore, Leonard, and Harrison, all

of the Geological Survey, for cooperation in the field and for useful

information. We used the 1000 ft per inch geological maps of Bastin

and Hill as our base map but added the short easternmost bostonite

dike of the Wood group. We believe that the results reported here

confirm the genetic interpretation advanced originally by Alsdorf

and later revived by Lovering and Goddard.

Our contributions to the problem follow:

1. The pitchblende deposits are related most closely in

space and in time not only to bostonite but, in particular, to the

quartz-rich variety of bostonite.

2. These quartz bostonites are among the most radioactive

igneous rocks in North America if not in the world according to the

literature now available.

3. The high uranium and high thorium contents are primary

features of these porphyries.

4. One effect of hydrothermal alteration sufficient to

bleach the bostonite is to leach a part of the uranium originally

present. Such bleached bostonite is extremely common throughout the

district.

Both Alsdorf (1916) and Bastin and Hill (1917) have shown that

the pitchblende belongs to the earliest (pyritic) stage of Tertiary

mineralization in the district. Alsdorf believed that most of the

pitchblende deposition preceded most of the auriferous pyrite, but

Bastin and Hill thought both ores were essentially contemporaneous.

All agree that the silver- and gold-bearing galena sphalerite ores
are distinctly younger than the pitchblende and pyrite. Chalcopyrite
is commonly associated with both the early pyrite and the later galena
and sphalerite.

The writer agrees with Bastin and Hill (1917) that the pitchblende
is a local and unusual variant in the normal pyritic gold mineralization.
The author believes that the regional iron-bearing solutions became
enriched in uranium in and around centers of quartz bostonite intrusion
as a result of:

1. The acquisition of residual solutions derived from crystallizing
uraniferous quartz bostonite at depth.

2. The leaching of uranium from the solidified quartz bostonite
en route to higher levels. Here as elsewhere in the mineral belt the
hydrothermal solutions tended to follow the porphyry dikes as channelways.

Under changing pressure-temperature-concentration conditions probably
in a reducing environment, the uranium in solution was deposited with
sulfides near, but not in, the still cooling dikes.

We do not propose the quartz bostonite-pitchblende relationship as
a unique solution to the problem of pitchblende deposition in the middle
and northern parts of the Front Range mineral belt. We have been encour-
aged, however, by the fact that the Survey geologists during the past
year and a half have found probable bostonite near the only three uranium
prospects in the nearby Georgetown Quadrangle mapped in detail to date.
In none of these localities had bostonite been previously reported. One
of these prospects, the Jo Reynolds mine near Lawson, has a history of
past production of pitchblende. It was upon the supposed absence of

bostonite from the environs of this mine that Bastin and Hill based part of their argument opposing the genetic relationship.

We should like to thank L. B. Riley, L. R. Stieff, and T. Botinelly all of the Trace Elements Section Washington Laboratory for reviewing this manuscript, as well as Professor E. S. Larsen for many helpful suggestions in the course of the work and Kiyoko Shimamoto for assistance in the field and laboratory. The many chemists and spectrographers without whose assistance this study would not have been possible are cited in the text. For advice on matters pertaining to the chemistry of uranium we are indebted to F. S. Grimaldi.

PETROGRAPHY AND SPACE RELATIONSHIPS OF THE PORPHYRIES

Petrography

Among areas of similar size in the Front Range the Central City district is unique for the large tonnage of pitchblende produced and for the large volume of bostonite present. The bostonite is concentrated in relatively few dikes which are narrow but remarkably long. All the bostonites are characterized by a distinctive groundmass texture in which the elongated feldspars show mutually sutured boundaries against each other but are idiomorphic against quartz and are arranged in a divergent to subparallel (trachitoid) pattern. We have subdivided the bostonites into three sub-types depending upon the presence or absence of quartz in excess of 5 percent by volume and upon the presence or absence of megascopic phenocrysts of pink potash feldspar. Each subtype is characterized by a particular range of radioactivities and, as a result, outcrop gamma counts obtained with the Geiger counter are

helpful in their field identification. These gamma counts are not adequate, however, to differentiate between a moderately radioactive bostonite and a slightly to moderately radioactive monzonite. The classification of the porphyries on the basis of decreasing equivalent uranium content is summarized as follows:

	Av. equiv. U (percent)	Diagnostic features
Nonporphyritic quartz bostonite	>0.014	quartz, no phenocrysts, bostonitic texture
Quartz bostonite porphyry	>0.007 <0.014	quartz, potash feldspar phenocrysts, bostonitic texture
Syenitic bostonite porphyry	>0.004 <0.007	no quartz, alkali feldspar phenocrysts, bostonitic texture
Monzonite porphyry	>0.002 <0.007	plagioclase phenocrysts, An > 10 percent, texture not bostonitic

The principle bostonite dikes included in each subtype of bostonite are as follows:

	Dike	Approximate length in miles
Nonporphyritic quartz bostonite	Nigger Hill Prosser Gulch	3 2
Quartz bostonite porphyry	Wood group Pewabic group	5 1/4 3
Syenitic bostonite porphyry	California Topeka	2 2

The Central City quartz bostonites consist very largely of alkali feldspar and contain very few dark minerals. In these respects they

resemble the type bostonite, from Marblehead Neck near Boston, as
originally defined by Rosenbusch and Osann (1923). The Central City
quartz bostonites contain more silica and less lime than does the
type. Their composition is approximately that of a lime-poor granite.
The composition of the so called "monzonite" in the Central City dis-
trict ranges from sodic granite to syenite both of which contain more
normal amounts of lime and magnesia.

Results of standard chemical analyses of one quartz bostonite
(sample P108, Station 2), one quartz bostonite porphyry (sample P118,
Station 23), and one monzonite porphyry (sample P42, Station 68) are
given in table 1. The CIPW norms for the same rocks are given in table
2. It will be noted that all these porphyries are alkalic rocks but
both types of quartz bostonite are characterized by an extreme defi-
ciency in lime and magnesia and by a slight excess of potash over soda
(table 1). In all the porphyries analyzed, however, albite exceeds
orthoclase in the norm. The extreme lime deficiency in the liquid
from which the quartz bostonites crystallized suppressed the crystal-
lization of plagioclase phenocrysts and probably resulted in the crys-
tallization of the anorthoclase noted by Bastin and Hill (1917).

In the coarser-textured varieties of quartz bostonite most of the
ground mass consists of a perthitic intergrowth of stubby potash feldspar
phenocrysts and elongated mutually sutured albite showing a broad and
indistinct polysynthetic twinning. No unmixed anorthoclase remains. It
may be present, however, in the finer-textured varieties. Megascopic
phenocrysts, when present, are of potash feldspar which is pink when fresh.
In all porphyritic varieties of monzonite studied, megascopic phenocrysts

Table 1.--Results of standard rock analyses of selected porphyries
from the Central City district 1/

Sample no.	P42	P108	P118
Rock type	"Monzonite"	Quartz bostonite	Quartz bostonite
Texture	Porph-grani-toid	Nonporph, bosto-nitic	Porph, bostonitic
Radioactivity	Low	Very high	Moderately high
Location	Sta. 68 Gilson GL.	Sta. 2 Nigger Hill dike	Sta. 23, Main Wood dike

SiO_2	66.78	68.56	68.10
Al_2O_3	16.05	15.88	15.89
Fe_2O_3	1.69	3.06	1.43
FeO	2.09	1.19	2.49
MgO	.46	.10	.08
CaO	1.65	.00	.22
Na_2O	5.49	4.80	4.95
K_2O	4.74	5.44	5.65
H_2O-	.10	.20	.18
H_2O+	.32	.64	.70
TiO_2	.32	.14	.10
CO_2	.04	.01	.21
P_2O_5	.13	.04	.14
MnO	.09	.03	.12
Total	99.95	100.09	.100.26

1/ Analyst, W. J. Blake, U. S. Geological Survey

Table 2.--Norms of analyzed porphyries from the Central City
district

Sample no.	"Monzonite" P42 (wt. %)	Quartz bostonite P108 (wt. %)	Quartz bostonite porphyry P118 (wt. %)
Q	12.24	19.74	15.96
or	27.80	32.25	33.36
ab	46.63	40.35	41.92
an	5.28	--	--
c	0.51	2.14	1.63
di	3.20	--	--
hy	2.61	--	3.84
il	0.61	.30	--
mt	2.55	3.02	2.09
		(hm) 0.96	(cc) 0.40
	99.95	99.22	99.20
	+	+	+
H_2O-	0.10	0.20	0.18
H_2O+	0.32	0.64	0.70
CO_2	0.04	0.01	0.21
P_2O_5	0.13	0.04	0.14
	100.54	100.11	100.29

P108

Approx. mode (vol. percent)

Quartz	18.2
Total feld.	79.1
(mt etc.)	2.6

of plagioclase averaging sodic oligoclase are present, and generally exceed the potash feldspar phenocrysts in abundance. Unlike the quartz in the monzonites, most of the quartz in the quartz bostonites is concentrated in patches in the groundmass, each of which shows a common extinction throughout and poikilitically encloses euhedral albite laths.

In summary the following three diagnostic features of the quartz bostonites can be seen easily under the petrographic microscope at low power: (1) the presence of potash feldspar phenocrysts and absence of plagioclase phenocrysts in porphyritic varieties, (2) the quartz patches in the groundmass, and (3) the bostonitic texture.

Interstitial fluorite is present in one or more samples from each of the three quartz bostonite dikes richest in uranium. As yet we have found no fluorite in the syenitic bostonites or in the monzonites from this distict. The possible genetic significance of the fluorite will be discussed in a later section of this report along with the alteration of the sparse mafic silicates.

As noted by Bastin and Hill (1917), the bostonites when fresh are "lilac" in color whereas the fresh monzonites are medium gray. With hydrothermal alteration, both types of porphyry bleach to light gray and when altered in this way it is difficult if not impossible to tell one from the other without thin-section study particularly if megascopic phenocrysts are not present.

In the Central City district bleached porphyry is more common than unbleached and almost all samples show signs of hydrothermal alteration. Away from mineralized veins the alteration may be described as extensive rather than intensive. Singewald (1951) has called a similar widespread alteration of the porphyries in the Alma district an "end phase alteration",

As seems to be true in the middle and northern parts of the mineral belt, almost all of the dikes are more altered than the associated small stocks, and all porphyry bodies are more altered than their wall rocks. Like other workers in the Front Range and in other areas of Tertiary minerali- zation (Butler, 1915; Wahlstrom, 1936; Lovering and Goddard, 1950) we have inferred that dikes served as flues and channelways for volatiles and aqueous solutions emanating from larger porphyry bodies cooling at depth. In the Central City district the alteration usually extends only a few inches into the gneiss and schist adjacent to the porphyry, but at the immediate contact the wall rock is commonly bleached and soft.

The ore in the veins occurs as fissure fillings rather than as wall-rock replacements. The bulk of the gneiss country rock in marked contrast to the porphyries is unaltered both in hand specimens and in thin section.

With progressive hydrothermal alteration the groundmass of the quartz bostonite takes on a lighter hue as iron becomes leached. The final result is a bleached, porous, light-gray to chalky rock typically developed in and around mineralized fissures but also occurring elsewhere. The relation of color to iron content is shown by the following analyses of selected samples from the Nigger Hill dike.

Sample	Station	Color in hand specimen	Total Fe (percent) [1]
P15	3	dark lilac	2.93
P108	2	red lilac	2.82
P103	7	tan gray	1.74
P94	10	bleached gray	.86

[1] Analyst, A. M. Sherwood, U. S. Geological Survey

Most of the felspars are less altered than the associated mafics, but even those least altered are clouded by sericite and kaolin with resulting fuzzy optics. The large salmon-pink orthoclase phenocrysts typical of the freshest quartz bostonite porphyry show sharp shiny cleavages in hand specimens but are found to be dirty with sericite under the microscope. With increased sericitization these pink pheno-crysts become altered to soft greenish aggregates and eventually to a chalky white mixture of clay minerals.
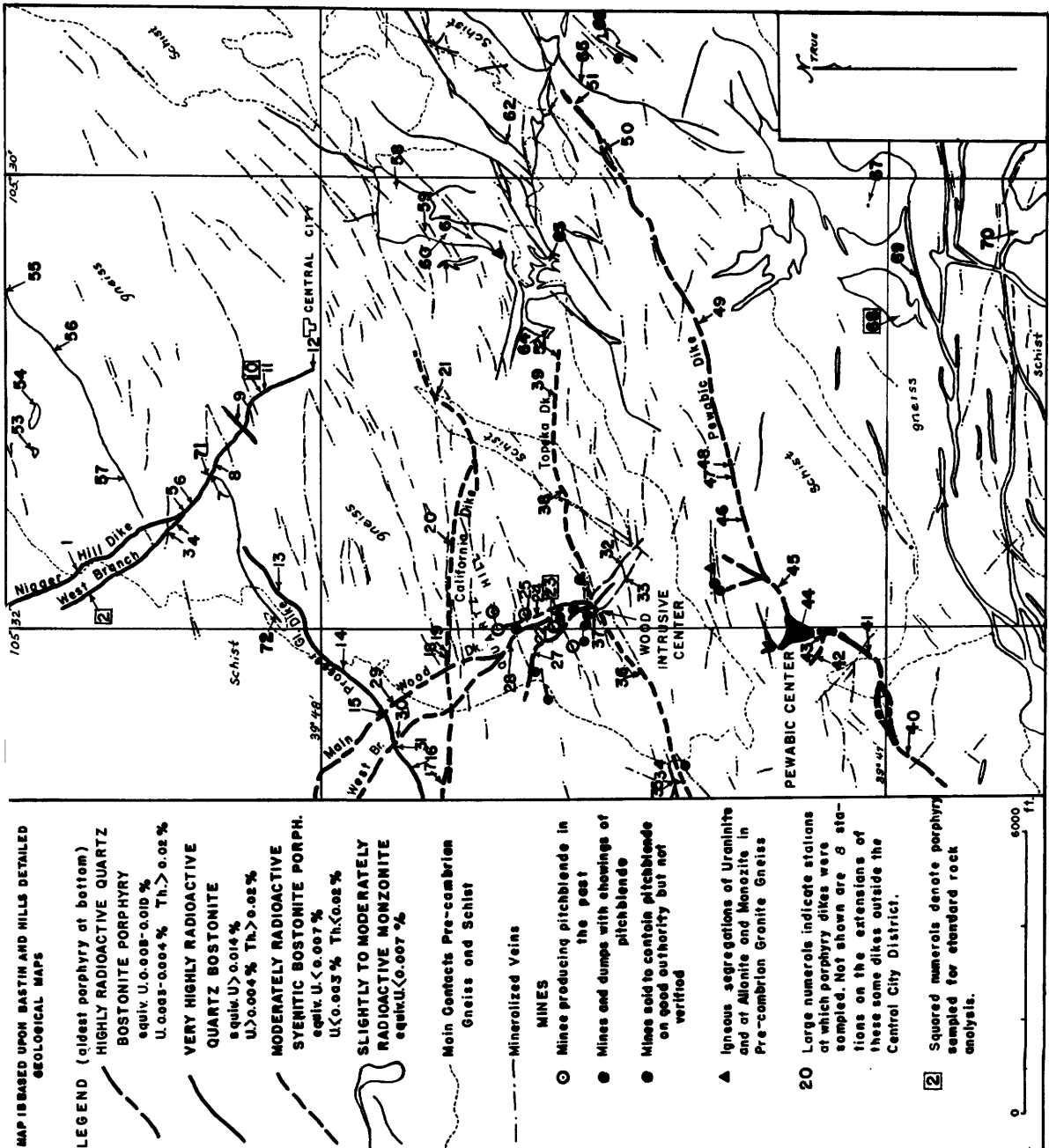
At least three types of sericitization are evident in thin section, but these types are not necessarily successive stages:

1. Development of sericite in clouds of small specks

2. Development of sericite in plates

3. Development of chains or festoons of sericite by the linking
   of plates.

In none of the 80 thin sections studied has sericitization completely obliterated the original grain boundaries of the feldspars and all quartz bostonites retain their characteristic microtexture. The seri-citization probably explains the appearance of as much as 2 percent of corundum in the norms of the analyzed quartz bostonites.

Space relationships

Figure 1 shows the distribution of the different porphyries with respect to all verified occurrences of pitchblende in the district. The precise location of the pitchblende underground is in most instances not known and the points designated are the shafts of the uranium-bearing mines. Because most of the shafts are nearly vertical and drifts are

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DISTRIBUTION OF RADIO-ELEMENTS IN TERTIARY PORPHYRY INTRUSIVES NEAR CENTRAL CITY COLO.

FIGURE 1

short the actual location of the pitchblende underground will generally
be included within the area of the small circles. Also shown are the
stations at which the porphyries were sampled. From one to five samples
were collected at each station. (For further details see appendix.)

With respect to the pitchblende deposits, figure 1 shows that the
slightly radioactive intrusives (monzonite stocks and dikes) are scattered
abundantly throughout a broad outer region encircling on three sides an
inner area characterized by more radioactive (bostonite) dikes. Roughly
half the district is characterized exclusively by bostonite, and half by
monzonite. The most radioactive of the intrusives, the nonporphyritic
quartz bostonite dikes, form a partial outer frame to the bostonite area
and are at a minimum distance of 3,000 feet from the nearest pitchblende
deposits. The next most radioactive porphyries, the quartz bostonite
porphyry dikes, near which all occurrences of pitchblende are localized,
radiate from two centers of intrusion, one, the Wood center on Quartz
Hill, the other the Pewabic center on Pewabic Mountain. Also present
within this inner area are the two quartz-poor dikes having only moderate
radioactivity and provisionally designated "syenitic bostonite" on the
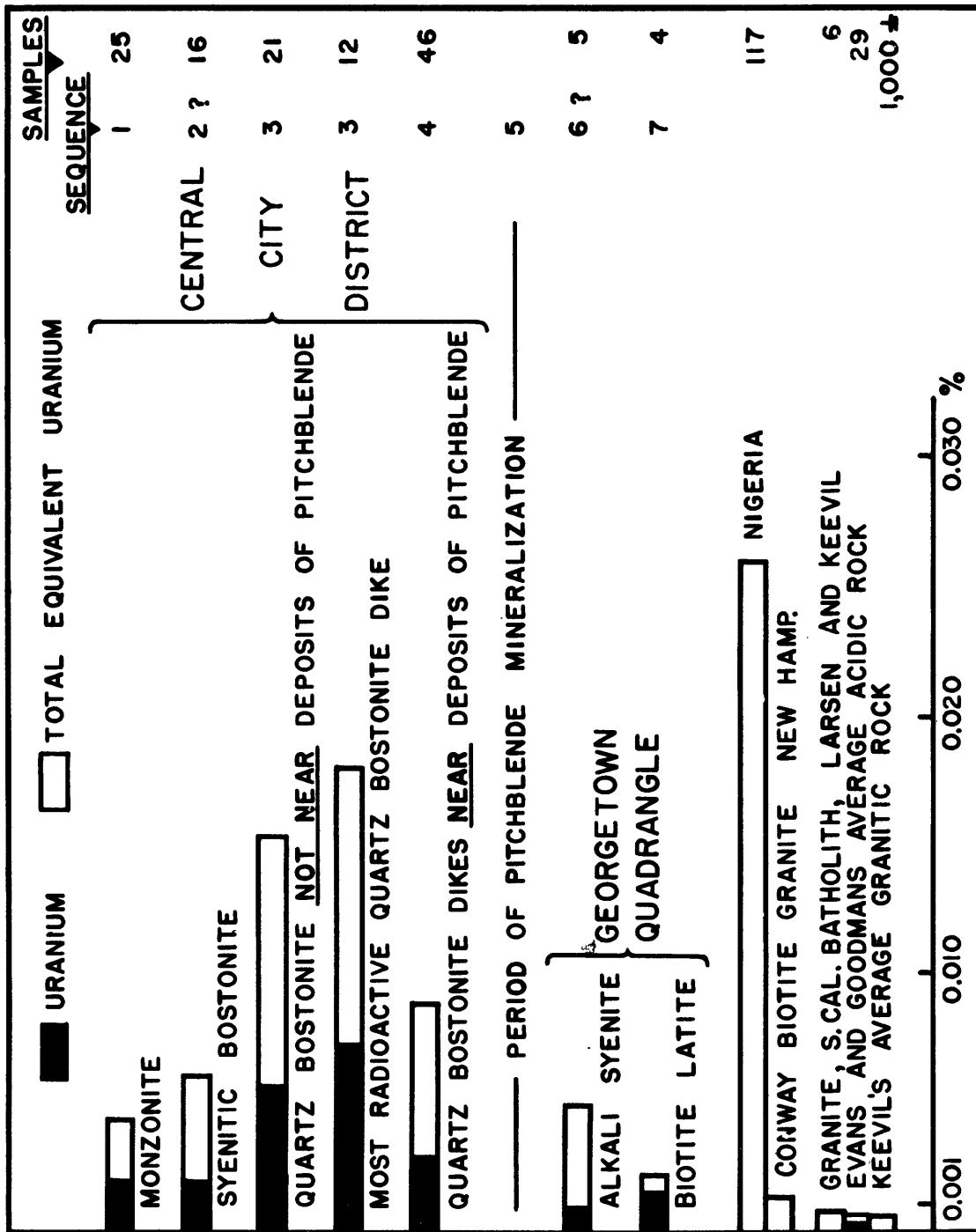basis of texture.

The belt of commercial pitchblende production trends north along
the projection of what is believed to be at depth a large quartz bostonite
body as inferred from the position of its probable apices, the centers
of intrusion on Pewabic Mountain and on Quartz Hill. This trend is nearly
at right angles to the strike of the associated mineralized veins and to
the regional boundaries of the ore zoning, as defined by Bastin and Hill
(1917). The past production of pitchblende has come from six mines on

four veins. In parts of these same veins, but outside of the pitch-blende belt, uranium if present at all is non-workable, but the associated gold content of the pyritic ore shows little change. The pitchblende in these veins is associated with early auriferous pyrite and chalcopyrite and is itself one of the earliest ores to be deposited (Alsdorf, 1916, Bastin and Hill, 1917). Subsequently more or less sphalerite, galena, and late chalcopyrite were introduced. Although all past pitchblende production has come from the vicinity of the Wood center of intrusion of quartz bostonite porphyry, the past production of gold has been about equally divided--half from the eastern monzonitic area and half from the western bostonitic area.

The commercial pitchblende belt is cut by the Wood group of quartz bostonite porphyry dikes. In addition to the 6 known sources of commercial pitchblende production, 11 noncommercial showings of pitchblende have been found or verified by the Geological Survey during the past 2 1/2 years, making a total of 17 mines known to contain pitchblende (Moore, King, Hinrichs, 1951). Of the 17 mines 16 are within 500 feet of the nearest bostonite porphyry dikes. The exception is the Bonanza mine in the eastern monzonitic area which is about 1,500 feet from the only bostonite dike recognized in that half of the district.

URANIUM AND THORIUM IN THE DIFFERENTIATING MAGMA

The sequence of intrusion of the majority of the porphyries indicated in the graphical compilation, figure 2, has been inferred from cross-cutting relationships and is known with reasonable certainty. The northwest-trending nonporphyritic Nigger Hill quartz bostonite cuts across a

Legend: ■ URANIUM □ TOTAL EQUIVALENT URANIUM

SAMPLES ▼
SEQUENCE ▼

SEQUENCE	SAMPLES
1	25
2 ?	16
3	21
3	12
4	46
5	
6 ?	5
7	4
	117
	6
	29
	1,000 ±

CENTRAL CITY DISTRICT

MONZONITE
SYENITIC BOSTONITE
QUARTZ BOSTONITE NOT NEAR DEPOSITS OF PITCHBLENDE
MOST RADIOACTIVE QUARTZ BOSTONITE DIKE
QUARTZ BOSTONITE DIKES NEAR DEPOSITS OF PITCHBLENDE
—— PERIOD OF PITCHBLENDE MINERALIZATION ——
ALKALI SYENITE } GEORGETOWN QUADRANGLE
BIOTITE LATITE
CONWAY BIOTITE GRANITE NEW HAMP.
GRANITE, S. CAL. BATHOLITH, LARSEN AND KEEVIL
EVANS AND GOODMANS AVERAGE ACIDIC ROCK
KEEVIL'S AVERAGE GRANITIC ROCK

NIGERIA

Scale: 0.001 0.010 0.020 0.030 %

URANIUM AND EQUIVALENT URANIUM CONTENTS OF THE SUCCESSIVE
PORPHYRIES COMPARED WITH OTHER GRANITIC ROCK
FIGURE 2

northeast-trending monzonite on Nigger Hill. The other nonporphyritic

quartz bostonite, the northeast-trending Prosser Gulch dike, is in turn

cut by porphyritic quartz bostonite intrusions, that is by the two

northwest-trending branches of the main Wood dike. In keeping with

their assigned younger age the porphyritic quartz bostonites radiating

from the Wood and Pewabic intrusive centers are the least altered

porphyry dikes in the district.

The place in the sequence of those porphyries followed by a question

mark has been inferred largely from the relative degree of hydrothermal

alteration and from their relationship to the mineralized veins. Included

in these doubtful classes are the syenitic bostonites in the Central City

district and the alkali syenites in the Georgetown district. Neither

type is present in a volume comparable to that of the monzonite and quartz

bostonite.

The quartz bostonites in the Central City district are in a direct

line of descent from the monzonites judging from their relative ages and

from the decreased lime alkali index, the decreased MgO/FeO index, and the

increased silica shown by the quartz bostonite analyses. Uranium, thorium,

and equivalent uranium show a marked increase in the quartz bostonites as

compared to the earlier monzonites. On the basis of chemical evidence

(table 3, figs. 3a, 3b), we have inferred that most of the uranium and

at least part of the thorium in the quartz bostonite is tied up in a

highly radioactive variety of zircon, such as cyrtolite or naegite.

Some of the earlier monzonites are just as highly enriched in zirconia

(as much as 0.22 percent) as the quartz bostonites but show no systematic

enrichment in uranium or thorium assignable to that cause. Because

the uranium contents of all monzonites, even those highly enriched in

the host mineral, zircon, are low, we have inferred that the concentration
of uranium and thorium in the monzonite liquid was low.

During the quartz bostonite stage immediately following, the concen-
tration of uranium and thorium in the differentiating liquid reached a
maximum. The least radioactive quartz bostonites contain on the average
about twice the radioactivity of the average monzonite. These less
radioactive quartz bostonites are porphyritic and are reduced in uranium
and thorium by about 50 percent compared to the earlier nonporphyritic
types. This difference is probably more apparent than real in terms of
the actual uranium and thorium contents of the liquids from which the
rocks crystallized. It probably reflects the fact that the liquid had
become depleted in zirconia by the time the latest quartz bostonites
were intruded; corresponding to the 50-percent reduction in uranium and
thorium is a 50-percent reduction in zirconia. Perhaps better indices
of the uranium and thorium contents of the liquid are provided by the
uranium and thorium contents of the zircon as inferred from the U/ZrO_2
and Th/ZrO_2 ratios. These ratios show much less variation than do the
total uranium and total thorium contents when comparing the very highly
radioactive quartz bostonites with the later less highly radioactive quartz
bostonite porphyries. If anything, the effect of the partial cessation
in crystallization of zircon was to throw uranium and thorium into the
residual liquids already enriched in these constituents just prior to the
vein-forming stage.

No porphyries younger than the mineralization are found in the Central
City district. However, of the porphyries in the adjacent Georgetown
Quadrangle, the biotite latites are definitely younger than the mineral

deposits (Ball, Spurr, and Garrey, 1908), as are the alkali syenites also.
Compared to the majority of the porphyries in the Central City district
these latites and syenites are of questionable ancestry and may have
stemmed from quite different parent magmas. At any rate the average ura-
nium contents of both these rocks, and the thorium contents of the biotite
latites as well are the lowest of all the Tertiary porphyries sampled to
date in the middle part of the Front Range.

The results of uranium and equivalent uranium analyses upon 50 samples
of pre-mineralization porphyries from the Georgetown Quadrangle, including
"alaskitic quartz monzonite", "granite porphyries", and "bostonites", have
not been included in the graphical compilation (fig. 2) because of un-
certainty as to their petrography and order of intrusion. In general
these have average uranium and thorium contents about as high as the
monzonites in the Central City district. Sixteen samples of so-called
"bostonite" from the larger area average about 20 percent lower in both
uranium and equivalent uranium contents than do the least radioactive bos-
tonites, the syenitic bostonites, in the Central City district.

Included in the compilation for purposes of comparison are the correspond-
ing data for two abnormally radioactive sodic granites and three so-called
"average granitic rocks". To convert radioactivity in terms of total alphas/
mg/hr as given in the literature to radioactivity in terms of percent equiv-
alent uranium we use the relation, $2.745 \times \text{alphas/mg/hr} \times 10^{-4} = \text{weight}$
percent equivalent uranium, as suggested by Professor E. S. Larsen (personal
communication). The average uranium contents of four of the five are not
known.

The averages for "granitic igneous rocks" represent the best data
available for North America but are at best only order-of-magnitude esti-

mates. An increase of as much as 100 percent in the general averages as eventually determined will not materially affect the conclusions presented in this report. Unquestionably many more abnormally radio-active igneous rock series exist than are presently known, but we doubt that the total volume of such rocks will be found adequate to increase the general average by as much as 100 percent. For all their limitations the present averages provide a basis for preliminary com-parison. Because of close petrologic similarities to the quartz bos-tonite, the sodic granites provide a more significant standard of comparison.

Figure 2 shows that the entire porphyry sequence in the region studied is more highly radioactive than the Conway biotite granite member of the White Mountain series, the next most radioactive granite so far described from North America. The least radioactive porphyry in the region, the post-mineralization biotite latite, contains on the average about twice as much equivalent uranium as the Conway biotite granite but the sampling of these scarce latites is admittedly scanty. The Conway biotite granite is in turn about twice as radioactive as the "average granitic rocks". The monzonites in the Central City district contain about 8 times as much equivalent uranium and 6 times as much uranium as the "average granitic rocks". The least radio-active quartz bostonites in the Central City district--the latest porphyritic types--contain on the average about 15 times as much equiv-alent uranium and 10 times as much uranium as the "average granite". The most radioactive quartz bostonites--the earlier nonporphyritic types--contain on the average about 25 times as much equivalent ura-nium and 20 times as much uranium as the "average granite". The only

igneous rocks known to exceed these non-porphyritic quartz bostonites
in radioactivity are the pyrochlore-bearing sodic granites from Nigeria
recently described by Greenwood (1952) and by Beer (1951). Their
average equivalent uranium content is graphed in figure 2.

The Th/U ratios in the least altered quartz bostonite and quartz
bostonite porphyries average about 6.4 and seem to be fairly constant
(within ± 0.5) from dike to dike. This compares with an average Th/U
ratio of 5 for Evans' and Goodman's "average granitic rocks" and of 3.3
for Keevil's "average granitic rocks". The individual measurements
upon which the published averages for granitic rocks are based depart
widely from the means but one fact seems certain--granitic igneous rocks
measured to date, like the quartz bostonites and related porphyries,
contain a large excess of thorium over uranium.

The Central City quartz bostonite, the Conway biotite granite, and
the Nigerian riebeckite granite have many unusual features in common.
Together these define the characteristics of one type of magmatic environ-
ment which favored in a peculiar way the co-concentration of both uranium
and thorium. In so doing these features throw light upon the probable
mechanisms by which this concentration was accomplished. Because of
their bearing upon uranium reconnaissance and upon the broader problem
of the distribution of uranium and thorium in the igneous rocks, an in-
vestigation of which was recently begun by the Geological Survey, these
features will be briefly described.

All three granites are soda rich, rather deficient in dark minerals
and belong to predominately alkalic suites. They represent the silica-
rich end members of series of differentiates, the intermediate members

of which were "syenites" and "monzonites". The syenites are markedly

deficient in thorium and uranium as compared to the later silica-rich

members. The combination of high soda and high silica, and not high

soda alone, is apparently prerequisite to, or at least correlative with

the optimum concentration of uranium and thorium in a magma series of

this type.

All three radioactive granites are characterized by very high con-

tents of zircon, and many phases of each contain interstitial fluorite

which has all the appearance at least of a late-magmatic primary acces-

sory. Abnormally abundant zircon and fluorite suggest crystallization

from a volatile-rich liquid. The bulk composition of the three rocks

and their general deficiency in mafic minerals indicate that their

liquids had compositions close to that of a sodic granite pegmatite--

a composition especially favorable to volatiles. The possible signifi-

cance of the fluorite in the quartz bostonites will be discussed in

greater detail in the section on "rock alteration".

The solid phases in which most of the uranium and thorium are con-

centrated differ in all three granites. Pyrochlore, a mineral generally

associated with pegmatites, contains most of the uranium and thorium in

the Nigerian riebeckite granite. Allanite and possibly zircon are said

to be the radioactive minerals in the Conway biotite granite (Billings

and Keevil, 1946). A considerable part of the radioactive content in

the Central City quartz bostonite seems to be present in zircon but

actual thorium minerals may be, and probably are present in the most

radioactive dikes.

Greenwood (1951) in comparing the White Mountain and Nigerian granites

states "texturally the granites resemble each other in the tendency of

their major constituents to clump ...". The same texture is typical of the quartz bostonites in which the quartz forms large clots poikilitically enclosing feldspar laths.

All three granites were intruded during a late stage of deformation, the Conway and Nigerian granites commonly in stocks and batholiths, the bostonites in exceedingly long narrow dikes. Porphyritic phases with fine-grained matrices and numerous "chilled" contacts suggest that the intrusion of all three took place at no great depth possibly under pressures which permitted the local separation of a vapor phase. Small tin deposits are said to be associated with the Conway biotite granite, and deposits of both tin and tungsten are associated with the Nigerian riebeckite granite. This "high temperature" mineralization suggests that the early ore solutions, like the liquids from which they were derived, were rich in volatiles.

Source of the radioactivity in the quartz bostonites

The difficulties inherent in the separation of the sparse ground-mass accessories from these fine-grained partly altered quartz bostonites and quartz bostonite porphyries, all of which contain less than 0.02 percent uranium and 0.05 percent thorium, have necessitated an indirect chemical approach to the problem of the uranium and thorium mineralogy. Bromoform separations using material crushed as fine as -200 mesh have been of value chiefly in confirming the relative abundance of magnetite and fluorite, two minerals previously identified in thin sections. Now in progress are heavy-liquid separations with the aid of the centrifuge, and planned for the immediate future are nuclear-emulsion studies of thin sections.

Preliminary semiquantitative spectrographic analyses of 19 selected porphyry samples indicated that many had zirconium contents above 0.1 percent, but that the rare earths, the common associates of uranium and thorium, were below the limits of detection in all samples. The same samples were analyzed specifically for ZrO_2 using the gravimetric method as described in Hillebrand and Lundell (1929) with the results listed in table 3. The standard gravimetric methods yield results which are only approximate in the range below 0.05 percent ZrO_2--the range of common granitic rocks. The porphyries, and in particular the quartz bostonites, average considerably higher in ZrO_2 than 0.05 percent and the relative weighing error is reduced proportionately. In addition certain precautions were taken to increase the precision of the determinations:

1. All samples were analyzed in duplicate

2. The final precipitates in all samples very high in zirconia were analyzed semiquantitatively by spectrographic methods and were found to be free of significant amounts of impurities.

The final check on the data is the internal consistency of the results. In general samples from the same dike have zirconia contents in a characteristic range, and in the quartz bostonites radioactivity increases with an increase in zirconia. The data suggest that the limits of error in the averaged duplicate determinations is less than $\pm$ 0.02 percent ZrO_2.

If 0.02 percent is taken as the average ZrO_2 content of a normal granite, the results show that all these alkalic porphyries with the exception of the alkali syenite are enriched in zirconia, but its distribution within the series as a whole is decidely erratic.

Table 3.--Results of analyses of rocks from various intrusives.

Rock type	Intrusive	Sample	Equiv. U 1/ (± .001)	U 2/ (± .0005)	Th 3/ (± .005)	ZrO$_2$ 4/ (± .02)
Alkali syenite	Stock, Idaho Springs	P23 A		0.001		0.01
"	" " "	P23 B		0.001	0.003	0.02
	Central City Intrusive					
Quartz monzonite	Bobtail Hill Dike	P9	0.007	0.004	0.009	0.01
"	Gregory Hill Stock	P21	0.004	0.001	0.008	0.06
"	Queen's Chair Dike	P88	0.003	0.003		0.22
Syenitic bostonite	Topeka Dike	P26	0.006	0.002		0.07
"	"	P27	0.005	0.001	0.010	0.05
"	"	P48	0.006	0.001	0.008	
"	California Dike	P112	0.004	0.002	0.006	0.19
"	"	P114	0.005	0.001	0.010	0.16

1/ Analyst, George Phair, U. S. Geological Survey
2/ Analysts, L. F. Rader and F. S. Grimaldi, U. S. Geological Survey
3/ Analyst, Harry Levine, U. S. Geological Survey
4/ Analyst, A. M. Sherwood, U. S. Geological Survey

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Table 3.--Continued.

Rock type	Intrusive	Sample	Equiv. U (± .001)	U (± .0005)	Th (± .005)	ZrO$_2$ (± .02)
Quartz bostonite	Nigger Hill Dike	P14	0.022	0.014	0.021	0.14
"	"	P15	0.020	0.007	0.026	0.13
"	"	P94 (bleached)	0.010	0.003	0.020	0.05
"	"	P103	0.024	0.017	0.026	
"	"	P107-108	0.013	0.005	0.023	0.18
"	Prosser Gl. Dike	P17	0.018	0.006	0.049	0.12
"	Pewabic Group of Dikes	P8	0.015	0.007	0.040	0.06
"	"	P133	0.013	0.004	0.026	0.11
"	Wood Group of Dikes	P29	0.008	0.002	0.021	0.06
"	"	P117-P118	0.007	0.003	0.024	0.07
"	"	P116 (Branch)	0.007	0.003	0.008	0.02

All 22 samples had been analyzed previously for uranium and equivalent uranium. Eighteen of the 22 were subsequently analyzed for thorium by recently developed chemical methods. The results range from 0.003 percent to 0.054 percent ThO_2. The analyst believes the results are reproducible to $\pm$ 0.003 percent. Contents below 0.04 percent ThO_2 were determined nephelometrically by comparison with known standards; for details of the method see Grimaldi and Fairchild (1946). Contents above 0.04 percent ThO_2 were determined gravimetrically in the manner described by Grimaldi and Marsh (1947); the heaviest of the final precipitates was analyzed by semiquantitative spectrographic methods and was found to contain negligible amounts of impurities. In table 3 ThO_2 has been converted to Th.

When the more radioactive porphyries--the quartz bostonites--alone are considered, several systematic trends are evident. Figure 3a indicates that radioactivity (equivalent uranium content) clearly increases with an increase in ZrO_2. In figure 3b the uranium contents are plotted as a function of ZrO_2. Although the points scatter rather widely, they are concentrated in a broad belt indicating that uranium increases with an increase in ZrO_2. Not shown is the plot of thorium versus zirconia. The analytical errors in the determination of both these constituents are so large that the points are widely scattered and even the direction of the trend is not obvious. The fact that only a part of the total thorium in the quartz bostonites seems to be tied up in zircon also tends to make the distribution of the points more erratic. In view of the correspondence between equivalent uranium and zirconia, (fig. 3a), between uranium and zirconia (fig. 3b), and between uranium and thorium (fig. 3c),
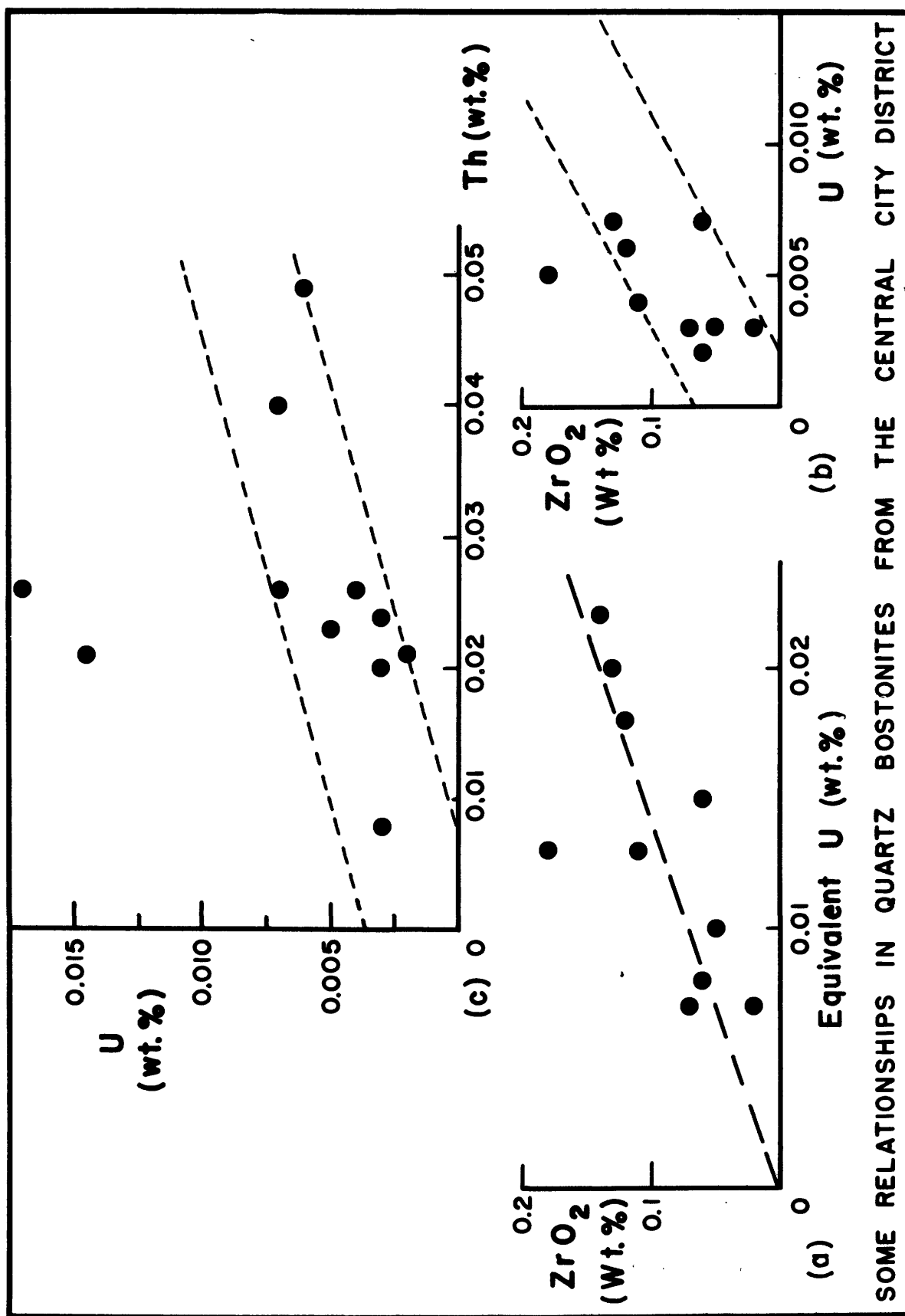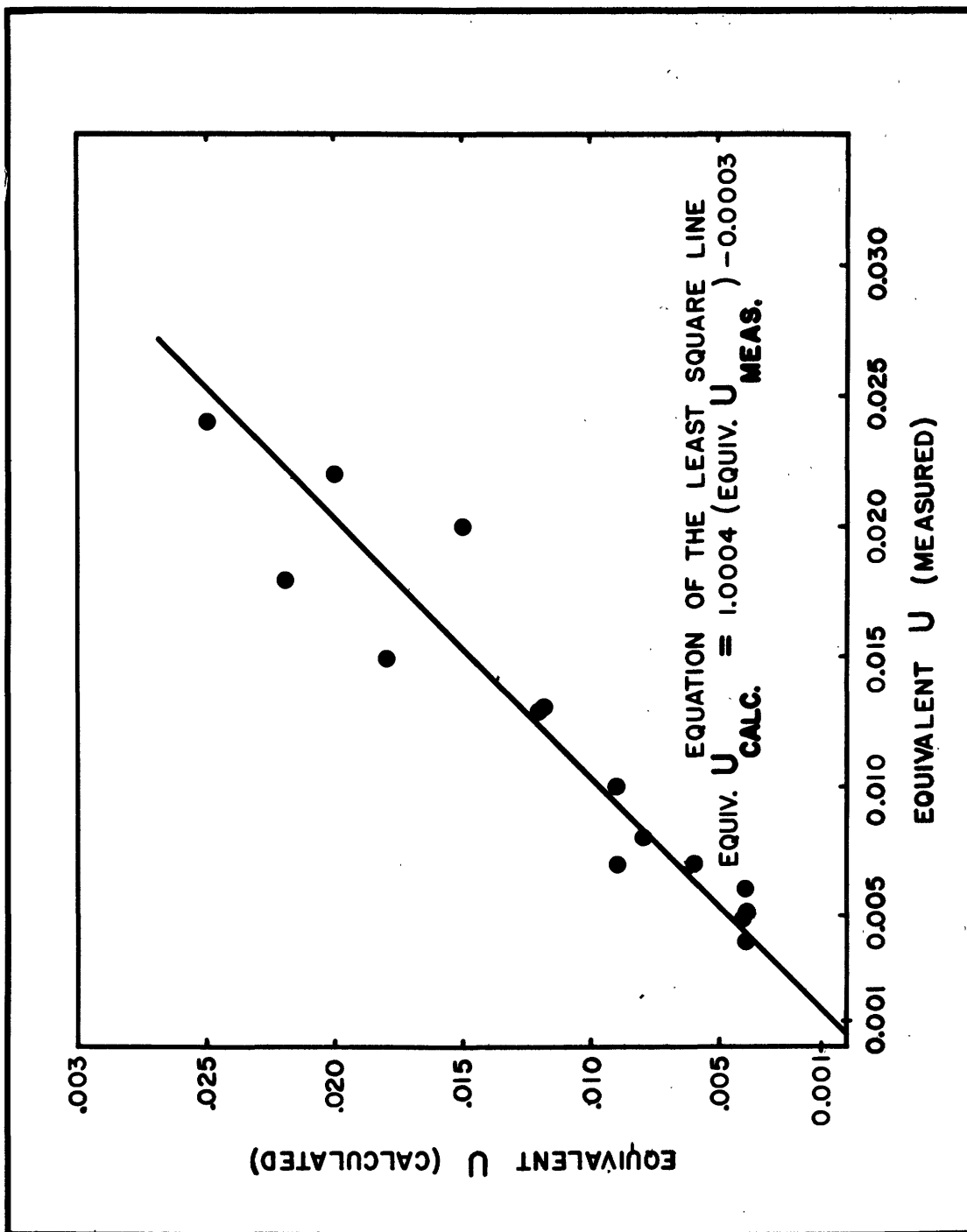
FIGURE 3

SOME RELATIONSHIPS IN QUARTZ BOSTONITES FROM THE CENTRAL CITY DISTRICT

it seems safe to infer that the thorium and zirconia are similarly but less closely related. In addition to highly radioactive zircon, actual thorium minerals may be and probably are present in the high thoria samples. Regardless of just how much of the thorium present is actually tied up in zircon the fact that all three constituents, uranium, thorium, and zirconia, have co-concentrated in the quartz bostonites is clear from the data.

Using an empirically determined constant for the beta-gamma counting rate of old age thorium in terms of old age uranium, we have calculated the equivalent uranium contents of the 15 quartz bostonite samples from their known contents of thorium and uranium. The relative agreement between calculated and measured values for equivalent uranium gives an estimate of the extent to which complete radioactive equilibrium has been attained by the thorium and uranium present in these rocks. With a National Bureau of Standards 0.01-percent-thorium standard, we found that old age thorium had $\frac{1}{3.6}$ (= 0.28) times the beta-gamma counting rate of an equal concentration of old age uranium under the particular experimental conditions employed. We obtained an independent check on this factor by measuring the equivalent uranium content of eight selected bostonites, both quartz-rich and syenitic varieties, for which the thorium and uranium contents were known and by determining the relative counting rate as follows: $C = \frac{eU-U}{Th}$. The mean relative counting rate so obtained turned out to be 0.28, identical with that obtained by the direct comparison of the counts obtained from the thorium and uranium standards. It is not surprising, therefore, that when calculated uranium contents are plotted against the measured values, the least square line passing among the 15 points has a slope

so close to unity that the difference cannot be plotted (fig. 4) where
a slope of unity indicates 100 percent equilibrium. The intercept
X = 0.0003 possibly represents the contribution of the K^{40} in the 5
percent K_2O presents in these small samples (approx. 6 g). Only in
beta-gamma counting methods utilizing much larger samples does the
effect of potassium become significant because of the increased gamma/
beta counting ratio.

In part the above agreement must be fortuitous; we claim no such
precision for the method. The difference between measured and calculated
equivalent uranium in one sample was as great as $\pm$ 14 percent of the
mean of the two values. This is about the limit of the expected experi-
mental error. More commonly the errors of the separate determinations
should tend to compensate and they apparently do. The maximum deviation
from the means in the remaining 14 samples is $\pm$ 10 percent. The moving
average represented by the slope of the least square line is, of course,
a much better measure of the relative equilibrium than are the data for
any single sample. We seem justified in concluding that the departure
from perfect equilbrium in these rocks is at most 10 percent and in all
probability considerably less. According to Kovarik's data (1931) it
requires approximately 260,000 years for the Ra/U ratio to reach 90
percent of its equilibrium value, and 600,000 years to reach 99.9 percent.
Once equilibrium has been set up between uranium and radium, only a very
short time is required for the daughter products below radium to reach
a steady state neglecting of course Pb^{206} which constantly accumulates,
and as a result, the time required for complete equilibrium in the entire
U^{238} series is similar to the time required to set up the Ra/U equilibrium.
Thorium requires less time (less than 200 years) to reach equilibrium

EQUATION OF THE LEAST SQUARE LINE

EQUIV. $U_{CALC.}$ = 1.0004 (EQUIV. $U_{MEAS.}$) −0.0003

EQUIVALENT U (MEASURED)

EQUIVALENT U (CALCULATED)

CALCULATED VERSUS MEASURED EQUIVALENT URANIUM CONTENTS
OF FIFTEEN BOSTONITE SAMPLES

FIGURE 4

than does uranium because of the shorter half lives of its daughter products.

The fact that the radioactive elements in these rocks are approximately in radioactive equilibrium simplifies the interpretation of their origin, condition, and manner of distribution. Investigators working with granitic rocks having the usual low radioactivity contents have met with anomalous results which complicate the determination of helium ages and lead-uranium ages for such rocks. Hurley (1950) states, "Granulated samples of acidic igneous rocks have been found to give a much higher rate of emission of alpha particles than corresponds to the known total contents of uranium and thorium. Abnormally large residual ranges of the alpha particles suggest a superficial distribution of the radioactive elements on the surface of the granules in the form of secondary mineral coatings. Most of the alpha-particle activity can be removed by dilute HCl leaving an activity corresponding to the low content of uranium and thorium found in sandstones and arkoses in which the essential mineral grains of granite have been rounded and cleaned by attrition."

Hurley found that the total alpha activity was reduced 90 percent by leaching the granulated samples in hot 1:4 HCl. Larsen (personal communication) found that 85 percent of the uranium content of a sample of crushed granite was leached by hot 1:1 HCl. Either treatment would dissolve all radioactive apatite present in addition to the surficial concentrations of radioactive elements. It would probably attack to some extent any monazite or allanite present, as well as any uraninite having a high UO_3/UO_2 ratio but how much leaching would result cannot be predicted. So far as we know zircon itself should not be attacked if not metamict. Professor Larsen plans to investigate this problem further.

Hurley attributed much of the excess radioactivity of his granites
to recent supergene reconcentration. The fact that the radio elements
present in the bostonites are in approximate equilibrium seems to rule
out the possibility that substantial reconcentration could have taken
place in these rocks within the past quarter of a million years. Never-
theless as a check upon the amount of older secondary uranium minerals in
the bostonite, we leached two samples (P14 and P103) with 1:4 HCl over a
steam bath for two days. These two samples (represented by the two
maverick points on figure 4) were selected because of their excessive
uranium contents and because their abnormally low Th/U ratios suggested
the likelihood that secondary reconcentration of uranium may have occurred.
In fact, one of the two samples, P14, contained a few yellowish specks
which gave positive flux tests for uranium and were almost certainly
secondary uranium minerals. After leaching, the uranium content of this
sample was reduced from 0.013 percent to 0.005 percent. This residual
uranium content is very close to the average for the four least altered
samples from the same dike (0.0058 percent U) and not too far from the
average for the dike as a whole (0.0075 percent). The equivalent uranium
content was reduced from 0.022 to 0.011 percent by the same treatment, the
difference being due largely to a loss of uranium rather than of thorium.

The other sample was similarly treated. Its uranium content was
reduced from 0.016 to 0.010 percent, and its equivalent uranium content
was reduced from 0.024 to 0.020 percent. The leaching of uranium with its
daughter products satisfactorily accounts for all the difference in equiv-
alent uranium. Again the calculated thorium content shows little change.

These results have led us to the opinion that uranium contents below
0.008 percent in unweathered quartz bostonite are probably present in

zircon and/or in primary uranium minerals. That part of the uranium content in excess of 0.008 percent may or may not be present as soluble secondary uranium minerals. Most quartz bostonite samples characterized by more than 0.010 percent uranium contain little, if any, nonhydrous iron oxides and are visibly weathered.

URANIUM AND THORIUM IN THE DERIVED HYDROTHERMAL SOLUTIONS

Some samples from all three quartz bostonite dikes richest in uranium contain fluorite. So far we have found no fluorite in the slightly less uraniferous Wood group of quartz bostonite dikes nor in the other types of porphyry that are less radioactive, but it may be present in scattered grains. The fluorite in the sample from the Nigger Hill dike concentrated in the heavy-mineral fraction during a bromoform separation amounted to several percent of that fraction. The fluorite in the samples from the Prosser Gulch and Pewabic dikes is sufficiently abundant to be conspicuous in thin section; in one section from the Pewabic dike fluorite is the most abundant of the sparse accessory minerals.

Under the microscope the fluorite shows the textural relationships one might expect of a late magmatic mineral. It is interstitial to the feldspar, forms separate discrete grains irregular in outline commonly larger in size than the groundmass feldspar and never, so far as we have been able to observe, does it form cross-cutting veinlets or aggregates.

Ball, Spurr, and Garrey (1908) found similar-appearing fluorite to be characteristic of certain "bostonite" dikes in the Georgetown Quadrangle. In most of these it seemed to be distributed throughout the length of the dike without regard to the nearby hydrothermal veins. Like the writer

they believe that such fluorite crystallized from the residual magma rather than from the derived hydrothermal solutions. We would hesitate to ascribe a late magmatic origin to a mineral on the basis of textural criteria alone, but when its restriction to porphyries of a single petrographic type is considered, we believe that the weight of the evidence favors such an interpretation.

The world-wide association of pitchblende and fluorite and similarities in crystallography of both minerals suggest that many conditions favoring the concentration of the one favors the concentration of the other. Not only is uraninite present in many hydrothermal fluorite deposits throughout the world, but at least some fluorite is associated with most of the world's larger pitchblende deposits. The fact that the radioactive granite from Nigeria and the significantly radioactive Conway biotite granite both contain late fluorite has been previously noted. Among the uraniferous ore deposits characterized by radioactive fluorites are those at Wollsendorf, Germany; Marysvale, Utah; Jamestown, Colorado; and in the Thomas Range, Utah.

The question arises as to what part of the uranium content of the quartz bostonites may be tied up in fluorite. All three minerals uraninite, thorianite, and fluorite have the Ax_2 lattice, and all three have face-centered cubic unit cells with cell edges close to 5.50A. Individual deeply colored, opaque to semiopaque grains of certain radioactive vein fluorites (Phair and Onoda, 1951) contain as much as 1 percent uranium in the form of minute uraninite inclusions suggesting that the amount of substitutes of U^{4+} (ionic radius 1.05A) for calcium (ionic radius 1.06A) at the temperature of formation of such fluorites may have been high.

However, judging from the purple color of the fluorite in the bostonite, by its lack of inclusion, and by its relative abundance we infer that only an insignificant part of the total uranium content of the rocks as a whole can be tied up in the mineral.

The presence of fluorite in these fine-grained quartz bostonites suggests the possibility that volatile transfer of uranium as one of the higher fluorides may have taken place. Intrusion took place at no great depth at pressures which may have permitted a vapor phase to separate. In view of the known high volatility of some of these fluorides, particularly UF_6, such a mechanism has its attractions. Professors Daniels, Emmons and coworkers at the University of Wisconsin have under study the possible application of volatile transport of uranium to certain problems of vulcanism. Complicating the picture with regard to the highly volatile fluoride, UF_6 however are the following factors: (1) special conditions are needed for the formation of UF_6 even in the laboratory, and (2) UF_6 seems to be unstable in systems containing water.

Because volatile transfer cannot account for the much greater co-enrichment in thorium, the fluoride of which is relatively involatile, such volatile transfer of uranium within these intrusive bodies seems to be ruled out. In fact the volatilization of uranium as UF_6 at temperatures below 500 C is one laboratory method for separating uranium from thorium and the rare earths (Rodden, 1950). As such, possibilities seem somewhat greater that this mechanism, or a similar one, may have been involved in the separation of uranium from thorium in the magmatic residuum. Up to the onset of hydrothermal conditions the paths of crystallization of U^{4+} and Th^{4+} have been parallel because of the similarity in

their ionic radii and charge of these two ions. Formation of volatile uranium fluorides would seem to imply an "acid gas" origin for at least a part of the ore-forming fluids. An alternative explanation, in some ways simpler, for the preponderance of uranium over thorium in the vein-forming solutions depends upon an increase in solubility of uranium salts as a result of late stage oxidation possibly brought on by a decrease in confining pressure, for instance by the Burbank (1936) mechanism. In aqueous solutions U^{6+} forms uranyl salts which are highly soluble as compared to the similar salts of U^{4+} and Th^{4+}.

Uranium in the higher valence states seems to be prerequisite to the operation of either of these two mechanisms. For the evidence of such a late magmatic-early hydrothermal change to more oxidizing conditions, we must look to the rocks themselves.

This evidence is in the widespread replacement of the sparse early formed mafic minerals, pyroxene, hornblende, and biotite, by the "high temperature" oxides, magnetite and specularite. Such replacement is nearly complete in even the freshest quartz bostonite samples. Commonly the magnetite and specularite were in turn replaced by "lower temperature" pyrite as hydrothermal alteration increased in intensity. Lovering (1935) noted a similar sequence of replacement in his study of the alteration of the Montezuma monzonite stock in the southern part of the Front Range mineral belt. A comparison of the oxidation potentials of U^{4+} and Fe^{2+} shows that about 40 percent less energy is required to oxidize U^{4+} to U^{6+} than to oxidize Fe^{2+} to Fe^{3+} in simple aqueous solutions (data of Kolthoff and Laitinen, 1941). It seems reasonable to infer as a first approximation that any uranium remaining in solution at this deuteric early hydrothermal stage would have been converted to U^{6+} at the time the Fe^{2+} was

oxidized to Fe^{3+}. Any early formed uranium minerals, but not the uranium tied up in less soluble silicates, would tend to be redissolved also and leached by the residual solutions at this stage.

It was repeatedly observed in the field that one effect of hydrothermal alteration sufficient to bleach the very highly uraniferous quartz bostonite by removing a part of the original iron was to reduce the total radioactivity. The difference is readily detected when making semiquantitative gamma counts on the outcrop. Laboratory analyses showed that the reduced radioactivity resulted from the leaching of as much as 50 percent of the original uranium content. In the only bleached sample analyzed for thorium the change in thorium content is close to the experimental error of the analysis ($\pm$ 0.003). Data for the unbleached and bleached phases of the highly uraniferous Nigger Hill dike are as follows:

Unbleached phases, 4 samples			Bleached phase (94), 2 splits of one sample		
Equiv. U	U	Th	Equiv. U	U	Th
0.013	0.005		0.009	0.003	0.022
0.014	0.005	0.027	0.010	0.003	
0.014	0.006				
0.018	0.007				
Av. 0.0148	0.0058	0.027	0.0095	0.003	0.022

The changes in radioactivity brought about by hydrothermal leaching of the less uraniferous porphyritic quartz bostonites were less easily estimated in the field. Because the differences in uranium content sought were of the same order as the precision of the individual analyses ($\pm$ 0.005

percent), it was necessary to make a large number of determinations on separate splits of the individual samples to minimize the effect of random errors in the analyses and in the sampling. The material used in these determinations came from the main Wood quartz bostonite porphyry dike and had been recently stoped from the new crosscut connecting the Wood and East Calhoun workings on the first level. Fifty-pound samples of the least altered porphyry and of two different bleached phases were collected in the field. These samples represented the least weathered bostonite obtainable in the district. Three pounds of material were hand-picked from each of the bulk samples, and these subsamples were each carefully crushed, mixed, and split into eight fractions with a Jones splitter. The average uranium and equivalent uranium contents of the 3 subsamples were found to be as follows:

	Equiv. U (%)	U (%)
P394 Unbleached (average of 8 splits)	0.008	0.0030
P393A Bleached (average of 8 splits)	0.008	0.0024
P393B Bleached (average of 8 splits)	0.008	0.0025

About 20 percent of the original uranium content has been hydrothermally leached, but the resulting change in equivalent uranium content was below the limits of detection of the routine beta-gamma counting method ($\pm$ 0.001 percent).

In short, both highly uraniferous and moderately uraniferous dikes have lost a part of their original uranium content as a result of intense hydrothermal leaching. Throughout the belt of commercial pitchblende production the volume of bleached bostonite exceeds the volume of unbleached. Our calculations suggest that the hydrothermal leaching of only 0.001

percent uranium from all the bostonite in the pitchblende belt down to

a depth of 1,500 feet would have mobilized a quantity of uranium 1.5

times as large as the estimated past production of uranium (50 tons)

from the district. Gold-silver ores have been mined down to a depth

of 2,200 feet in this district, but the pitchblende production has been

confined to depths between 100 and 500 feet from the present surface.

The quartz bostonite porphyry dikes now exposed at the surface are

in all probability merely the upward extensions of a much larger in-

trusive body at depth. Judging from the mining evidence this larger

body lies at a depth greater than 1,500 feet. It probably continued to

crystallize and to give off uranium-rich aqueous solutions long after

its upward extensions had completely solidified. As such it is believed

to have been the main source for the uranium now concentrated in the

veins. These uranium-rich solutions probably mingled with the regional

iron- and gold-bearing solutions in which the entire district was soaked,

rose along the planes of weakness provided by the porphyry dikes, and

reacted with and leached part of the uranium present. Not until the

temperature had fallen sufficiently to permit reducing conditions to set

in, did the solutions become saturated with uranium, at which time pitch-

blende, consisting chiefly of uranium in the quadrivalent state, started

to precipitate along with iron sulfide and copper iron sulfide. By this

time the solutions had ascended to within 500 feet of the present surface.

Perhaps a similar thermal gradient around the cooling dikes accounts for

the localization of the pitchblende near but not in the quartz bostonite

channelways.

Station 10 on the Nigger Hill dike seems to afford a local and small

scale demonstration of the effects of uranium reconcentration brought about

by hydrothermal solutions in this district. During alteration more than half the total iron content of the quartz bostonite has been leached together with a proportionate amount of uranium. Preliminary analyses of the bleached phase, not yet confirmed, indicate an almost complete replacement of soda by potash, the result of sericitization. Hydrothermal alteration at this station is at a maximum and ⁓⁓⁓ ⁓⁓⁓ for all 12 stations on this dike at which the porphyry was sampled the average uranium content is at a minimum. Cutting a part of the outcrop is a thin stringer consisting of a typical hydrothermal assemblage of quartz, sphalerite, specularite partly altered to limonite, and a black uranium mineral, probably pitchblende. This is the only occurrence known to us of hydrothermal uranium minerals associated with either of the two very highly uraniferous quartz bostonite dikes. The stringer is about 1/8 inch thick and is confined to the quartz bostonite; the most radioactive part of the aggregate contained 0.27 percent uranium by chemical analysis. The volume of bleached bostonite is more than adequate to have supplied the small quantity of uranium now concentrated in the stringer. The granite gneiss is bleached to a depth of 3 inches along the quartz bostonite contact and shows only the low content of uranium (maximum 0.002 percent) typical of the normal gneiss. These relationships are regarded as evidence, though not proof, that the black uranium mineral in the hydrothermal veinlet was leached from the associated bleached porphyry.

APPLICATIONS TO URANIUM PROSPECTING IN THE FRONT RANGE

According to our calculations, quarrying the entire Nigger Hill dike, the most radioactive of the quartz bostonites, to a depth of 10 feet

would make available only about 3 tons of uranium and 15 tons of thorium,
assuming perfect recovery. It clearly does not merit serious consideration
as a source of uranium at this time.

All quartz bostonites originating in this district contain at least
0.02 percent Th, that is about 0.40 pound of thorium per ton of rock. As
estimated from Bastin and Hill's detailed maps, roughly 80 percent of all
quartz bostonite outcropping within the confines of the map area (fig. 1)
is concentrated in the broad mile-long southwestward extension of the
Pewabic body as exposed on the slopes of Bellevue and Pewabic Mountains.
Assuming an average grade of 0.02 percent Th for the porphyry, we estimate
that about 100 tons of thorium are tied up within 10 feet of the surface
in this body exclusive of the narrow 2-mile-long east-west dike which
forms its eastward extension. The same volume contains about 15 tons of
uranium. Should an unusual demand for thorium arise in the future, it
might prove feasible to work this body by open-cut methods provided a
suitable method for processing the bulk rock could be developed. This
possibility seems remote at present. The immediate value of this investi-
gation lies rather in its application to the search for new deposits by
hydrothermal uranium.

In summary, our studies in the Central City district have shown
that:

1. The pitchblende deposits are associated with centers of
intrusion of porphyry of a distinct type, petrographically and chemically--
quartz bostonite.

2. All quartz bostonites in the district are significantly
higher in both uranium and thorium than any other porphyries in the region.
The difference in radioactivity can generally be detected with a field

counter.

3. The pitchblende deposits cluster around quartz bostonite dikes of moderately high uranium content rather than about those excessively enriched in uranium.

These results have encouraged us to extend our search for centers of intrusion of radioactive porphyry to surrounding areas in the Front Range in the hope that the results will be helpful in narrowing down the field for more detailed uranium prospecting, the first step in regional uranium reconnaissance. Areas characterized by intrusions mapped by earlier workers as "bostonite" are now under investigation, particularly those in which bostonite is present in dike swarms rather than in large stocks.

Once a favorable area has been blocked out, these investigations will not show just what parts offer the most promise beyond the fact that the probability for pitchblende concentrations seems to be higher near dikes moderately rich in uranium than near those excessively enriched in this constituent. The particular local conditions under which the uranium was precipitated remains the problem of the local field geologist and can only be attacked via detailed structural and paragenetic studies. The radioactive porphyry provided a source from which uranium-bearing solutions may be derived by a number of mechanisms. Prominent, but by no means unique, among these mechanisms is the combination of late magmatic concentration and hydrothermal leaching for which we have rather clear cut evidence in the Central City district. Lacking regional information it would be premature to conclude that all pitchblende deposits in the Front Range mineral belt had similar origins. We hope to obtain further information bearing upon this point during the field season of 1952.

REFERENCES

Alsdorf, P. R., 1916, Occurrence, geology and economic value of the
    pitchblende deposits of Gilpin County, Colorado: Econ. Geology,
    vol. 7, no. 3.

Ball, S. H., Spurr, J. E., and Garrey, G. H., 1908, Economic geology
    of the Georgetown quadrangle, Colorado: U. S. Geol. Survey Prof.
    Paper 63, 422 pp.

Bastin, E. S., and Hill, J. M., 1917, Economic geology of Gilpin
    County and adjacent parts of Clear Creek and Boulder Counties,
    Colorado: U. S. Geol. Survey Prof. Paper 94, 379 pp.

Beer, K. E., 1951, The petrology of some of the riebeckite-granites of
    Nigeria: Great Britain Geol. Survey, Atomic Energy Div. Rept. 116.

Billings, M. P., and Keevil, N. B., 1946, Radioactivity of the four
    Paleozoic magma series in New Hampshire: Geol. Soc. America Bull.
    57, no. 9.

Burbank, W. S., 1936, A source of heat energy in crystallization of
    granodiorite magma and some related problems of volcanism:
    Am. Geophys. Union Trans., 17th Annual Meeting, Pt. 1.

Butler, B. S., 1915, Relations of ore deposits to different types of
    intrusive bodies in Utah: Econ. Geology, vol. 10, no. 2.

Evans, R. D., and Goodman, C., 1941, Radioactivity of rocks: Geol.
    Soc. America Bull. 52, no. 4.

Greenwood, R., 1951, Younger intrusive rocks of Plateau Province, Nigeria,
    compared with the alkalic rocks of New England: Geol. Soc. America
    Bull. 62, no. 10.

Grimaldi, F. S., and Fairchild, J. G., 1946, The U.S.G.S. phosphate-
    fluoride-iodate method for the determination of very small amounts
    of thorium in naturally occurring materials: U. S. Geol. Survey
    Trace Elements Investigations Rept. 31E.

Grimaldi, F. S., and Marsh, C. A., 1947, The determination of thorium
    in high-grade and low-grade ores: U. S. Geol. Survey Trace
    Elements Investigations Rept. 44.

Hillebrand, W. F., and Lundell, G. E. F., 1929, Applied inorganic anal-
    ysis, John Wiley and Sons, Inc., 929 pp.

Hurley, P. M., 1950, Distribution of radioactivity in granites and its
    possible relation to helium age measurements: Geol. Soc. America
    Bull. 61, no. 1.

Keevil, N. B., 1938, Thorium-uranium ratios of rocks and their relation to lead ore genesis: Econ. Geology, vol. 23, no. 7.

Kolthoff, I. M., and Laitinen, H. A., 1941, pH and electrotitrations, John Wiley and Sons, Inc.

Kovarik, A. F., 1931, Age of the earth: Nat. Research Council Bull. 80, pp. 73-123.

Larsen, E. S., and Keevil, N. B., 1947, Radioactivity of the rocks of the batholith of southern California: Geol. Soc. America Bull. 58, no. 6.

Lovering, T. S., 1935, Geology and ore deposits of the Montezuma quadrangle, Colorado: U. S. Geol. Survey Prof. Paper 178, 119 pp.

Lovering, T. S., and Goddard, E. N., 1950, Geology and ore deposits of the Front Range, Colorado: U. S. Geol. Survey Prof. Paper 223, 312 pp.

Moore, F. B., King, R. U., and Hinrichs, E. C., 1951, Proposed exploration for uranium in the Front Range mineral belt, Colorado: U. S. Geol. Survey Trace Elements Memorandum Rept. 215, Official Use Only.

Phair, G., and Onoda, K., 1951, Hydrothermal uranothorite in fluorite breccias from the Blue Jay mine, Jamestown, Boulder County, Colorado: U. S. Geol. Survey Trace Elements Investigations Rept. 144.

Rodden, C. J., 1950, Analytical chemistry of the Manhattan Project, McGraw-Hill Book Co., Inc.

Rosenbusch, H., and Osann, A., 1923, Elements der Gesteinlehre, Stuttgart, pp. 305-306.

Singewald, Q. D., 1935, Relations of hydrothermal alteration of porphyries to ore deposition in the Alma district, Colorado: Econ. Geology, vol. 30, no. 5.

Wahlstrom, E. E., 1936, The age relations of the Ward ores, Boulder County, Colorado: Econ. Geology, vol. 31, no. 1.

APPENDIX--FIELD SAMPLING AND ANALYTICAL METHODS

The sample-to-sample variation in uranium and equivalent uranium
for any single porphyry body is relatively much less than that usually
encountered in studies of igneous intrusions in spite of changes brought
about by mild hydrothermal alteration. Obviously the problem of sampling
long narrow dikes of uniform composition and average fine-grain size
is immensely simplified as compared to the problem involved in the
sampling of a large heterogeneous body such as a batholith made up of
coarse-grained igneous rocks of variable composition. By making semi-
quantitative field counts with a Geiger counter (method described in a
note now in preparation), it was possible to find out in advance of sampling
whether a particular part of a porphyry outcrop was approximately represen-
tative of the whole with respect to radioactivity. In the course of the
1949 field season alone, over 100 such field counts on porphyry were made.

From 1 to 5 samples of porphyry were collected at each of the 72
stations in the Central City district. All bostonite dikes were sampled at
at least 5 stations along the strike. Most samples weighed from 2 to 10
pounds but three 20-pound samples were collected to obtain material for
standard rock analyses and three 50-pound samples were selected for
studies of progressive hydrothermal alteration. Before analyses were made
the samples collected in the field were again inspected and any visibly
weathered material was discarded.

Contributing to the reproducibility of the results is the fact that
the analyzed rocks had uranium and equivalent uranium contents greater
than 0.001 percent but less than 0.03 percent, a range for which the
particular laboratory beta-gamma counting methods and fluorimetric method

of uranium determination are especially suited. In the range of uranium contents between 0.001 and 0.02 percent the fluorimetric method, as applied to silicate rocks, yields results which are reproducible within $\pm$ 0.0005 percent provided special precautions are taken to avoid over-heating the flux. In a routine way differences of $\pm$ 0.001 percent are to be expected. Because platinum from the crucibles and certain other interfering elements cause a quenching of the fluorescence, results in the range above 0.002 percent uranium tend to be low rather than high. Separate parts of 20 hand specimens of bostonite ranging from 0.001 to 0.018 percent uranium were analyzed for uranium by the Trace Elements Section Washington Laboratory and by the Trace Elements Section Denver Laboratory. In only one sample pair did the difference between the separate determinations exceed the sum of the combined experimental error (0.002 percent) in spite of sampling differences. Not only do these results give a satisfactory cross check between the two laboratories but they show that the uranium is uniformly distributed within each hand specimen. In the course of the work reported here about 225 uranium analyses, not including duplicate determinations, and an equal number of equivalent uranium determinations were made.

The equivalent uranium contents reported were determined for the most part in the Washington Laboratory by the writer using a standard volume of sample pulp (about 6 g), an end window GM beta-gamma counter, and a vertical chamber. The set up was the same as that devised by Mr. Flanagan of the Trace Elements Section Washington Laboratory for the routine radiometric analyses, but the procedure was modified to increase the precision. A five-minute count was made on each of two

splits of each sample. The background was measured before and after each pair of measurements and frequent calibrations against a 0.01-percent uranium standard (pitchblende in dunite) supplied by the National Bureau of Standards were carried out. The average of the two counts on each sample was found to be reproducible to ± 0.001 percent equivalent uranium in the range from 0.001 to 0.030 percent.

Separate parts of 20 porphyry specimens analyzed for equivalent uranium by this small-sample method were analyzed also, by the routine large-sample method employing 75-100 g and a coaxial counter. The agreement between the results obtained by the two methods was equal to or better than 0.002 percent in 18 out of the 20 pairs analyzed. Like the comparable uranium analyses, these results indicated that a satisfactory level of precision was obtained and that the radioactive constituents were uniformly distributed throughout most hand specimens.