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Lead and sulfur isotope systematics in sulfide deposits of the Piedmont and Blue Ridge provinces of the southern Appalachians

by

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LEAD AND SULFUR ISOTOPE SYSTEMATICS IN SULFIDE DEPOSITS OF THE PIEDMONT AND BLUE RIDGE PROVINCES OF THE SOUTHERN APPALACHIANS

by

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ABSTRACT

Lead isotope ratios of galenas from stratabound massive sulfide deposits in upper Precambrian metasediments of the Blue Ridge (BR) geologic province are too radiogenic for their presumed synsedimentary, late Precambrian age. A positive correlation between lead and sulfur isotope ratios in galenas from Ducktown, Tennessee, is interpreted as an original characteristic of the ores, and indicates that the radiogenicity of the lead is not the result of metamorphic processes, but of derivation of lead from U/Pb-enriched elastic sediments. At Ducktown, however, lead and sulfur isotope ratios indicate a component derived from a mafic source, and suggest that rift basin faulting may have controlled mineralization. Lead isotope ratios in Mount Rogers Formation rhyolites and in BR Paleozoic plutons indicate different sources of lead than those contributing

to lead in massive sulfide deposits.

Lead isotope ratios of galenas from Piedmont province polymetallic massive sulfide (PMS) deposits define a trend of decreasingly ensialic volcanism from northeast to southwest. A regression through the data has a slope that corresponds to a secondary isochron age of about 3.7 b.y. The line is proposed to represent mixing between variable amounts of upper crustal lead (decreasing to the southwest) with lead from a source depleted in U/Pb and Th/Pb ratios relative to upper crust. The depleted source has, however, experienced either continuous or episodic enrichment of uranium relative to lead. The occurrence of a similar trend in galenas from Kings Mountain belt ores is further evidence for such a source. Sulfur isotope ratios in PMS are consistent with derivation of sulfur from lower Paleozoic seawater sulfate.

Rocks and ores from the southern Appalachians have lead isotope patterns that suggest three distinct isotope provinces. Rocks and vein deposits of the Blue Ridge and Inner Piedmont appear to be dominated by lead derived from Grenville-age crust. Some rocks of the eastern Piedmont are characterized by lower $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios than BR and Inner Piedmont rocks. PMS and the Kings Mountain belt have isotope ratios suggesting a mixed source with Grenville-age basement as one end member and mantle or mantle-derived material as the other.

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List of abbreviations used in tables and in sample descriptions (Appendix A).

<u>Mineral names</u>

bar	barite	bio	biotite
bn	bornite	calc	calcite
cc	chalcocite	mg	magnetite
cpy	chalcopyrite	qtz	quartz
gn	galena	ser	sericite
py	pyrtie	trem	tremolite
po	pyrrhotite		
sp	sphalerite		

<u>Rock names</u>

qtzte	quartzite
amph	amphibolite
m.s.	massive sulfide (>50% sulfide minerals, by volume)

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Part I: INTRODUCTION

1. SULFIDE DEPOSITS IN THE SOUTHERN APPALACHIANS

In the crystalline Appalachians many stratabound (massive) sulfide deposits can be classified as Blue Ridge (or Ducktown) type deposits (Ross, 1935) or as Piedmont (or Silver Hill) type deposit (Brown, 1976).

Ducktown-type ores are characterized by pyrrhotite and/or pyrite with minor, but sometimes economic, concentrations of copper and zinc as well as magnetite. The largest and best known of these bodies are the Ducktown, Tennessee, deposits. Blue Ridge massive sulfide deposits (Fig. 1) are generally found in upper Precambrian metasedimentary and metavolcanic rocks at amphibolite facies. Often the relationship between country rock and ore is unclear, as at Ore Knob, North Carolina, where the ore body, located in a shear zone, is slightly offset from the grain of the enclosing rocks (Kinkel, 1967).

Silver Hill-type deposits are found in uppermost Precambrian to lower Paleozoic metavolcanic and metasedimentary rocks of the Piedmont geologic province. They are generally richer in Zn, Pb, Cu and Ag than those of the Ducktown-type and are generally conformable with respect to surrounding rocks. In the slightly metamorphosed Carolina slate belt (Fig. 1) some ores retain evidence of

Figure 1. Index map of the southern Appalachians showing major lithotectonic blocks and the locations of some of the sulfide deposits (numbered) discussed in this study.

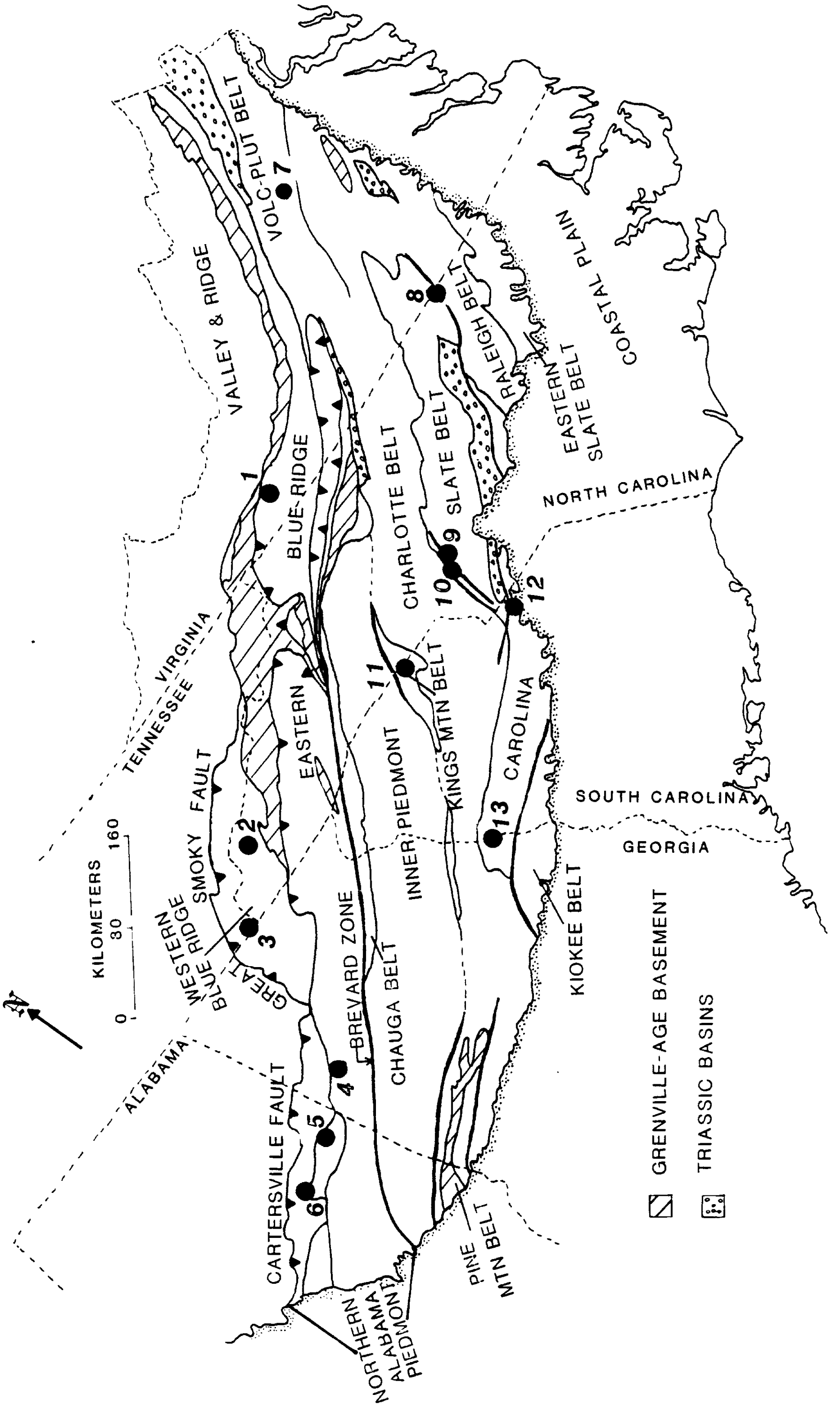
1. Gossan Lead district
2. Fontana district
3. Ducktown district
4. Swift and Little Bob mines
5. Stone Hill
6. Pyriton
7. Mineral District
8. Hamme tungsten district
9. Cid district
10. Gold Hill district
11. Kings Creek area
12. Haile-Brewer area
13. Lincolnton-McCormick district

soft sediment deformation. Piedmont province massive sulfides are also more clearly related to volcanic activity whereas those of the Blue Ridge are often found in metasedimentary sequences with scant evidence of igneous activity of any sort. The Silver Hill-type bodies have been compared to volcanic exhalative "kuroko" ores of Japan (Bell *et al.*, 1980; Indorf, 1981).

Southern Appalachian rocks are also host to ore concentrations that do not fit either of the above categories. The Haile and nearby deposits in the Carolina slate belt of north-central South Carolina (Fig. 1), are important for their gold, and are associated with massive pyrite lenses with little or no base metal content. They have been described as hot springs-fumarolic deposits by Spence *et al.*, (1980), who compared Haile with modern hot springs systems at Steamboat Springs, Nevada, and the Broadlands geothermal field, New Zealand.

The Carolina barite belt represents another style of mineralization found in the Piedmont. It is a linear zone of massive barite associated with felsic volcanism (Sharp and Hornig, 1981), in the Kings Mountain belt, North and South Carolina. Locally abundant galena is the major base metal sulfide associated with the deposits.

Numerous districts containing gold-quartz veins were formerly of economic significance in the southern Appalachians. These include the Virginia gold-pyrite belt and


VALLEY & RIDGE
VOLC-PLUT BELT
7
8
COASTAL PLAIN
RALEIGH BELT
EASTERN SLATE BELT
SLATE BELT
CHARLOTTE BELT
BLUE RIDGE
1
9
10
12
NORTH CAROLINA
VIRGINIA
TENNESSEE
EASTERN
11
KINGS MTN BELT
INNER PIEDMONT
CAROLINA
SOUTH CAROLINA
GEORGIA
13
GREAT SMOKY FAULT
2
KILOMETERS
0
30
160
WESTERN BLUE RIDGE
3
N
BREVARD ZONE
CHAUGA BELT
KIOKEE BELT
ALABAMA
4
5
CARTERSVILLE FAULT
6
PINE MTN BELT
NORTHERN ALABAMA PIEDMONT
▨ GRENVILLE-AGE BASEMENT
⁘ TRIASSIC BASINS

the York County (South Carolina) district in the Piedmont and the Dahlonega district in the eastern Blue Ridge of Georgia.

The Hamme tungsten district, North Carolina, is unique in the southern Appalachians. The mineralized quarts veins are closely associated with the emplacement of a late Precambrian albite granodiorite. Huebnerite is the major ore mineral and a variety of sulfide minerals are also disseminated throughout the veins.

Pardee and Park (1948) cited the southern Appalachians as an example of regional zonation of ore deposits. Their zonation centered on gold-pyrite associations in the Piedmont. West of these deposits the type of mineralization progresses, in their model, from pyrrhotite/pyrite (Gossan Lead, Virginia) to pyrrhotite-chalcopyrite (Ducktown, Tennessee) and farther west, in the unmetamorphosed sediments of the Valley and Ridge province, Pb-Zn (e.g. Mascot - Jefferson, Tennessee), and finally barite deposits (e.g. Sweetwater, Tennessee).

Strong (1974) related localization of the types of ore deposits of Paleozoic age to their plate tectonic environments by extending his metallogenic model for the Newfoundland Appalachians southward. He noted that Mississippi Valley-type Zn (±Pb) deposits are found in Cambro-Ordovician platformal carbonates along the western side of the Appalachian orogen; in the south, in the Valley and Ridge province. Strong (1974) speculated that some of the small pyrite-chalcopyrite bodies of the Inner Piedmont and eastern Blue Ridge may be Cyprus-type ores associated with ophiolites. Eastward of these, polymetallic Cu-Pb-Zn±Ag, Au (kuroko-type or Silver Hill-type) are found associated with calc-alkaline volcanism. Strong (1974) further notes that tin and tungsten deposits tend to lie to the east of other deposits in the southern Appalachians.

Recently, Gair and Slack (1980) proposed a model for stratabound mineralization in the upper Precambrian of the Blue Ridge which relates sulfide deposition to rifting associated with the opening of the lapetus (proto-Atlantic) ocean. In the model graben-like basins formed on either side of the Grenville-age core of the Blue Ridge. The basins were rapidly filled with sediments stripped off the high-standing core and, in the eastern basins, with flows of mafic volcanic rock. High heat-flow regimes associated with the rifting were conducive to hydrothermal cell formation which lead to the deposition of sulfides on the basin floors.

The sequences that play host to stratabound sulfides in the Piedmont geologic province are more usually associated with island arc environments at converging plate boundaries. Pavlides (1981) describes the Chopawamsic Formation, host of the massive sulfide deposits in the Mineral district, Virginia, as a tholeiitic to calc-alkaline metavolcanic sequence formed in a Cambrian (?) island arc. Cox et al., (1979) and Miller et al., (1978, 1979), have favorably compared the massive sulfide deposits of the Mineral district with kuroko-type ores. The central Virginia volcanic-plutonic belt also contains numerous gold-quartz veins which may be related to metamorphism.

Numerous authors (e.g. Butler and Ragland, 1968; Hatcher, 1972; Black, 1980), have described the metavolcanics and meta-argillites of the Carolina slate belt as having formed in a volcanic island arc setting. Recently, however, Long (1979) drew analogies between the Carolina slate belt and a rift basin environment based on gravity and magnetic patterns. As is the case with the Mineral district, a number of workers have seen similarities between slate belt polymetallic massive sulfides and Kuroko-type ores (e.g. Carpenter and Allard, 1980; Indorf, 1981).

The metavolcanics of the Carolina slate belt also contain pyritic deposits in highly sericitized and silicified zones, which contain appreciable gold. Spence et al., (1980) and Worthington et al., (1980), developed a model for hot springs-fumarolic deposits, ancient and modern, using the Haile mine of South Carolina as an example. The nearby Brewer mine has also been described as a potential porphyry molybdenum deposit (Schmidt, 1978).

The tectonic environment in which the Kings Mountain belt formed is the subject of controversy. Posey (1981) presents a model for the sequence of formation and local settings of a number of the different types of mineralization in the belt.

The Stone Hill copper mine, Alabama, is a massive sulfide lense within an amphibolite unit in the Ashland Supergroup. The Ashland is a thick sequence of predominantly clastic metasediments that is believed to be correlative with the sedimentary sequences of the upper Precambrian of the Blue Ridge because of lithologic and tectonic similarities owing to its position northwest of the Brevard zone (Tull, 1978; Thomas *et al.*, 1980).

The Pyriton (Cu) district, Alabama, occurs in the Hillabee greenstone which is the uppermost unit in the Talladega belt whose tectonic position is also open to question but may have developed as a continental margin of the Andean-type (Tull, 1978; Tull and Stow, 1982).

Scope and purpose of study

The lead and sulfur isotope data presented in this report include mineral deposits from Virginia to Alabama. The emphasis is on stratabound (massive) sulfide deposits of the crystalline southern Appalachians, but data from other types of deposits are also included.

There were several geologic problems in the southern Appalachians which prompted this study. Through the application of lead isotope systematics models, such as Doe and Zartmans' (1979) plumbotectonics, I hoped to be able to contribute to the knowledge of the petrogenetic and tectonic regimes of southern Appalachian mineral deposits individually and regionally. The earth's various broad crustal regimes and the upper mantle have distinct lead isotopic characteristics due to the characteristic behavior of U, Th, and Pb in each regime. In a compilation of lead isotope data from the western U.S., Zartman (1974) found that the patterns of isotope ratios in galenas closely reflected the type of crust underlying the various regions. Rocks of the crystalline southern Appalachians have been variably deformed and metamorphosed and some terrains are apparently far-traveled allochthons whose original positions relative to other terrains are poorly known. A study of lead isotope systematics in the mineral deposits and their host rocks undoubtedly could contribute to the knowledge of the individual terrains and their regional relationships.

Late Precambrian to Ordovician time was marked by distinctive and relatively rapid changes in the isotopic composition of sulfur in sea water sulfate. In the latest Precambrian $\delta^{34}S$ in seawater sulfate began a sharp rise from a constant Proterozoic value of about 17 per mil, reaching over 30 per mil during Cambrian time. The $\delta^{34}S$ of seawater sulfate remained relatively "heavy" (i.e. enriched in the heavier isotopes of sulfur, or high $\delta^{34}S$) during the Cambrian and most of the Ordovician (Claypool *et al.*, 1980). Late Precambrian to Ordovician (?) is also the time period during which the stratabound (massive) sulfide deposits of the southern Appalachians were formed. A reconnaissance sulfur isotope study of minerals in these deposits was made to determine the contribution of this distinctive seawater sulfate to sulfur in the deposits. Relationships between lead and sulfur isotopic variations in individual deposits were also looked for.

Additional results hoped for from this study were 1) a data base of lead and sulfur isotopic ratios in the southern Appalachians on which future studies may be anchored; and 2) a basis for comparison of isotope systematics with similar mineral deposits and terrains in the Appalachian-Caledonide orogen and other orogenes worldwide.

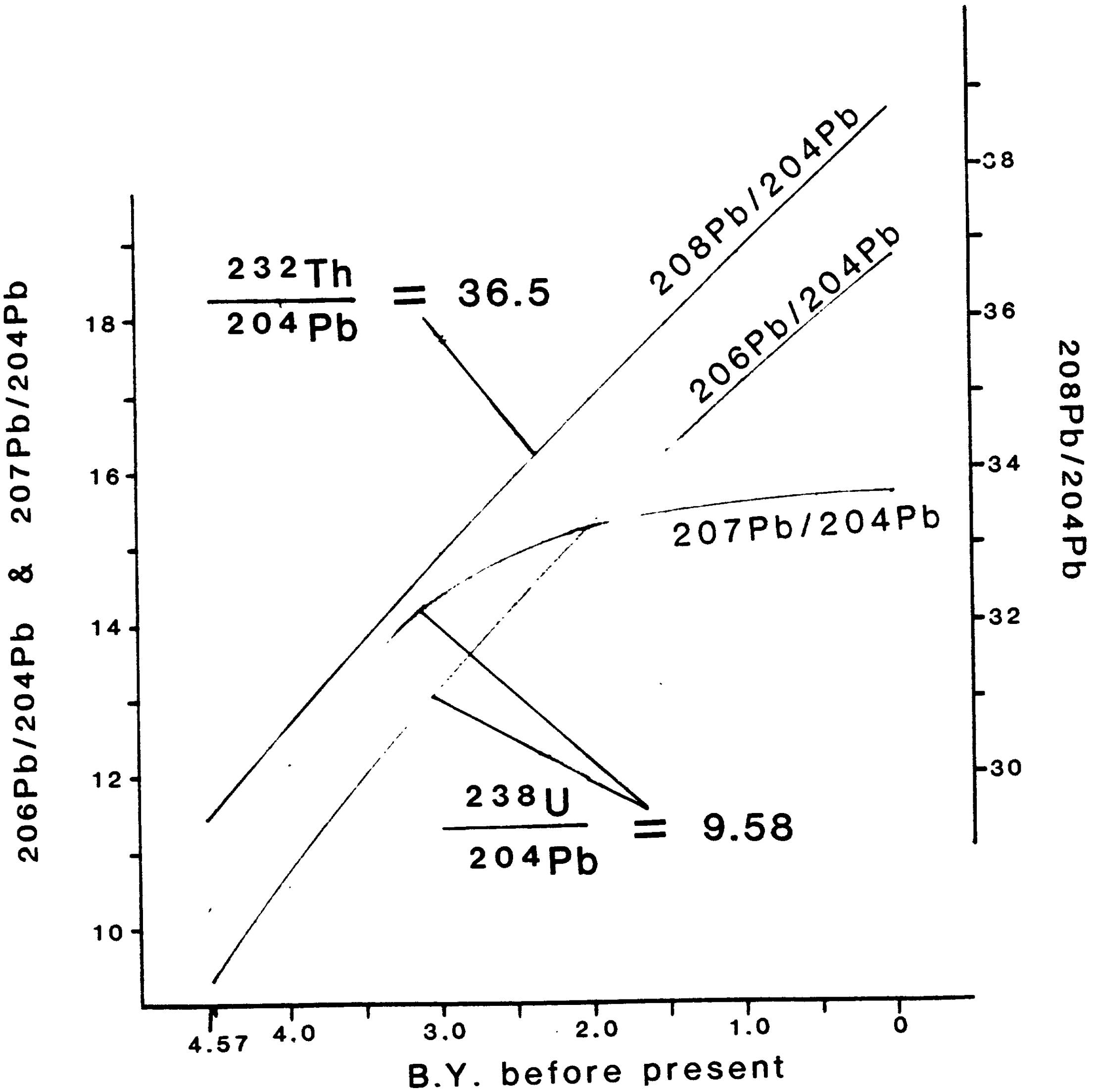
Previous isotope studies of southern Appalachian sulfide deposits have been limited. Doe and Zartman (1979) published several high-precision lead isotope analyses from the region. Lead in deposits of the North Carolina slate belt was the subject of a study by Kish and Feiss (1982). Some of the results of this study have been presented in LeHuray (1980, 1981, 1982a, b, and c). The only published report of sulfur isotope investigations in the southern Appalachians is from the Ducktown district, Tennessee (Mauger, 1972).

2. AN OVERVIEW OF THE THEORY AND USES OF LEAD ISOTOPE STUDIES

Theoretical Basis of Lead Isotope Variation

Of the four effectively stable isotopes of lead (^{204}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb) only ^{204}Pb has no long-lived radioactive parent isotope and so the others are expressed as ratios to constant ^{204}Pb. ^{206}Pb, ^{207}Pb, and ^{208}Pb are the final stable products of the decay of ^{238}U, ^{235}U, and ^{232}Th, respectively. The rate of increase in the various isotopes of lead through geologic time is the inverse of the rates of decay of parent isotopes. The long half-lives of ^{238}U and ^{232}Th have kept the production of ^{206}Pb and ^{208}Pb at constant levels through time. ^{207}Pb, however, accumulated in large quantities early in geologic history due to the relatively short half-life of ^{235}U (Fig. 2) The production of ^{207}Pb since about 2.5 b.y. has been relatively small. As a result, contributions of lead by Archean rocks to younger rocks or minerals are often characterized by high ^{207}Pb/^{204}Pb ratios relative to corresponding ^{206}Pb/^{204}Pb and ^{208}Pb/^{204}Pb ratios. The initial isotopic composition of lead in the Earth has been approximated as that found in meteoritic lead. In this study the value of

Figure 2. The growth of lead isotope ratios with time is illustrated beginning with the lead isotope ratios of the troilite phase of the Canyon Diablo meteorite (Tatsumoto *et al*., 1973), and with constant U/Pb and Th/Pb ratios.


$\frac{^{232}Th}{^{204}Pb}$ = 36.5
$\frac{^{238}U}{^{204}Pb}$ = 9.58
208Pb/204Pb
206Pb/204Pb
207Pb/204Pb
206Pb/204Pb & 207Pb/204Pb
208Pb/204Pb
18
16
14
12
10
38
36
34
32
30
4.57
4.0
3.0
2.0
1.0
0
B.Y. before present

lead from the troilite phase of the Canyon Diablo meteorite (Tatsumoto et al., (1973), is used as the initial lead isotopic composition. Table 1 lists some of the conventions used in this paper.

The present lead isotope ratios in rocks and minerals are a function of the processes which have affected the U, Th, and Pb in the system through geologic time. When lead is separated from U and Th in Pb-rich, U and Th-poor phases, such as galena or K-feldspar, lead isotope ratios are "frozen", providing us "fossil" ratios which allow study of lead isotope systematics in ancient rocks. Mathematical treatments of the systematics of lead isotope growth have been presented by Russell and Farquhar (1960), Kanasewich (1968), Doe (1970), Doe and Stacey (1974), Stacey and Kramers (1975), and Cumming and Richards (1975) and have recently been reviewed by Faure (1977) and by Koppel and Grunenfelder (1979).

Lead Evolution Models

Early lead isotope studies show that the regular rates of growth of the radiogenic isotopes of lead could be described as a set of curves known as "growth curves" (Fig. 3). The position of the curve is determined by the $^{238}U/^{204}Pb(\mu)$ and $^{232}Th/^{204}Pb(w)$ ratios of the system and by the initial ("primordial") lead isotope ratios, which

TABLE 1

Values of isotopic parameters used in this study.

A. Decay constants

Isotope	Decay Constant	Symbol	Reference
^{238}U	1.55125×10^{-10}/yr	λ_8	Jaffey *et al.*, 1971
^{235}U	9.8485×10^{-10}/yr	λ_5	Jaffey *et al.*, 1971
^{232}Th	4.9475×10^{-11}/yr	λ_2	LeRoux and Glendenin, 1973

B. Isotopic composition of primordial lead

Troilite phase of Canyon Diablo meteorite (Tatsumoto *et al.*, 1973):

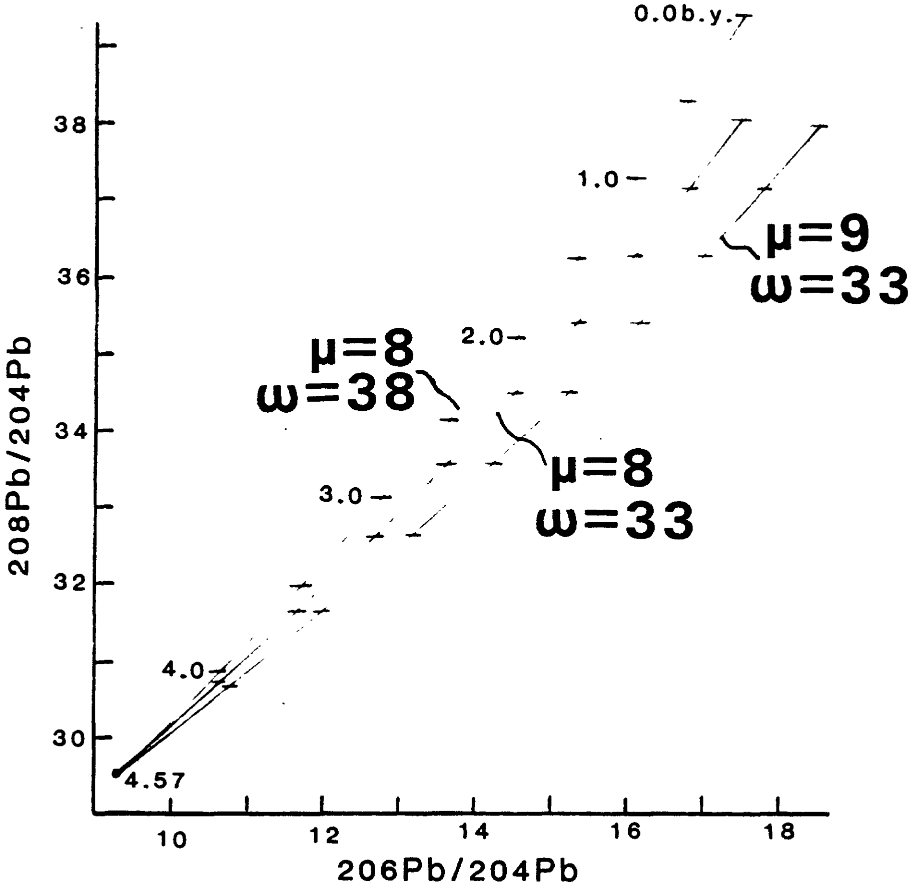
$$\frac{^{206}Pb}{^{204}Pb} = 9.307 \qquad \frac{^{207}Pb}{^{204}Pb} = 10.294 \qquad \frac{^{208}Pb}{^{204}Pb} = 29.476$$

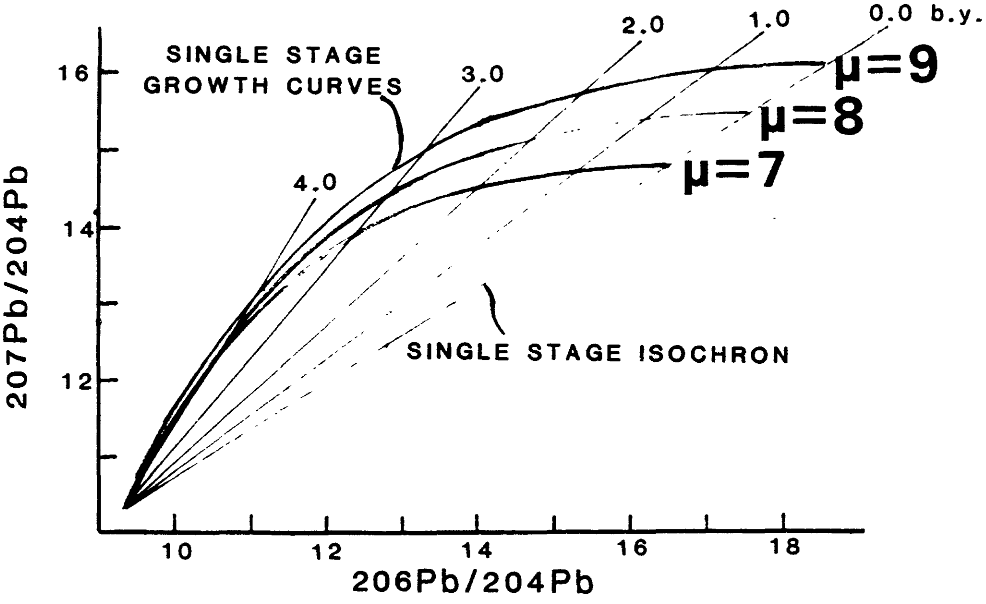
C. Isotopic composition of lead at 3.7 b.y.

Beginning of second stage growth (Stacey and Kramers, 1975):

$$\frac{^{206}Pb}{^{204}Pb} = 11.152 \qquad \frac{^{207}Pb}{^{204}Pb} = 12.998 \qquad \frac{^{208}Pb}{^{204}Pb} = 31.23$$

Figure 3. Single-stage $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ growth curves with $^{238}U/^{204}Pb$ (μ) and $^{232}Th/^{204}Pb$ (ω) as parameters. Single-stage isochrons are shown on the uranogenic lead diagram.


0.0b.y.
1.0
2.0
3.0
4.0
4.57
μ=9
ω=33
μ=8
ω=38
μ=8
ω=33
30
32
34
36
38
208Pb/204Pb
10
12
14
16
18
206Pb/204Pb

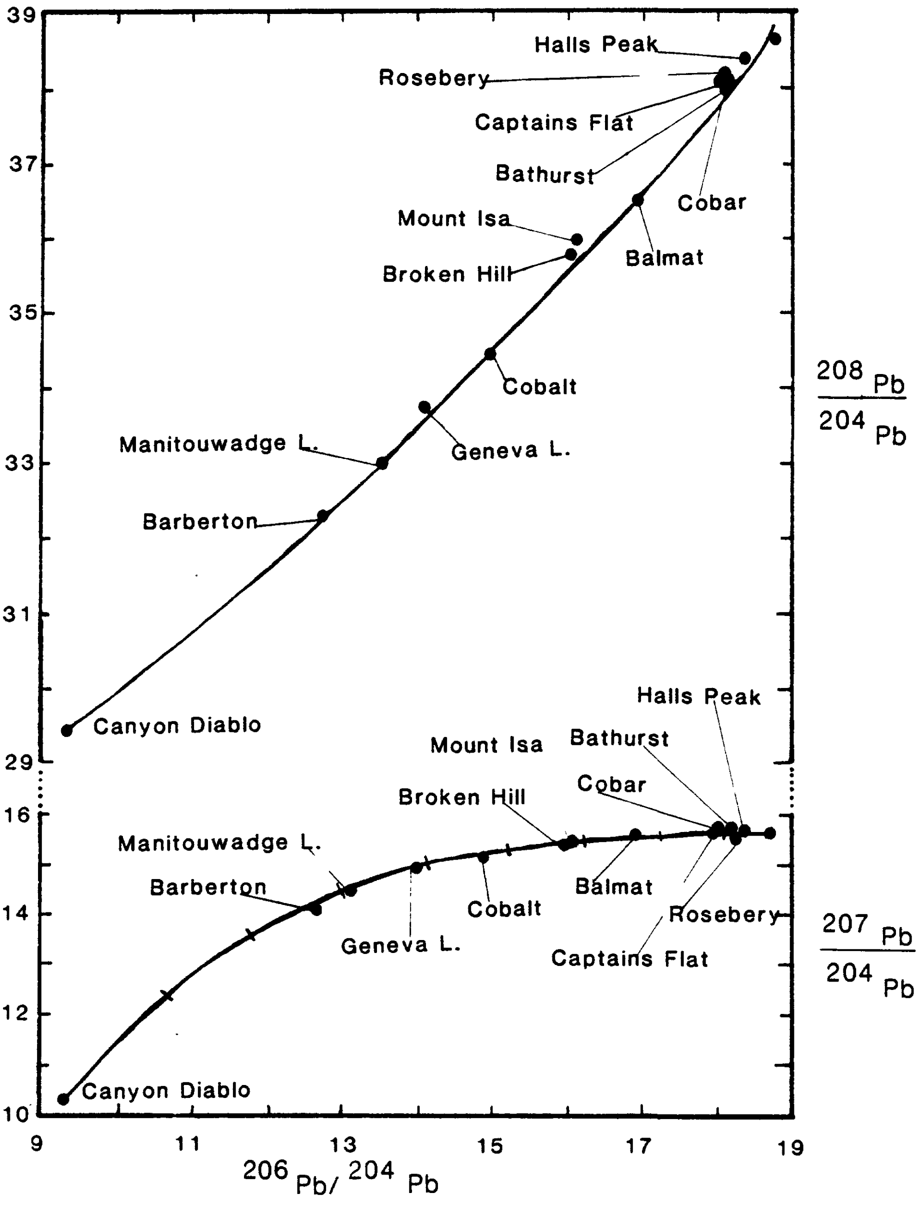

SINGLE STAGE
GROWTH CURVES
4.0
3.0
2.0
1.0
0.0 b.y.
μ=9
μ=8
μ=7
SINGLE STAGE ISOCHRON
12
14
16
207Pb/204Pb
10
12
14
16
18
206Pb/204Pb

are usually taken to be the values found in meteoritic lead. This single-stage model assumes that the earth was originally homogeneous with respect to lead isotope composition and the distribution of U, Th, and Pb. It further assumes that ratios of parent-to-index isotopes ($^{238}U/^{204}Pb$, $^{235}U/^{204}Pb$ and $^{232}Th/^{204}Pb$) changed only as the result of radioactive decay. Leads that conform to this model have been called "single-stage", "conformable", "normal", and "model" leads.

Stanton and Russell (1959) demonstrated that lead from the submarine exhalative class of stratabound (massive) sulfide deposits associated with volcanic island arcs approaches single stage conditions. A growth curve can be fit through data points from these deposits and their model ages are rough approximations of the actual times of deposition. Figure 4 shows one such set of curves, with $^{238}U/^{204}Pb \simeq 9.5$ and $^{232}Th/^{204}Pb \simeq 36.5$. Single-stage growth requires that these ratios remain essentially constant through time. The mantle was thought to be the only source region large enough to act as an "infinite reservoir" from which U, Th, and Pb could be intermittently withdrawn without effecting their relative abundances.

Even those deposits which most closely approach single-stage evolution, however, deviate slightly from the model (Kanasewich, 1968; Oversby, 1974), and improved analytical techniques have revealed complexities not evident

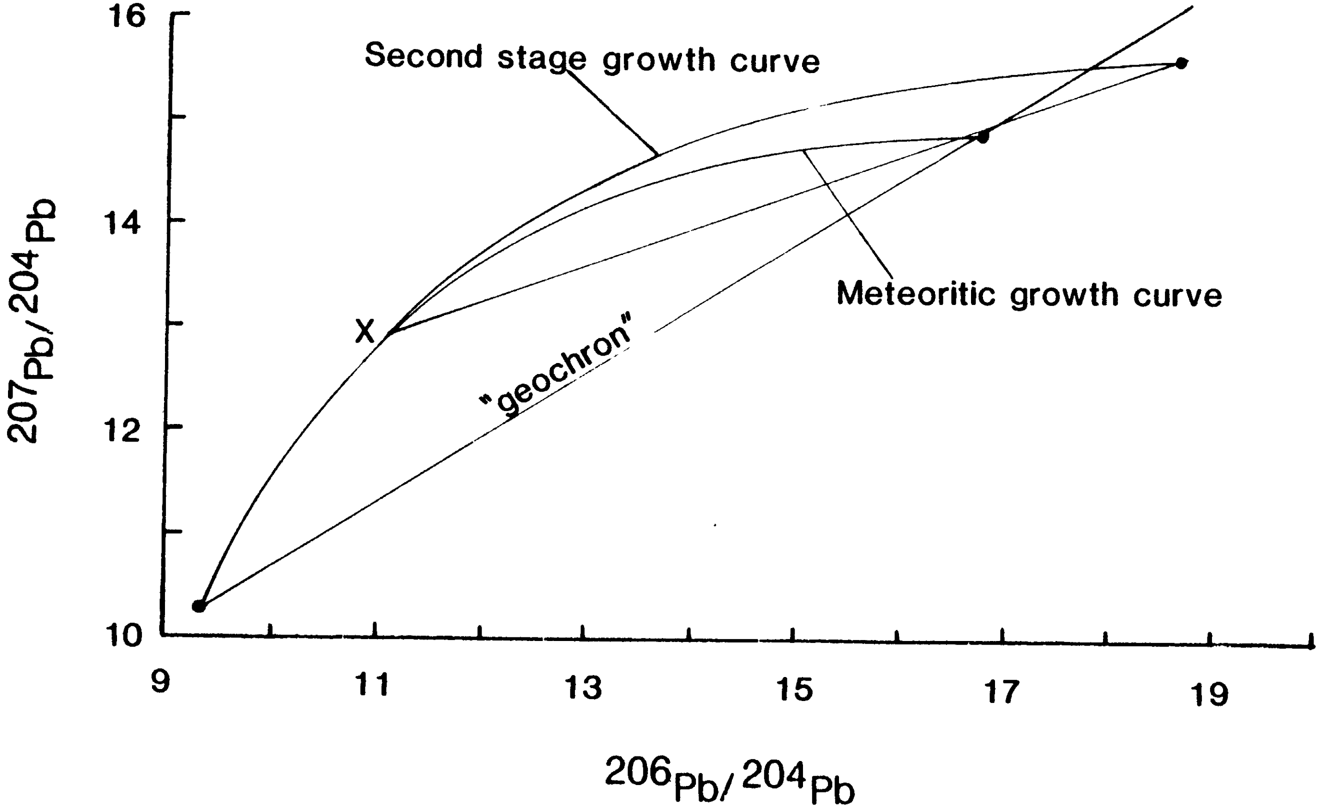
Figure 4. Model single-stage lead isotope ratio growth curves, with nearly "conformable" deposits indicated. (After Doe and Stacey, 1974).


39
37
35
33
31
29
16
14
12
10
9
11
13
15
17
19
206 Pb/ 204 Pb
208 Pb / 204 Pb
207 Pb / 204 Pb
Halls Peak
Rosebery
Captains Flat
Bathurst
Cobar
Mount Isa
Broken Hill
Balmat
Cobalt
Geneva L.
Manitouwadge L.
Barberton
Canyon Diablo
Halls Peak
Mount Isa
Bathurst
Cobar
Broken Hill
Manitouwadge L.
Barberton
Balmat
Cobalt
Rosebery
Geneva L.
Captains Flat
Canyon Diablo

in earlier work. Kanasewich (1968) noted the tendency of younger deposits to have $^{206}Pb/^{204}Pb$ ratios that are too radiogenic to fit a simple single-stage model. Russel's (1972) and subsequent studies of oceanic volcanics have ruled out the mantle as the major source of lead in the classical comformable ores. Several models have since attempted to reconcile conformable leads with modified single-stage evolution.

Doe and Stacey (1974) suggested that the approach to apparent single-stage evolution is the result of the mixing of several isotopically heterogeneous source materials. Cumming and Richards (1975) proposed that U/Pb and Th/Pb ratios of source materials of conformable ores have been continuously increasing through time. The effect of their continuous evolution model is that younger deposits are expected to contain "excess" radiogenic lead relative to simple single-stage evolution. Stacey and Kramers (1975) approached the problem by proposing a simple two-stage model which brings model lead ages of comformable lead ores to within 100 m.y. of their known or inferred ages of formation. During the first stage of their model (Figure 5; 4.57-3.70 b.y.), the earth's bulk $^{238}U/^{204}Pb = 7.19$. A bulk differentiation event at 3.7 b.y. resulted in an episodic increase to $^{238}U/^{204}Pb = 9.74$, for that part of the earth which contributes lead to comformable ores. That ratio has persisted during the second stage, from 3.7 b.y.

Figure 5. The two-stage growth curve of Stacey and Kramers (1975). At about 3.7 b.y. ("X") bulk differentiation of the Earth resulted in an increase in average U/Pb ratios to about 9.74.


16
14
12
10
9
11
13
15
17
19
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$
Second stage growth curve
Meteoritic growth curve
"geochron"
X

to the present. The Stacey and Kramers (1975) evolution curves will be used throughout this report as average reference growth curves.

The divergence of the various modified single-stage model growth curves is usually minimal for most of the Precambrian but differ substantially for Phanerozoic time. The models differ in some of their basic assumptions, but have the same essential goal: to fit the lead isotope data of conformable ores to a mathematically describable evolution curve.

Model-lead ages

When lead is removed from a system which approaches single-stage characteristics and segregated in a lead-rich, U- and Th-poor phase such as galena or feldspar, lead isotope evolution is frozen and a "model age" can be calculated. The resulting model ages depend on the particular model and parameters used, although they are not drastically model-dependent. Model ages from Stacey and Kramers (1975) model for instance, are calculated from the isotopic composition of lead that prevailed after the 3.7 b.y. differentiation event (Table 1) and are believed to bring model ages to within 100 m.y. of actual ages in many instances.

Model-lead ages have large errors and are generally not a precise age-dating tool, but can be useful when an approximate age of mineralization is required. They can be particularly useful in this respect in Precambrian ore deposits where age relationships are imperfectly known and in identifying periods of mineralization in complex terrains.

Model-lead ages have also been used as descriptive devices with little actual "age" connotation. Reporting, for instance, that a given model age is too old or young for the age of mineralization is another way of saying that the lead is either less or more radiogenic, respectively, than predicted by single-stage models.

Anomalous leads

Anomalous (or "extraordinary" or "J-type") leads generally contain lead that is much too radiogenic for the time of mineralization. The Mississippi Valley deposits, for example, contain lead which gives negative ("future") model ages (e.g. Doe and Delevaux, 1972). Anomalous leads derive the greater portion of their lead from sources with high U/Pb ratios.

Ore deposits with conformable lead isotope ratios usually have a high degree of internal isotopic consistency. Ratios from throughout a deposit often are essentially the same. Deposits which contain anomalous lead, however, often have a wide range of $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values. The range of $^{207}Pb/^{204}Pb$ ratios depends in part on the age of the source material: lead in a young deposit derived from Archaen rocks may have a wide range of $^{207}Pb/^{204}Pb$.

Anomalous lead isotope data often lie along straight lines on $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plots which may be interpreted as secondary isochrons. A secondary isochron is the result of a two-stage process. During the first stage lead isotopic composition evolves in a system approximating single-stage growth until an event occurs which changes the $^{238}U/^{204}Pb$ ratio into a number of values. Continued evolution during this second stage results in an array of ratios falling on a line. If the approximate age of mineralization is known, the age of the source material may be calculated. In some cases the source of ore lead has been identified where matching secondary isochrons have been found in rocks (e.g. Doe and Delevaux, 1972; Rye *et al.*, 1974).

Doe and Stacey (1974) point out that when single-stage processes are assumed for two-stage systems, model lead ages are younger than the age of mineralization if $^{238}U/^{204}Pb$ values are greater than average for single-stage systems and older if $^{238}U/^{204}Pb$ is lower in the second stage. Analysis of several samples from deposits where age relationships are poorly known is desirable.

The interpretation of secondary isochrons in southern Appalachian rocks has been complicated by the "young" (i.e. < 1.3 b.y.) rocks which alone seem to have contributed lead to various systems. Because $^{207}Pb/^{204}Pb$ has changed little in the last billion years, the slopes of the isochrons are shallow. Slopes corresponding to secondary isochron ages decreased rapidly during the first half of geologic time, and therefore a given slope has a better constrained solution for Archaen leads and slope errors are minimized. During the second half of earth history, however, and especially during the last billion years when ^{207}Pb production has approached zero, slope error has become an increasingly significant factor so that even a well defined line with a wide range of data and a small mean square of weighted deviates (MSWD) can yield a Pb-Pb isochron age with a large 2σ error. Figure 18 (to be discussed later) presents a good example of this effect. A slope of 0.061 ± 0.008 (2σ) with an MSWD of 0.24 yields an error of almost 50% in its Pb-Pb isochron age (which happens, at about 640 m.y., to be a good estimate of the rocks' actual ages). In contrast, the regression in Figure 40 corresponds to a secondary isochron age of 3.7 ± 0.3 b.y. - an error of less than 10% on a much less well defined line.

There is a subtle difference in the methods used to calculate the slopes (and corresponding ages) of the above examples of a "Pb-Pb isochron" and a "secondary isochron". That which I will refer to as a "Pb-Pb isochron" assumes an upper intercept age of zero and is valid when (a) the event which disturbed or derived lead from a system approximating single stage growth occurred relatively recently, or (b) the secondary system has remained relatively undisturbed since its time of formation and the spread of data is due to <u>in situ</u> radioactive decay. Ages corresponding to slopes of Pb-Pb isochrons are taken directly from the tables of Stacey and Stern (1973).

A "secondary isochron" is calculated from the time, t_2, (other than zero) of mineralization (crystallization of rocks) and some earlier time of formation of source material, t_1, at which secondary growth began.

The equation governing both calculations is:

$$\frac{\left(\frac{^{207}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{t_2} - \left(\frac{^{207}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{t_1}}{\left(\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{t_2} - \left(\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{t_1}} = \left(\frac{^{235}\mathrm{U}}{^{238}\mathrm{U}}\right)_p \left[\frac{e^{\lambda_5 t_1} - e^{\lambda_5 t_2}}{e^{\lambda_8 t_1} - e^{\lambda_8 t_2}}\right]$$

where $(^{235}\mathrm{U}/^{238}\mathrm{U})_p$ is the present day ratio. This equation assumes closed-system behavior of uranium and lead between times t_2 and t_1.

Several cases of three-stage (and higher order) systems, which can result in highly complex patterns of lead isotope data, are known, and some, in favorable circumstances, are interpretable. Doe and Stacey (1974) summarize some examples of high order lead evolution interpretations.

Linear relationships have also been interpreted as mixing lines of end-member lead isotope compositions. In a recent example Dickin (1981) interpreted a linear array of lead isotope compositions from Isle of Skye Tertiary igneous rocks as representing a mixing line between Lewisian crustal lead and Tertiary mantle-derived lead.

Plumbotectonics

Doe and Zartman (1979) and Zartman and Doe (1981) presented a model for observed lead isotope evolution trends which they called "plumbotectonics". The model takes into account the geological and geochemical processes which have effected lead evolution through time. These include the redistribution and recycling of U, Th, and Pb during orogenic, weathering, and sedimentation processes, and the fractionaction of U, Th, and Pb in four broad crustal environments. These are the upper and lower continental crust, the mantle, and the orogenic environment.

The upper crust is characterized by open-system processes and by a $^{238}U/^{204}Pb$ value which, on average, has gradually increased through time. The $^{238}U/^{204}Pb$ values of the upper crust can be high and thus give rise to a rather radiogenic lead *in situ* (Doe, 1970; Rosholt *et al.*, 1973) which in turn can contribute radiogenic lead to ore deposits with "anomalous" leads. The $^{232}Th/^{204}Pb$ ratios of upper crustal rocks are variable, but tend to be relatively high (Doe and Zartman, 1979).

The lower continental crust frequently consists of pyroxene granulite and other highly metamorphosed and refractory rocks. Typically, uranium concentrations and $^{238}U/^{204}Pb$ ratios are low in these rocks (Moorbath *et al.*, 1969; Gray and Oversby, 1972). Thorium and lead contents are not as drastically depleted relative to upper crustal values as uranium. $^{232}Th/^{204}Pb$ is variable, but averages slightly greater than in the upper crust (Doe and Zartman, 1979).

The depletion of uranium in the lower crust and the excess in the upper crust have opposite effects on lead isotope compositions and result in distinctive patterns in lead derived from one source or the other. Lead with a large component derived from a lower crustal source will be retarded in its uranogenic lead evolution while lead from upper crustal sources will tend to be enriched in uranogenic lead. The depletion of uranium relative to thorium in lower crustal rocks also has profound effects on $^{208}Pb/^{204}Pb$ ratios. The field of lower crustal ("cratonized crust") lead isotopic ratios (Fig. 6) falls to the left of the other fields on a $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram, the result of retarded uranogenic lead evolution combined with near average thorogenic lead growth.

The upper mantle has relatively low $^{238}U/^{204}Pb$ and $^{232}Th/^{204}Pb$ ratios (Tatsumoto, 1978), and thus is retarded in lead evolution relative to upper and average crustal lead. The effect of a contribution of lead from the mantle is particularly evident in the resulting low $^{207}Pb/^{204}Pb$ ratios (Doe and Zartman, 1979), whereas $^{206}Pb/^{204}Pb$ ratios may be somewhat radiogenic due to an apparent increase with time of mantle $^{238}U/^{204}Pb$ ratios (Tatsumoto, 1978).

Plumbotectonics fourth environment is the orogene. In the orogene, lead from the other three major environments is mixed and the result is an average lead evolution curve. The orogene curve in Figure 7 closely approximates Stacey and Kramers' (1975) two-stage evolution curve. In the orogene, the excess uranium of the upper crust is mixed with uranium-poor lower crust resulting in a system approaching model single-stage characteristics. The mantle also contributes lead through material caught up in orogenic processes.

Figure 7 illustrates the position of some Phanerozoic volcanogenic massive sulfides in relation to plumbotecton-

Figure 6. Fields of lead isotope data of rocks from various crustal environments. From Doe and Zartman (1979).

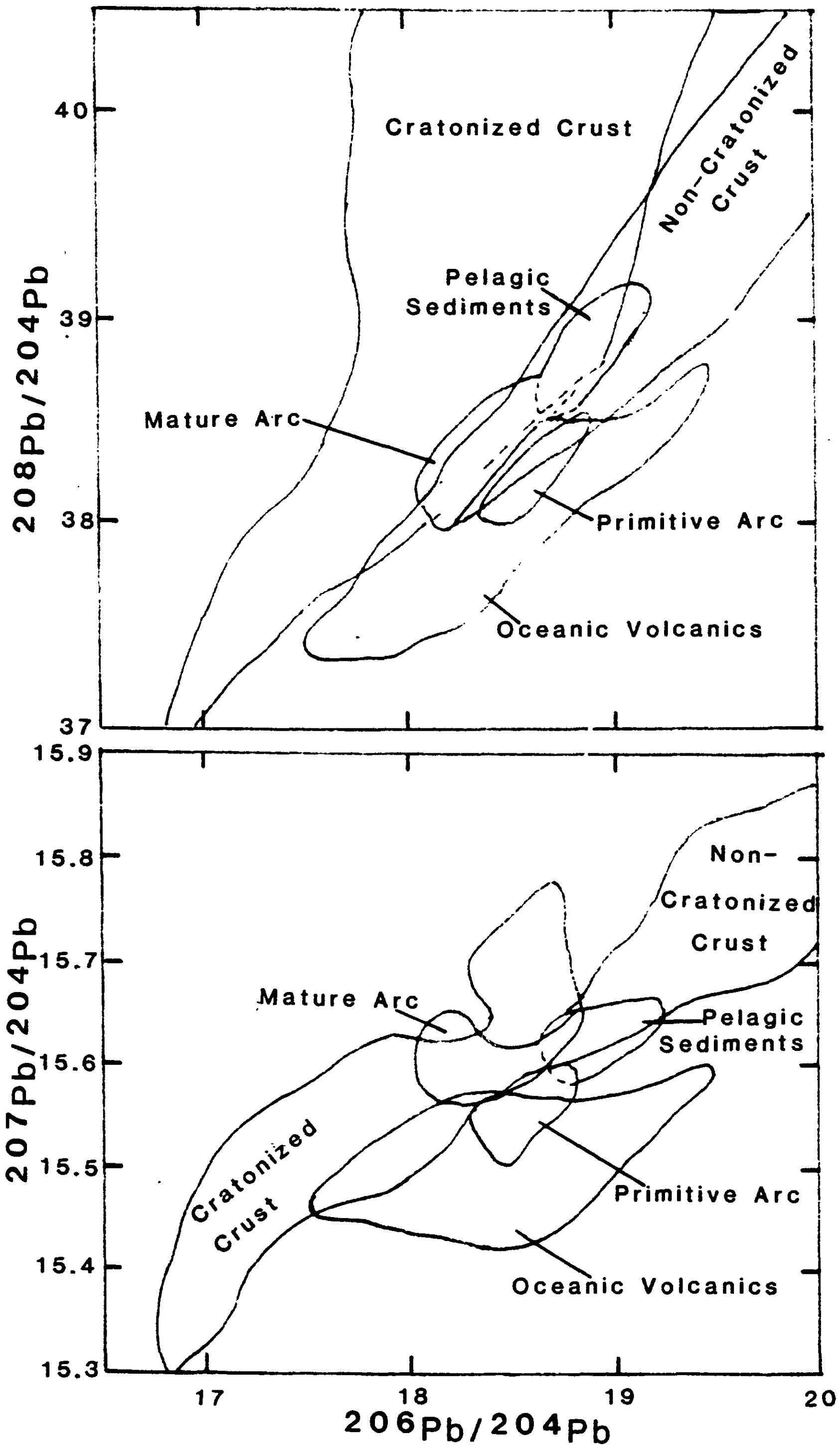
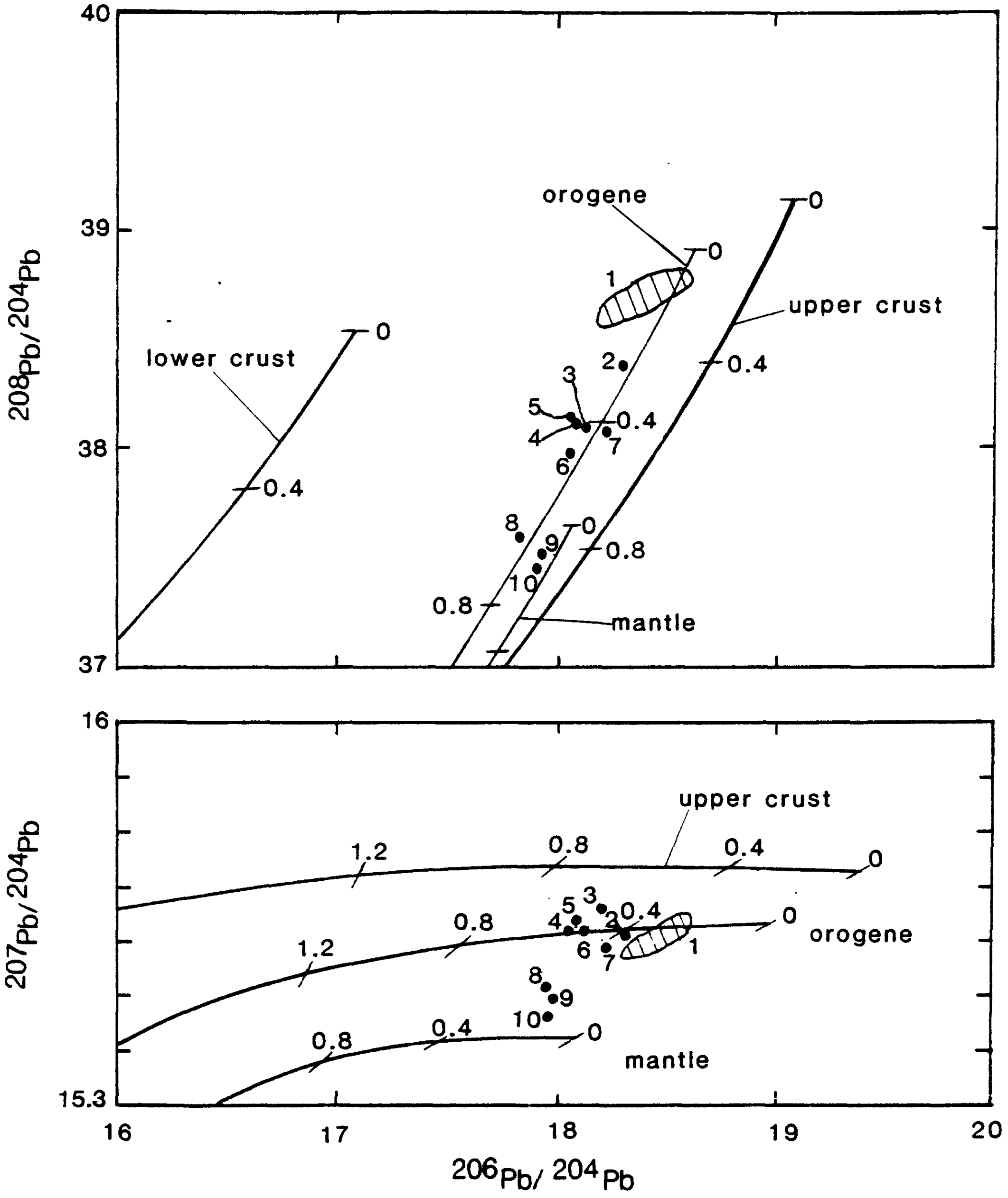

Cratonized Crust
Non-Cratonized Crust
Pelagic Sediments
Mature Arc
Primitive Arc
Oceanic Volcanics
208Pb/204Pb
37
38
39
40
Non-Cratonized Crust
Mature Arc
Pelagic Sediments
Cratonized Crust
Primitive Arc
Oceanic Volcanics
207Pb/204Pb
15.3
15.4
15.5
15.6
15.7
15.8
15.9
17
18
19
20
206Pb/204Pb

Figure 7. Lead isotope growth curves generated by the plumbotectonics model of Doe and Zartman (1979). Numbers indicate individual deposits, as follows: 1. Kuroko ores of Japan; 2. Halls Peak, New Zealand; 3. Mineral Virginia and Bathurst, New Brunswick; 4. Cobar, Ontario; 5. Captain's Flat, Australia; 6. Black Hawk, Maine; 7. Roseberry, Tasmania; 8. Buchans, Newfoundland; 9. West Shasta, California; 10. East Shasta, California. (after Doe and Zartman, 1979).


40
39
38
37
$^{208}Pb/^{204}Pb$
orogene
0
1
upper crust
0
0.4
2
lower crust
0
3
5
4
0.4
7
6
0.4
8
9
0
0.8
10
0.8
mantle
16
15.3
$^{207}Pb/^{204}Pb$
upper crust
1.2
0.8
0.4
0
3
5
0.4
4
0.8
0
orogene
1.2
6
7
1
8
9
10
0.8
0.4
0
mantle
16
17
18
19
20
$^{206}Pb/^{204}Pb$

ics evolution curves. The position of lead isotope data from Buchans, Newfoundland, and the Shasta district, California, are thought to represent a substantial contribution of lead from the mantle because of their low ^{207}Pb/^{204}Pb ratios (Doe and Zartman, 1979). Their geologic settings seem to support this assessment. Also of interest to this study in Figure 7 is the data point from Bathurst, New Brunswick, in the Canadian Appalachians. Lead from the Mineral district, Virginia, has similar lead isotope compositions.

3. A REVIEW OF SULFUR ISOTOPE SYSTEMATICS

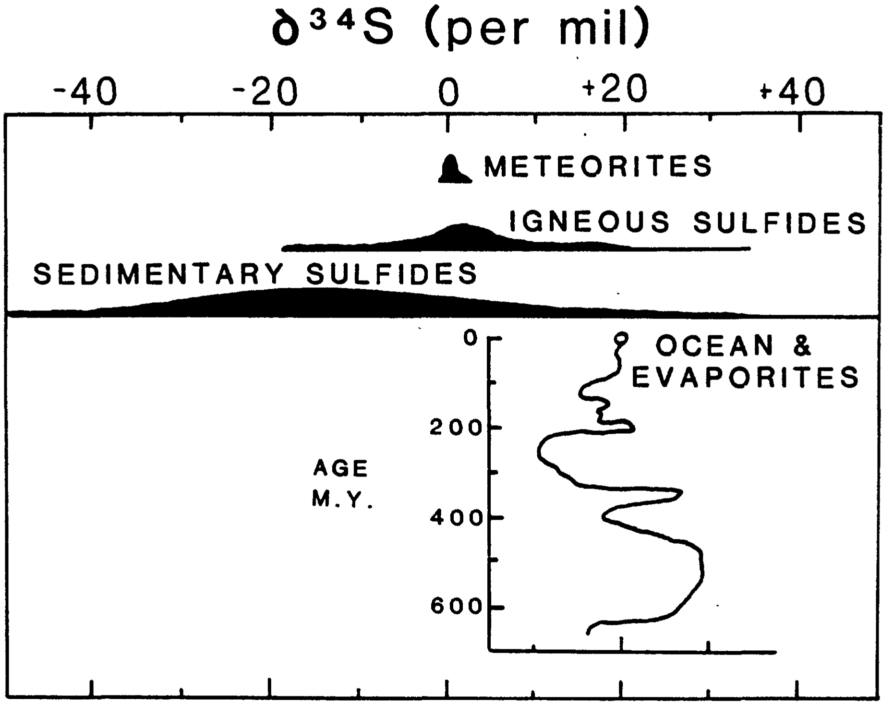
Sulfur Isotope Variation In Nature

There are four naturally occurring stable isotopes of sulfur with approximate abundances of ^{32}S = 95.02%, ^{33}S = 0.75%, ^{34}S = 4.2% and ^{36}S = 0.017%. The majority of sulfur isotope studies are based on variations in $^{34}S/^{32}S$ ratios, which are usually expressed as $\delta^{34}S$ values. $\delta^{34}S$ represents the per mil (°/oo) deviation of the $^{34}S/^{32}S$ ratio of a sample relative to that observed in the troilite phase of the Canyon Diablo meteorite ($^{34}S/^{32}S$ = 0.0450045, Ault and Jensen, 1963) which is defined as $\delta^{34}S = 0$. The $\delta^{34}S$ value of a given sample may be expressed as:

$$\delta^{34}S_{\text{sample}} = \left[\frac{(^{34}S/^{32}S)_{\text{sample}}}{(^{34}S/^{32}S)_{\text{standard}}} - 1 \right] \times 1000$$

Figure 8 summarizes the variation of sulfur isotopic compositions observed in naturally occurring materials. Sulfides in igneous rocks are generally isotopically similar to meteoritic values with $\delta^{34}S$ averaging close to 0 °/oo. Sulfates in seawater and evaporite deposits are generally

Figure 8. Sulfur isotope variation in nature. From Ohmoto and Rye (1979).



SULFUR ISOTOPIC VARIATION IN NATURE
(FROM OHMOTO & RYE, 1979)

enriched in the heavier isotope (higher $\delta^{34}S$) by about 10 to 30^{o}/oo, depending in part on geologic age. Sedimentary sulfides have a wide range of $\delta^{34}S$ values (-70 to +70^{o}/oo), but tend to be depleted (lower $\delta^{34}S$) in the heavier isotope (Ohmoto and Rye, 1979).

The mechanisms responsible for variations in the isotopic composition of sulfur are totally different than those producing lead isotopic variations. Changes in lead isotopic composition are due to radioactive decay of uranium and thorium; kinetic fractionation effects on the isotopes of lead do not occur in nature because of the small relative mass differences between them. The relative mass difference between ^{34}S and ^{32}S, however, is large enough to effect the thermodynamic properties of the isotopic species. Bachinski (1969) for example, found that $\delta^{34}S$ variations among coexisting sulfides correlate with metal-sulfur bonding energies, with the heavy isotope preferentially residing in sites with the highest bond energies.

Isotopic fractionation of sulfur can occur in a variety of situations described by Ohmoto and Rye (1979, p. 522). During the history of an ore fluid "... fractionation may take place (1) at the source of sulfur such as during separation of fluids from a magma, or during leaching of sulfides, (2) during the evolutionary history of hydrothermal fluids involving reduction of seawater sulfate, (3) during cooling of hydrothermal fluids, and (4) during precipitation or replacement of minerals."

Sulfur isotope geothermometry

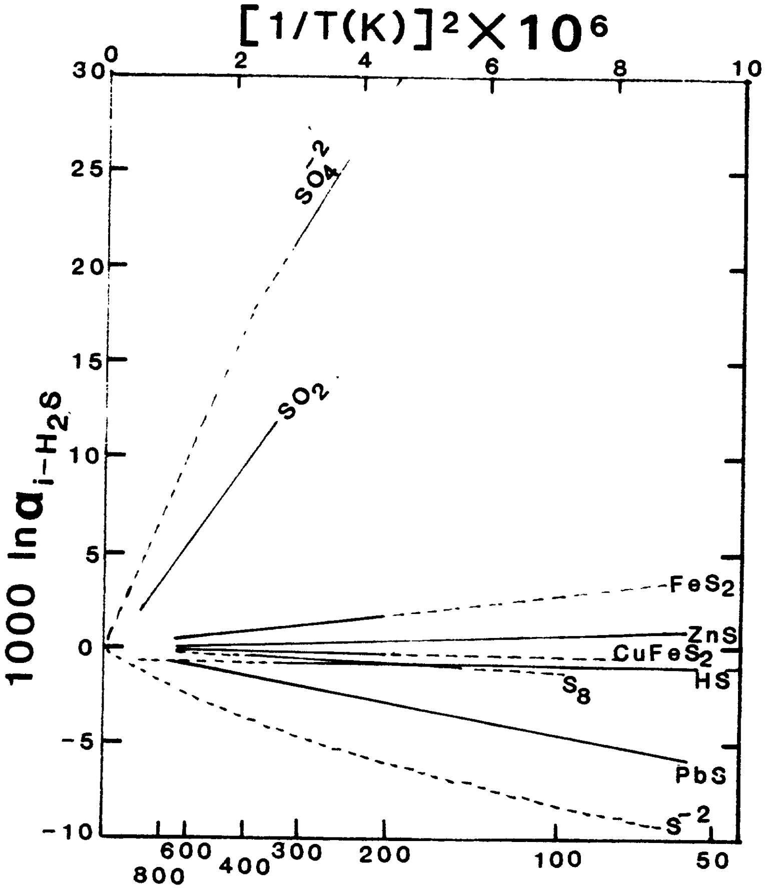
Rye and Ohmoto (1974), noted that the major factors which control the sulfur isotopic composition of hydrothermal minerals are: (1) temperature, which determines fractionations between sulfur-bearing species; (2) the sulfur isotopic composition of the fluid system ($\delta^{34}S_{\Sigma S}$), which is controlled by the source of sulfur; and (3) the proportions of oxidized and reduced sulfur species in solution.

In a system in which isotopic equilibrium is approached, the isotopic fractionation factor between two co-existing sulfur bearing compounds is related to the equilibrium constant. Isotopic equilibrium constants are primarily a function of temperature and when the temperature function is accurately known, the equilibration temperature of the compounds can be calculated from the difference in their $\delta^{34}S$ values (Ohmoto and Rye, 1979). Figure 9 graphically depicts a summary of fractionation factors for sulfur-bearing compounds (Ohmoto and Rye, 1979). The data illustrate that in a system approaching equilibrium at a given temperature the δ^{34}value of sulfate species > pyrite > sphalerite > chalcopyrite > galena.

Equilibration temperatures can be calculated from the experimental curves (Fig. 9) and the equations of Ohmoto and Rye (1979, p. 518). Those authors cite several conditions that must be met for meaningful application of sulfur isotope thermometry to a mineral pair. First, the two mineral phases must have formed in equilibrium. To satisfy this criterion the paragenesis of ore minerals in a deposit must be well known. In metamorphosed deposits such as those in the southern Appalachians, deformation and metamorphism have often obliterated primary textures and paragenetic clues are scarce. Secondly, after mineral formation no isotopic exchange should have taken place between the mineral phases or between a mineral phase and a fluid phase. Whether original isotopic composition is maintained during metamorphism or re-equilibrated to a greater or lesser extent is not well known, but there is some indication that isotope exchange between sphalerite and galena occurs at lower grades of metamorphism than that of pyrite and other minerals (Ohmoto and Rye, 1979). The effects of metamorphic "desulfidization: (i.e. pyrite → pyrrhotite + S) are not well known.

A third criterion for successful sulfur isotope thermometry is that pure mineral phases are separated for analyses.

Figure 9. Equilibrium isotopic fractionation factors among sulfur compounds relative to H_2S. α is the fractionation factor of a species, i, relative to H_2S. From Ohmoto and Rye (1979).


$[1/T(K)]^2 \times 10^6$
0
2
4
6
8
10
30
25
20
15
10
5
0
-5
-10
$1000 \ln \alpha_{i-H_2S}$
SO_4^{-2}
SO_2
FeS_2
ZnS
$CuFeS_2$
HS
S_8
PbS
S^{-2}
800
600
400
300
200
100
50
Temperature, °C

Sulfur isotopic variation in hydrothermal systems

Sulfide and sulfate minerals in hydrothermal ore deposits ultimately derived their sulfur from an igneous and/or a seawater source. Seawater sulfur occurs as aqueous sulfate which may find its way into sulfide deposits in a number of ways. Ohmoto and Rye (1979) listed the possible paths as:

- _in situ_ reduction of sulfate to H_2S by sulfur-reducing bacteria, generating sedimentary sulfides;
- Leaching of sedimentary sulfides by hydrothermal fluids;
- Replacement of sedimentary sulfides by other sulfide minerals when encountered by metalliferous brines; and
- Reduction of aqueous sulfates to aqueous sulfides non-bacterially at elevated temperatures.

This last process allows sulfate-rich waters to participate in sulfide deposition.

Igneous sources of sulfur include sulfur in magmatic fluids and sulfur leached from sulfur-bearing phases in igneous rocks.

Hydrothermal systems may leach sulfur from either igneous or sedimentary sources, or from a mixture of the two. Ohmoto and Rye (1970) reviewed the equilibrium and kinetic factors involved in isotopic fractionation of sulfur under various conditions.

The large numbers of processes which cause sulfur isotopic fractionation and the considerable variability of sulfur isotopic composition in environments which may contribute sulfur to a hydrothermal cell result in sulfur isotope studies alone being insufficient to define the conditions of sulfide mineralization. Nevertheless, sulfur isotope studies can provide useful information and can place constraints on mineralization parameters.

$\delta^{34}S$ of sulfides has been observed to decrease upward in the stratigraphic section of some volcanogenic stratabound deposits. Given the proper conditions, use of sulfur isotope variations as evidence of stratigraphic succession in deposits where structural complications have confused the issue may be possible.

Sangster (1968) noted that average $\delta^{34}S$ value of sulfides in volcanogenic exhalative deposits is about $17^{o}/oo$ lower than the $\delta^{34}S$ value of contemporaneous seawater.

Seawater sulfate age curve

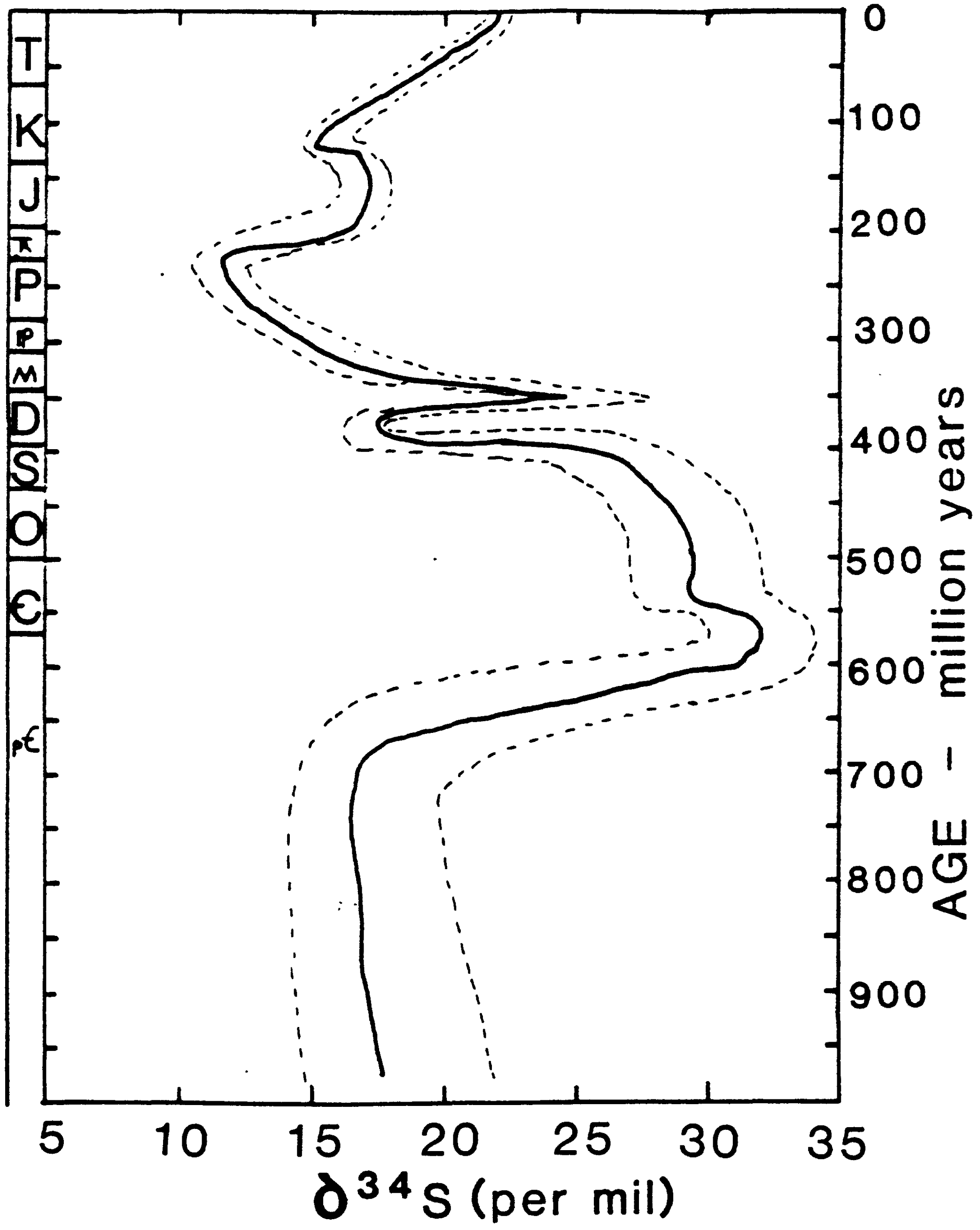
Claypool _et_ _al_. (1980) recently presented abundant new evidence for the variation through time of the sulfur isotope composition of marine sulfate, based on the analysis of sulfur in evaporitic sulfate. The application of evaporite sulfate to ancient seawater is based on the observation that (1) present day ocean sulfate has a uniform $\delta^{34}S$ (= + 20°/oo) worldwide, indicating rapid mixing (Sasaki, 1972) and (2) present day sulfate evaporites show a uniform enrichment of 1-2°/oo in $\delta^{34}S$ relative to dissolved sulfate (Thode and Monster, 1965).

Figure 10 depicts the variation of seawater sulfate $\delta^{34}S$ ($\delta^{34}S_{sw}$) from about 1.0 b.y. to the present. The total range of $\delta^{34}S_{sw}$ is about 10 to 30°/oo. The age range of interest to discussion of southern Appalachian sulfide deposits (late Precambrian to Ordovician(?)) is seen to be a time of rapid change in the sulfur isotopic composition of seawater sulfate. Sometime during the late Precambrian seawater began to become enriched in ^{34}S relative to ^{32}S and rose from a Proterozoic $\delta^{34}S_{sw}$ value of about 17.0 ± 3°/oo. $\delta^{34}S_{sw}$ may have reached a peak in the latest Precambrian-lowermost Cambrian of about 33°/oo, but seems to have maintained a value close to 30°/oo for most of the Cambrian. The curve is less well defined for Ordovician seawater, but there seems to have been a gradual decline of $\delta^{34}S_{sw}$ to about 27°/oo by the end of the Ordovician, which perhaps cannot be statistically distinguished from Cambrian on the basis of $\delta^{34}S_{sw}$.

Sangster's (1968) observation that volcanogenic stratabound sulfide deposits contain sulfide $\delta^{34}S$ values approximately 17°/oo less than contemporaneous seawater $\delta^{34}S_{sw}$ can be related to the $\delta^{34}S_{sw}$ age curve. During the

Figure 10. Sulfur isotope variation of seawater sulfate through time. Dashed lines represent approximate limits of error. From Claypool _et_ _al_., 1980.

SEAWATER SULFATE - age curve



from Claypool et al. (1980)

late Precambrian when $\delta^{34}S_{sw} \simeq 17.0^{o}/oo$ a sulfide deposit which derived its sulfur from seawater would have sulfide $\delta^{34}S \simeq 0^{0}/00$. A similar Cambrian deposit would have sulfide with $\delta^{34}S$ up to about $13^{o}/oo$. It has also been noted that sulfur in barite associated with volcanogenic massive sulfides is enriched $1\text{-}2^{o}/oo$ relative to contemporaneous seawater (see Ohmoto and Rye, 1979, p, 547), which is the same relative enrichment often found in marine evaporite sulfates through time (Sasaki, 1972).

The effect of the secular variations of $\delta^{34}S_{sw}$ and the consistent relationship of sulfur in massive sulfides to the age curve is strong evidence for the dominant role played by seawater in the formation of volcanogenic stratabound sulfide deposits.

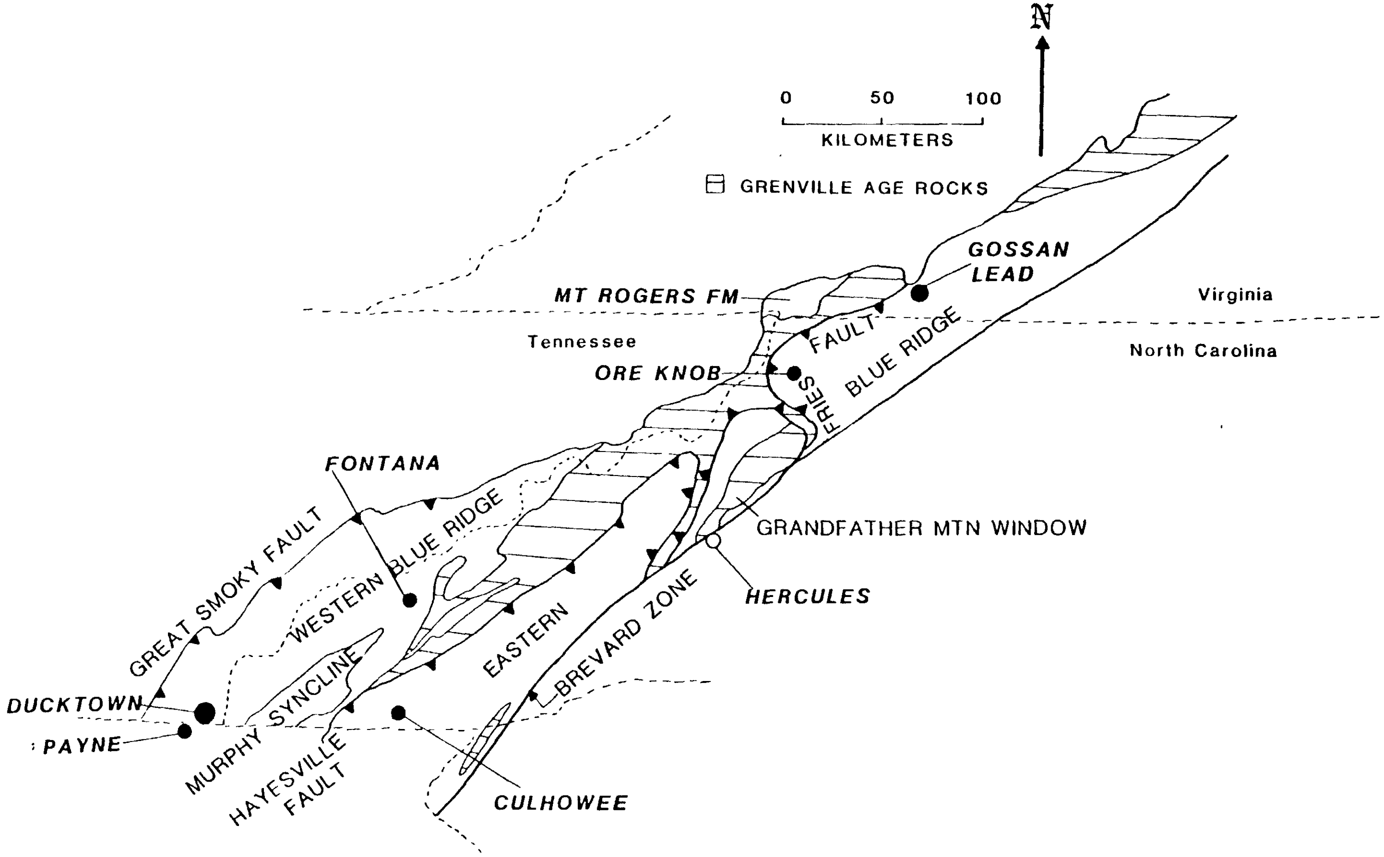
Part II. BLUE RIDGE STRATABOUND SULFIDE DEPOSITS

1. GENERAL GEOLOGY OF THE BLUE RIDGE GEOLOGIC PROVINCE

The Blue Ridge geologic province (Fig. 11) is an allochthonous anticlinorium consisting of a thick pile of upper Precambrian and lower Paleozoic metamorphosed volcanic and predominantly clastic sedimentary rocks nonconformably averlying a core of Grenville-age (1.0 to 1.3 b.y.) granites and gneisses, all thrust to the northwest over unmetamorphosed Paleozoic sediments of the Valley and Ridge province. From Virginia into Georgia the Blue Ridge is bounded on the southeast by the Brevard Fault zone.

The Blue Ridge may be further subdivided into eastern and western zones based on lithological characteristics (Hatcher, 1978). The western Blue Ridge is characterized by abundant outcrop of Grenville-age basement rocks and by the scarcity of Paleozoic intrusions. In the eastern zone outcrops of Grenville-age basement are scarce (probably occurring only in windows) and Paleozoic plutons relatively abundant. Additionally, recognizable evidence of volcanic activity is much more abundant in the metamorphosed upper Precambrian of the eastern Blue Ridge than in the western zone, and the eastern zone contains virtually all of the ultramafic rocks of the Blue Ridge (Hatcher, 1978). The boundary between the two subprovinces is the Hayesville

Figure 11. Index map of the Blue Ridge geologic province in Virginia, Tennessee, and North Carolina showing locations of sulfide deposits discussed in text. For continuation in Georgia and Alabama, see figure 37.


N
0 50 100
KILOMETERS
▤ GRENVILLE AGE ROCKS
GOSSAN LEAD
MT ROGERS FM
Virginia
Tennessee
North Carolina
FAULT
BLUE RIDGE
ORE KNOB
FRIES
FONTANA
GRANDFATHER MTN WINDOW
HERCULES
GREAT SMOKY FAULT
WESTERN BLUE RIDGE
EASTERN
BREVARD ZONE
DUCKTOWN
PAYNE
MURPHY SYNCLINE
HAYESVILLE FAULT
CULHOWEE

fault south of the Grandfather Mountain window and the Fries fault north of the window.

Stratabound sulfide bodies of the Blue Ridge are found in the upper Precambrian metasediments and metavolcanics in basins flanking the Grenville core (Gair and Slack, 1980). The basins are thought to have formed near the eastern edge of the late Precambrian North American continent during the rifting associated with the opening of the proto-Atlantic (Iapetus) ocean (Gair and Slack, 1979, 1980; Odom and Fullagar, 1973; Rankin, 1975).

To the west of the Grenville-age core, sediments accumulated in what may be called the "Ocoee Basin". Rocks of the upper Precambrian Ocoee Supergroup dominate western Blue Ridge lithologies and consist largely of metamorphosed flysch-like sediments (Hadley, 1970). Stratabound massive sulfide bodies of the "Ocoee Basin" are found within the Great Smoky Group of the Ocoee Supergroup, and include the Ducktown district, Tennessee, and the Fontana district, North Carolina. The Great Smoky Group consists of as much as 7,600 meters (25,000 feet) - neither top nor bottom is exposed - of metamorphosed, interbedded graywackes, quartzites, and schists. Several small, conformable amphibolite bodies in the vicinity of Ducktown are the only recognizable evidence of igneous activity in the sequence (Magee, 1968; Hadley, 1970).

Rankin *et al.*, (1973), considered the Great Smoky

Group to be at least partially correlative with the Ashe Formation, mainly a sequence of metagraywackes and sulfidic and graphitic phyllites deposited in the "Ashe Basin" on the eastern flank of the Grenville-age core. The Ashe Formation is host to the Great Gossan Lead, southwestern Virginia, and of the Ore Knob district, North Carolina. Abundant amphibolite units within the Ashe were recognized as metamorphosed mafic volcanic rocks by Rankin (1970) and Rankin _et_ _al_., (1973).

The sediments and volcanics of the Ocoee and Ashe basins are presumably at least partially correlative with the volcanics of the Mount Rogers Formation which have been interpreted as rift volcanics (Odom and Fullagar, 1973; Rankin, 1975). The Mount Rogers is currently restricted in outcrop to the area around the common border of Virginia, North Carolina and Tennessee.

The correlation of Blue Ridge lithologies becomes more problematical to the southwest, in Georgia and Alabama. In parts of these two states Piedmont province stratigraphy can be traced across the Brevard fault zone Hatcher, 1972, 1978; Kline, 1980; Medlin and Crawford, 1973). On the northwestern boundary of the Blue Ridge, the Great Smoky fault system makes a sharp bend from a northeasterly to a north trend at about the Tennessee - Georgia border. The continuation of the Great Smoky fault as the northeasterly trending Cartersville fault is speculative

(McConnel and Costello, 1980).

The southeastern-most Appalachians will be further discussed in a later chapter.

Rb/Sr whole-rock (Fullagar and Bottino, 1970), ^{40}Ar/^{39}Ar incremental release patterns (Dallmeyer, 1975a), and field geologic constraints (Butler, 1972), place the time of peak regional metamorphism in the Blue Ridge between 480 and 430 m.y. Retrograde metamorphic effects are locally evident and are prominent in the Ducktown district (Magee, 1968). The major thrusting events and final placement of the Blue Ridge occurred during the late Paleozoic.

5. DUCKTOWN DISTRICT, TENNESSEE

Economically, the Ducktown mining district has been the most significant sulfide deposit in the crystalline southern Appalachians. Mining of supergene copper ore began soon after discovery in the 1840's and continued until the secondary enrichment zones were exhausted in 1877 (Magee, 1968). Mining of primary ore began in 1889 and continues to the present, although the current operation produces mostly sulfur for sulphuric acid.

District Geology

Eight major ore bodies in Polk County, Tennessee, and a number of sub-economic lenses and disseminated concentrations which extend into nearby Fannin County, Georgia, constitute the Ducktown district. The lithology of the Great Smoky Group in the area is dominated by metagraywackes and mica schists with minor amounts of metamorphosed conglomerates, and chlorite-garnet-staurolite schist. There are also several generally conformable amphibolite bodies which, although the subject of much speculation, have no apparent association with ore lenses (Magee, 1968). Occasional calc-silicate nodules in the graywackes are thought to be metamorphosed calcareous concretions (Hadley and Goldsmith, 1963).

From the Great Smoky fault west of Ducktown the grade of regional metamorphism increases rapidly eastward (Carpenter, 1970). The isograds generally parallel the regional northeast-southwest trend. Ducktown lies on the flank of a dome in the grade of metamorphism defined by the staurolite isograd (Nesbitt and Kelly, 1980) and it reaches kyanite grade in the district (Carpenter, 1970).

A retrograde metamorphic event is evident in the district and surrounding areas (Magee, 1968), but it apparently was not a "strong" enough event to disturb ^{40}Ar/^{39}Ar release patterns of biotite which show little or no disturbance since peak regional metamorphism (Dallmeyer, 1975b).

Theories of Origin

Until relatively recently most geologists believed the ores at Ducktown to be the result of hydrothermal replacement processes. Emmons and Laney (1926) proposed that hydrothermal solutions replaced limestone lenses along a single horizon, and that calc-silicate and calcite gangue represented recrystallized original host rock. Ross (1935) agreed with the hydrothermal replacement model, but believed that solutions were introduced along shear zones and that the calcareous as well as the quartz and ferromagnesian gangue minerals accompanied ore deposition. Carpenter (1965), Kalliokoski (1965) and Kinkel (1965, 1967) all recognized recrystallization and remobilization features in the ore which have obscured primary textures and relationships and which require a premetamorphic origin of the deposits. In 1968, Magee proposed that hydrothermal replacement occurred along several impure calcareous mud horizons and along shear zones which served as conduits for the fluids.

The widespread acceptance of syngenetic models of ore deposition has led more recent investigators to focus on syngenetic mechanisms of emplacement of the Ducktown lenses. From a study of sulfur isotope systematics of Ducktown ore minerals, Mauger (1972), concluded that metals were leached from basinal clastic sediments by pore waters which were later expelled and deposited as sulfides around submarine hot spring vents.

Addy and Ypma (1977), proposed a two-stage model based on oxygen, carbon, and hydrogen isotope systematics. They proposed that local bedded sulfide horizons and ubiquitous disseminated occurrences accumulated within sediments of the Ocoee Supergroup. Subsequent deformation resulted in isoclinal folds and the development of shear zones through the sulfidic horizons. Meteoric waters circulating during metamorphism leached sulfides and trace metals from the sedimentary pile and added to pre-existing concentrations among the shear zones. The circulating cell continued, in their model, into the waning stages of metamorphism and was the agent of some of the retrogressive effects.

Nesbitt and Kelly (1980), showed that the metamorphic zonation of sulfides, oxides, and graphite in ores and wall rock indicates unusually high f_{O_2} and f_{S_2} during regional metamorphism and thus indicates a premetamorphic origin of the ore. They also report, however, that geothermal gradients were abnormally low for the regional metamorphic event in the area, and that, therefore, a synmetamorphic hydrothermal cell enhancing the metal content of the ore zones is unlikely. Nesbitt and Kelly (1980), were not able to distinguish between syngenetic and premetamorphic-epigenetic origins on the basis of metamorphic mineral zonations.

Description of the Ore Bodies

There are eight major ore bodies in the Ducktown district, ranging widely in shape and size. All are generally tabular in shape and conform to the regional trend of the strike and dip of bedding and of metamorphic lineation (Magee, 1968). Magee (1968) reports that the ore lenses are approximately 65 percent massive sulfides and 35 percent gangue. Ore mineralogy consists of about 60 percent pyrrhotite, 30 percent pyrite, 4 percent chalcopyrite, 4 percent sphalerite, 2 percent magnetite, and traces of galena, gold, silver, and other metallic minerals (Magee, 1968).

The district can be described in terms of three trends of ore bodies: the northwest deposits, central deposits, and southeast deposits. Deposits within each of the three groups are generally similar in mineralogy although varying in size and shape and in some structural details. The northwest and southeast deposits are mineralogically similar and have higher copper and zinc but lower total sulfide content than the central deposits. In the central ore bodies pyrite is more abundant, although pyrrhotite is still the predominant sulfide (Magee, 1968). The northwest deposits - Burra Burra, London, and East Tennessee - have all been mined out. There is no current mining in the southeast deposits (Calloway and Mary-Polk County). Only the Cherokee ore body of the central group (which also includes Eureka and Boyd) is being worked at this time.

For this study core from four ore bodies was sampled (see Appendix A for sample locations and descriptions). From the southeast district samples were selected from both the Calloway and Mary-Polk County lenses. Calloway has higher Cu and Zn content that most other bodies in the district. Mary-Polk County also has high Cu and Zn and appears to contain more galena and less magnetite than other lenses. It is also the only body in which molybdenite has been identified (Magee, 1968).

The Boyd and Cherokee ore bodies were sampled from the central district group. Mineralogically, these are distinguished by local concentrations of up to about 15 percent magnetite and abundant pyrite which locally predominates over pyrrhotite.

As noted above, galena is rather scarce in all of the ore bodies at Ducktown. Galena most commonly occurs in sphalerite-rich zones. Several examples were found, however, of galena associated with pyrrhotite and chalcopyrite in remobilized masses filling fractures in quartz.

Along strike with Ducktown to the southeast in Fannin County, Georgia, there are several minor occurrences of stratabound sulfides of sub-economic importance. These consist largely of disseminated sulfides in quartz-biotite schists.

Results of lead isotope studies

Doe (In Kinkel, 1967) reported three lead isotope ratios for galenas from Ducktown. These showed that the lead in Ducktown ore is anomalously radiogenic for a late Precambrian deposit. High precision analyses reported here confirm this observation.

Nine galenas from four ore bodies were analyzed for lead isotopic composition (Table 2). The total range of observed values are: $^{206}Pb/^{204}Pb$ = 18.37 - 18.74; $^{207}Pb/^{204}Pb$ = 15.61 - 15.65; and $^{208}Pb/^{204}Pb$ = 37.86 - 38.25. The isotopic ratios do not form a continuum along this range, however, but appear to fall into three distinct groups (Fig. 12). The least radiogenic cluster (group 1, Table 2) has $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ranging from 18.36 - 18.42, 15.61 - 15.63, and 37.87 - 37.95, respectively. A second group (group II, Table 2) has a range of ratios of, in the same order, 18.51 - 18.54, 15.63, and 38.02 - 38.07. The most radiogenic galena analyzed constitutes the sole member of group III (sample DK-48, Table 2).

Groups I and II do not seem to be related to variations in the rock type, ore body, or type of ore in which the galena occurs (see Appendix A for sample descriptions). The four samples from the Calloway body occur in different types of ore. DK-19 is from a Cu-Zn ore zone and DK-31 from what is known in the district as a siliceous mineralization zone. Galena from the two have lead isotope composition which fall in group 1. These two samples are also from the highest and the lowest Calloway levels, respectively, sampled. DK-1 and DK-29 are from intermediate levels. The former occurs in a quartz vein and the latter in massive ore: both have galena lead isotope ratios falling in group II. A sample from disseminated ore (DK-47, Table 2)

Figure 12. Lead isotope ratio diagrams showing results from Ducktown galenas. Groups I, II, and III are discussed in the text. Note that the $^{207}Pb/^{204}Pb$ scale has been exaggerated to achieve resolution of data points.

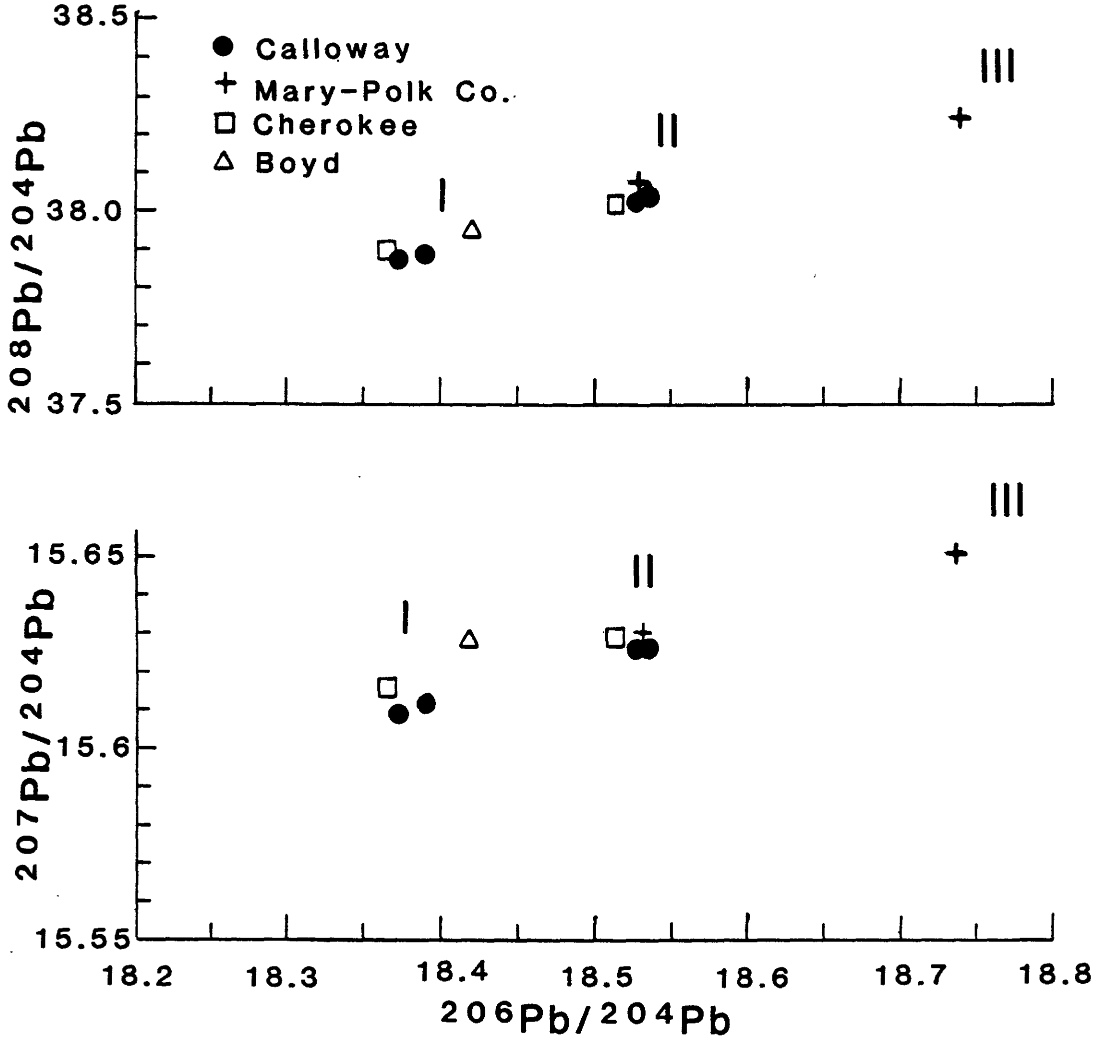

38.5
38.0
37.5
208Pb/204Pb
● Calloway
+ Mary-Polk Co.
□ Cherokee
△ Boyd
I
II
III
15.65
15.6
15.55
207Pb/204Pb
18.2
18.3
18.4
18.5
18.6
18.7
18.8
206Pb/204Pb

TABLE 2

Lead isotope ratios of galenas from the Ducktown district, Tennessee. See text for discussion of groups I, II, and III. See Appendix A for sample descriptions and locations.

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Group
Calloway ore body				
DK-1	18.538	15.626	38.044	II
DK-19	18.390	15.612	37.887	I
DK-29	18.529	15.626	38.036	II
DK-31	18.372	15.609	37.873	I
Mary-Polk County ore body				
DK-47	18.532	15.631	38.073	II
DK-48	18.738	15.651	38.251	III
Boyd ore body				
DK-52	18.420	15.628	37.948	II
Cherokee ore body				
DK-74	18.514	15.629	38.019	II
DK-83	18.365	15.616	37.893	I
Payne prospect, Fannin County, Georgia				
DK-36	18.277	15.595	37.865	--

falls in group II along with massive occurrences and galena in quartz veins. Galena found in quartz veins and impure quartzites have lead isotope ratios falling in all three groups. Groups I and II are represented in both central district bodies (Boyd, Cherokee) and in southeastern district bodies (Calloway, Mary-Polk County). The lone occurrence of group III lead isotopic composition is found in Mary-Polk County sample DK-48.

Sample DK-52 from the Boyd ore body (Table 2) may be slightly different from the other members of Group I. Its $^{207}Pb/^{204}Pb$ ratio is more like those found in group II and its ^{206}Pb- and $^{208}Pb/^{204}Pb$ ratios are different from other group I ratios by slightly more than the maximum 0.1% error. If the Boyd sample is not included, the range of group I ratios becomes much narrower: $^{206}Pb/^{204}Pb = 18.36 - 18.39$; $^{207}Pb/^{204}Pb = 15.61$; and $^{208}Pb/^{204}Pb = 37.87$-$37.89$.

Three samples of massive ore not containing visible galena were also analyzed for lead isotope composition (see Appendix B for analytical procedures). Two of the samples were predominantly pyritic (DK-16 and DK-89, Table 3) and were analyzed for lead isotope composition of the HCl-soluble fraction (essentially, all sulfides but pyrite) and of the HCl-insoluble fraction (essentially, pyrite).

Massive pyritic ore from the Calloway body (DK-16, Table 3) has similar lead isotope ratios in its HCl-soluble and -insoluble fractions, which fall within the range of

TABLE 3

Lead isotope ratios in massive pyritic and massive pyrrhotitic ore. "L" after sample number designates HCl leachate: "R" indicates HCl insoluble fraction (essentially pyrite). See text for discussion on groups I and II.

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Group
Calloway ore body				
Massive pyritic ore				
DK-16(L)	18.527	15.632	38.041	II
DK-16(R)	18.552	15.631	38.037	II
Cherokee ore body				
Massive pyrrhotitic ore				
DK-82*	18.520	15.622	37.974	II
Massive pyritic ore				
DK-89(L)	18.313	15.611	37.829	I
DK-89(R)	18.421	15.610	37.824	I

* Whole ore analysis: 404 ppm Pb; 3.10 ppm U; 0.212 ppm Th.

group II galenas. Both fractions contain lead in amounts estimated to be greater than 100 ppm (a qualitative estimation based on the experience of the author). The slight difference in $^{206}Pb/^{204}Pb$ ratios of the soluble and insoluble fractions may be the result of <u>in situ</u> decay of uranium and of different uranium concentrations of the two fractions.

Massive pyritic ore from the Cherokee ore body (DK-89, Table 3) was also analyzed as HCl-soluble and -insoluble fractions. This sample also is estimated to contain greater than 100 ppm Pb in each fraction. In this case there is a distinct difference in $^{206}Pb/^{204}Pb$ ratios of the two portions. The HCl-soluble fraction has a $^{206}Pb/^{204}Pb$ ratio somewhat lower than group I galenas while the same ratio in the insoluble fraction is similar to that found in the slightly anomalous Boyd ore body galena (DK-52, discussed above). If lead from the two fractions were mixed, the resulting isotopic ratio might fall in the main spectrum of group I galena ratios. The $^{208}Pb/^{204}Pb$ ratios of the two fractions however, are similar to each other and are both slightly lower than those found in any of the galenas analyzed. <u>In situ</u> decay of uranium may account for some of the $^{206}Pb/^{204}Pb$ difference between the fractions, but the isotopic ratio of a rock or mineral containing 100 ppm (or more) lead would not be greatly changed by the decay of uranium in the concentrations usually found in sulfide minerals, even in 600 to 800 million years.

A sample of massive pyrrhotite ore from the Cherokee lense (DK-82, Table 3), was analyzed for its lead isotope composition which was found to be similar to group II galenas. As in the pyritic sample from Cherokee (DK-89) the $^{208}Pb/^{204}Pb$ ratio may be slightly less than that of the corresponding galena group.

A sample of galena from the Payne prospect, a disseminated sulfide occurrence along strike with Ducktown in Fannin County, Georgia, has lead isotopic composition that is significantly less radiogenic than any observed in the Ducktown ore bodies (DK-36, Table 2). The $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios of the Payne prospect galena cause the point to fall slightly above the trend defined by Ducktown ores on $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagrams (Fig. 18; to be discussed in a later section).

Results of Sulfur Isotope investigation

Mauger (1972) reported that sulfide minerals from the Calloway and Cherokee ore bodies have a mean $\delta^{34}S$ value of $+ 4^{o}/oo$ and a range of 0 to $10^{o}/oo$. He also reported that sulfur isotopic composition shows a gross variation with stratigraphy and that high pyrite ores have lower $\delta^{34}S$ ratios for pyrite and pyrrhotite than low pyrite ores.

In order to determine if a correlation exists between lead and sulfur isotope compositions in the Ducktown ore bodies, $\delta^{34}S$ was determined for mineral separates of some of the samples analyzed for galena lead isotope composition (Table 4). The range of $\delta^{34}S$ for all minerals from this suite is + 2.7 to + 5.6°/oo. The assemblage appears to be approaching isotopic equilibrium in most samples.

As illustrated by Figure 13, there appears to be a positive correlation between sulfur and lead isotope composition in Ducktown ores. The lightest sulfur (lowest $\delta^{34}S$) is found in samples which have the least radiogenic lead isotopic compositions (group 1 galenas); the heaviest sulfur is found in sample DK-48, which also contains the most radiogenic galena of the suite.

The sample from the Boyd mine which, as noted above, has galena lead isotope composition slightly different from both group I and group II galenas also has anomalous sulfur isotopic characteristics (DK-52, Table 4). Sulfur in pyrite and sphalerite from this sample does not reflect isotopic equilibrium, as is demonstrated by $\delta^{34}S_{py} < \delta^{34}S_{sp}$. Whether this is an effect of metamorphic processes or a primary feature of the ore is unclear.

Sulfur in the sample from the Payne prospect (DK-36) is heavier than that observed from Ducktown in this study, with a range of + 8.1 to + 9.3°/oo for three mineral analyses, but falls within the range reported by Mauger (1972).

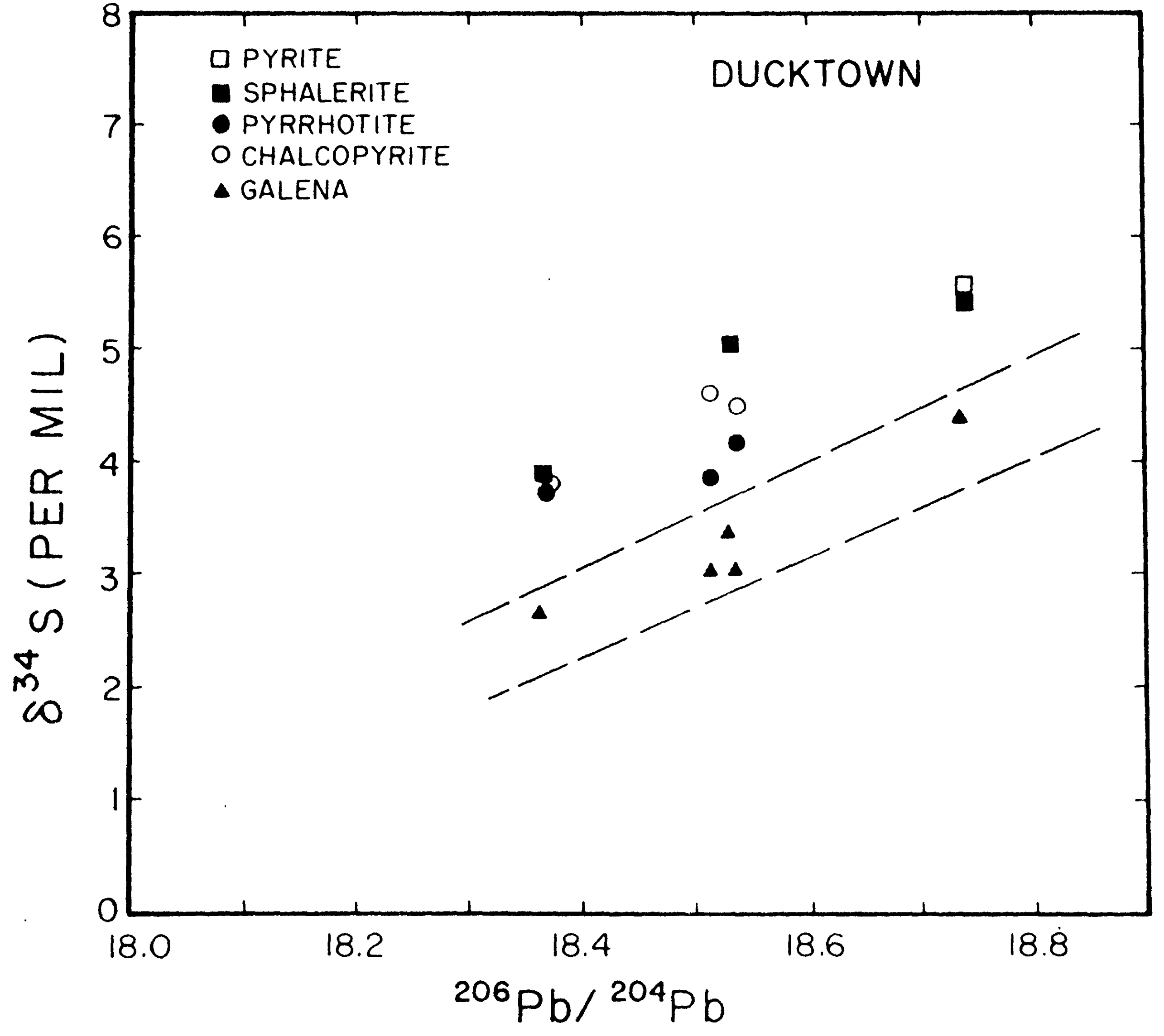
TABLE 4

Sulfur isotope ratios of sulfide minerals from Ducktown ore bodies, for which galena lead isotope ratios are presented in Table 2. Mineral abbreviations: Py = pyrite; po = pyrrhotite; cpy = chalcopyrite; sp = sphalerite; gn = galena.

Sample no.	Group	$\delta^{34}S_{py}$	$\delta^{34}S_{po}$	$\delta^{34}S_{cpy}$	$\delta^{34}S_{sp}$	$\delta^{34}S_{gn}$
Calloway ore body						
DK-1	II		4.15	4.48		3.06
Mary-Polk County ore body						
DK-47	II				5.05	3.39*
DK-48	III	5.58			5.43	4.36
Boyd ore body						
DK-52	I	4.49			4.73	
Cherokee ore body						
DK-74	II		3.87	4.61		3.01
DK-83	I		3.86	3.94	3.94	2.69
Payne prospect, Fannin County, Georgia						
DK-36	--	9.27			9.17	8.10

* This galena contained a small amount of sphalerite, which would tend to increas the $\delta^{34}S$ value.

Figure 13. $\delta^{34}S$ versus $^{206}Pb/^{204}Pb$ diagram of galena and other sulfide minerals from Ducktown ore bodies.


8
7
6
5
4
3
2
1
0
$\delta^{34}S$ (PER MIL)
□ PYRITE
■ SPHALERITE
● PYRRHOTITE
○ CHALCOPYRITE
▲ GALENA
DUCKTOWN
18.0
18.2
18.4
18.6
18.8
$^{206}Pb/^{204}Pb$

The lead and sulfur isotopic compositions of the Payne sample do not fall on the lead-sulfur isotopic trend defined by Ducktown ores.

The seventeen sulfur isotope analyses reported here fall close to the average values of Mauger's (1972) more complete study (Fig. 14). If seawater sulfate was a significant contributor of sulfur to Ducktown ores, then the average $\delta^{34}S$ value of about $4.0^{o}/oo$ might suggest by "Sangster's (1968) rule" a value of about $21^{o}/oo$ for $\delta^{34}S$ of seawater sulfate. The frequency distribution diagram of Ducktown sulfide $\delta^{34}S$ values, however, seems to indicate a slight skewing towards zero. About ten percent of Mauger's samples have $\delta^{34}S$ values of zero to $1.0^{o}/oo$, but no negative values were found.

Figure 14. Frequency distribution diagrams of sulfur isotope ratios of Ducktown sulfide minerals. A. Individual sulfide minerals indicated. B. Patterned blocks are from this paper; unpatterned from Mauger (1972).

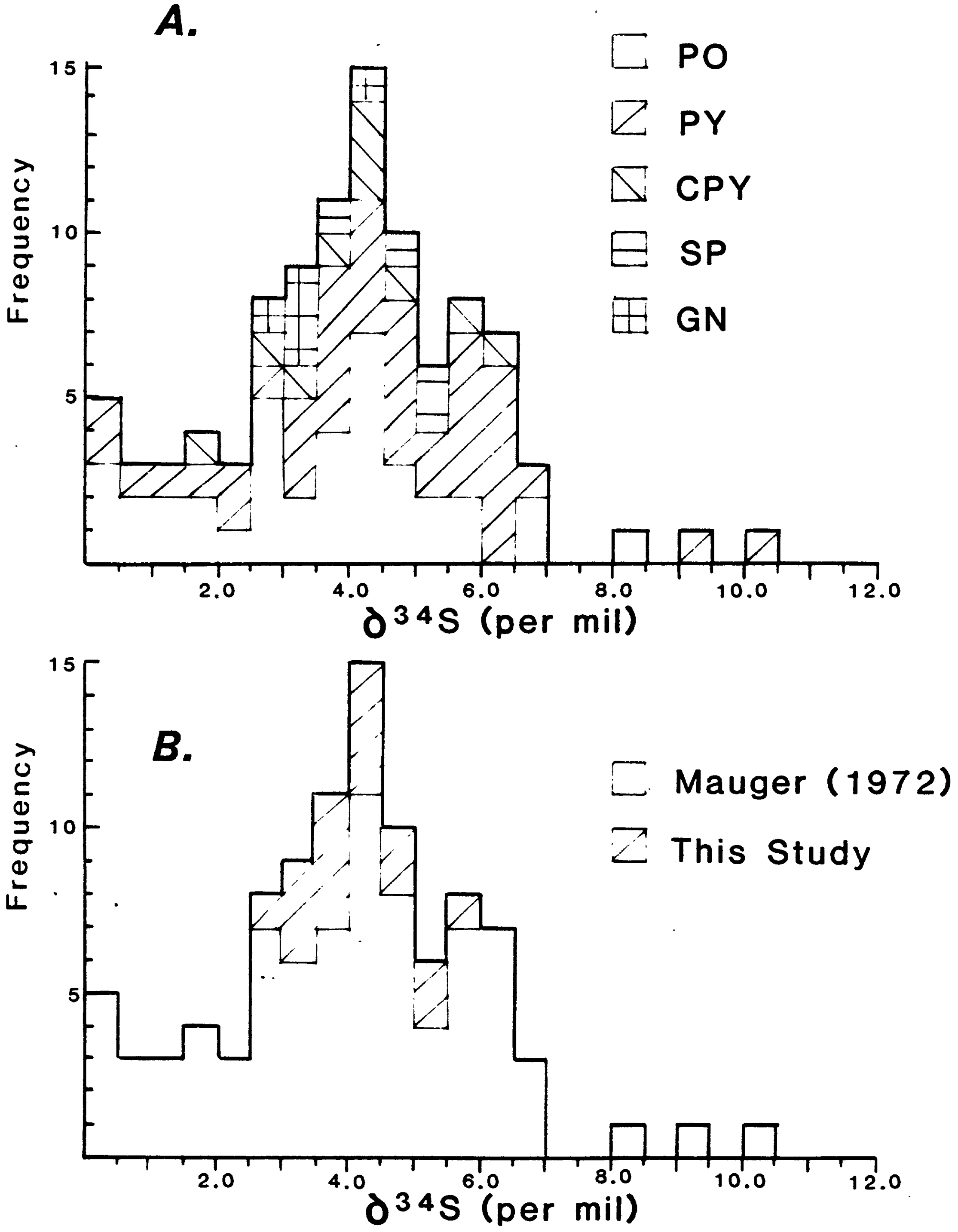
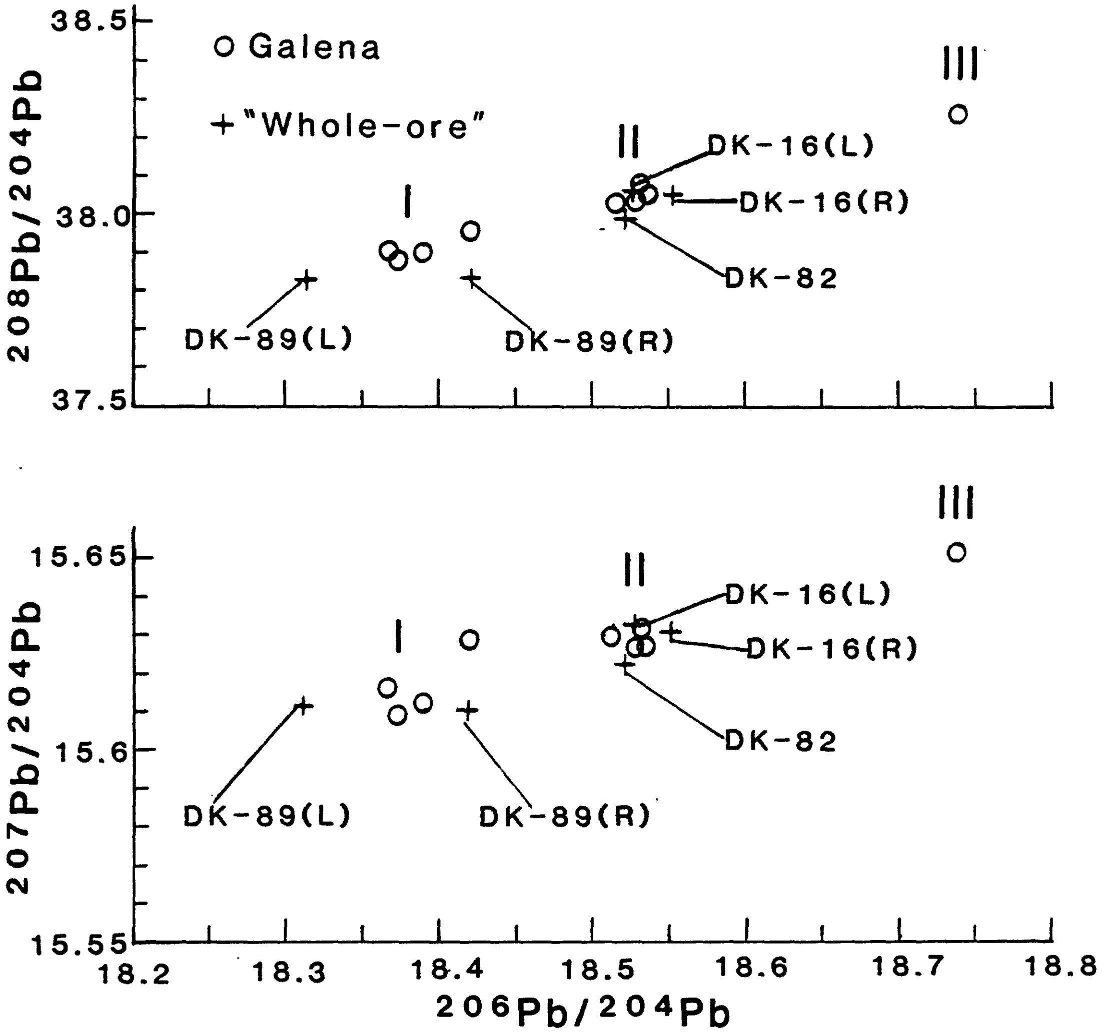

A.
Frequency
15
10
5
PO
PY
CPY
SP
GN
2.0
4.0
6.0
8.0
10.0
12.0
$\delta^{34}S$ (per mil)
B.
Frequency
15
10
5
Mauger (1972)
This Study
2.0
4.0
6.0
8.0
10.0
12.0
$\delta^{34}S$ (per mil)

Figure 15. Lead isotope ratios diagrams showing results residue and whole-ore analyses of massive sulfide ores from Ducktown relative to galena lead isotope ratios. Groups I, II, and III are discussed in text.


○ Galena
+ "Whole-ore"
I
II
III
DK-16(L)
DK-16(R)
DK-82
DK-89(L)
DK-89(R)
208Pb/204Pb
207Pb/204Pb
206Pb/204Pb
38.5
38.0
37.5
15.65
15.6
15.55
18.2
18.3
18.4
18.5
18.6
18.7
18.8

Implications of lead and sulfur isotope systematics of Ducktown ores

A syngenetic or premetamorphic-epigenetic origin of the Ducktown deposits restricts the age of formation to the late Precambrian or Cambrian. Lead isotope compositions of galenas from Ducktown are highly anomalous for the age of formation. The radiogenic character of lead in Ducktown ores indicates that the lead was derived from a source highly enriched in uranium relative to lead.

Volcanogenic massive sulfide deposits, such as the classic "kuroko" ores of Japan or those of the southern Appalachian Piedmont to be discussed in a later section, usually have a high degree of internal uniformity in lead isotope composition. Galenas analyzed from Ducktown, however, have a relatively wide range of $^{206}Pb/^{204}Pb$ ratios (Table 2, Fig. 12), a phenomenon often observed in radiogenic ore lead. The radiogenic character of the ^{206}Pb component coupled with the narrow range of $^{207}Pb/^{204}Pb$ indicates that much older continental crustal rocks were probably not involved in the ore forming process. Rather, a hydrothermal cell operating in the thick pile of clastic sediments (containing detritus of somewhat older age) that form the bulk of the upper Precambrian of the Blue Ridge is indicated as the primary source of lead and, presumably, of at least some of the other metals. In such an environment the radiogenic component of ^{206}Pb is enhanced by the concentration of uranium in the sediments, whereas ^{207}Pb would show little effect because its parent ^{235}U had virtually decayed away by late Precambrian time. The pattern of $^{208}Pb/^{204}Pb$ ratios from Ducktown ores and minerals also supports a sedimentary source of lead. As is shown in Figure 12, the $^{208}Pb/^{204}Pb$ ratios fall to the low Th/U ratio side of an average growth curve, nearly paralleling the pattern predicted for upper continental crustal lead by the plumbotectonics model of Doe and Zartman (1979; see Fig. 7).

Addy and Ypma (1977) suggested that the massive sulfides at Ducktown have been enriched since original deposition by ore mineralization introduced during deformation and metamorphism. The lead isotope data can be used to support a modified synmetamorphic origin for galena, the added lead giving a more radiogenic component to produce the observed isotopic compositions.

Previous sulfur isotope (Mauger, 1972) and mineral zonation (Nesbitt and Kelly, 1980), studies at Ducktown, however, favor a premetamorphic origin for the ores. $^{40}Ar/^{39}Ar$ incremental release patterns of minerals from Ducktown indicate that mineralization could not have occurred after peak regional metamorphism (Dallmeyer, 1975b). Galena, which is relatively rare at Ducktown, and its lead isotope composition, may have been affected by metamorphic remobilization. As previously discussed, galena in quartz veins or in the Cu-Zn-rich ore zones or the massive pyrrhotite bodies cannot be distinguished on the basis of their lead isotope composition. Lead in non-galena bearing massive ore is similar in isotopic composition to the galenas and may have provided lead for the formation of galena during metamorphism.

If real, however, the positive correlation between lead and sulfur isotope compositions is a strong argument against the secondary origin of galena and may also indicate that the lead and sulfur were not derived from purely sedimentary sources.

Lead leached from rocks by circulating hydrothermal fluids should be enriched in radiogenic lead because, as leaching experiments have shown (e.g. Ludwig and Silver, 1977), it is concentrated in incompatible and interstitial sites and is readily leached. Sulfur leached from sediments and that released during metamorphic desulfidization should be enriched in the lighter isotopes (i.e. have lower $\delta^{34}S$).

Processes operating in sedimentary rocks which bring the two elements together should show, if any, a negative correlation between $\delta^{34}S$ and lead isotope composition. That is to say that light sulfur should be associated with radiogenic lead and that as the system evolves the sulfur should become heavier and the lead less radiogenic. Negative correlation patterns have been observed in Mississippi Valley-type deposits (Sverjensky et al., 1980; Sverjensky, 1981), and in the Laisvall sandstone-hosted Pb-Zn deposit (Rickard et al., 1981). How a positive correlation could be produced by metamorphic processes is difficult to explain. If the ores that originally contained the most radiogenic lead also had the heaviest sulfur isotopic composition then galena with the observed pattern could have been produced by local remobilization during metamorphism. Mauger (1972) found a rough correlation of sulfur isotopic composition with stratigraphy in the Calloway lense, but there is no apparent stratigraphic pattern in lead isotopic composition. Even should the metamorphic origin of galena be the case, any scenario envisioned for producing the positive correlation of lead and sulfur isotopic compositions requires that the pattern derived from a primary characteristic of the ores.

To produce a positive correlation between lead and sulfur isotopic composition in a synsedimentary sulfide deposit requires that processes other than pure leaching of trace metals and sulfides from a single reservoir pile contributed to the system. For the reasons discussed above, leaching alone should result in a negative correlation. If the ore-forming hydrothermal cell was active for a long enough period of time to be affected by the relatively rapid change in average $\delta^{34}S$ of seawater sulfate that occurred during late Precambrian time (See Fig. 10), and if seawater sulfate was a significant component of the fluid, a negative correlation should also result. The earlier fluids would contain lighter sulfur which would presumably be associated with the earlier, more radiogenic lead leached from the sedimentary column. This scenario, however, probably requires an unreasonably long life-span (>1m.y.) for individual hydrothermal vents.

A possible explanation for the correlation of lead and sulfur isotopic compositions is a deep-seated source contributing a component of magmatic sulfur, which commonly has $\delta^{34}S \simeq 0$, and a less radiogenic lead to a hydrothermal cell operating within the sedimentary sequence. Figure 16 illustrates a system in which fluids containing metals and sulfur are expelled from depth along a fault/fracture zone which may be related to a rift basin model. Minor amounts of mafic magma could have travelled along the fault zone to form sills represented today by conformable amphibolite bodies. A hydrothermal cell circulating through the clastic sediments of the Great Smoky Group would contribute leached metals, trace sulfides, and seawater sulfate.

The initial "pulse" of mineralization may have contained a significant component of lead and sulfur from the deep-seated source which modified the composition of sediment- and seawater-derived components, resulting in sulfides with less radiogenic lead and lighter sulfur. As the system progressed the component from the unradiogenic, light sulfur source decreased so that the mineralizing system contained increasingly radiogenic lead and heavier sulfur. The time sequence outlined here could have as effectively worked in reverse order.

The presence of amphibolite bodies suggests a mafic composition of the proposed deep-seated source. Low $^{207}Pb/^{204}Pb$ ratios in the least radiogenic group I galenas support this inference. Metals derived from a basaltic source would be expected to be predominantly Cu (+Zn) and to be lead-poor. A large contribution from a mafic source area may explain the lead-poor, Cu-Zn-rich composition of Ducktown ores. It may also help to explain the radiogenic character and wide range of lead isotope ratios, which indicates a large proportion of upper continental lead in the system.

The slight skewing of $\delta^{34}S$ values towards 0 per mil and the absence of negative values may reflect the influence of a magmatic component with $\delta^{34}S$ close to zero per mil. The range of sulfur isotope values may, however, be a reflection on changing conditions of temperature, pH, f_{O_2}, or water/rock ratios in a mineralizing hydrothermal system. Whatever the cause, the apparent correlation between lead and sulfur isotopes indicates a relationship between sulfur and lead isotope variation.

A fault zone such as that envisioned has not been recorded at Ducktown, however, and if it exists it may be impossible to identify today after multiple deformation events and intense metamorphic overprinting. In addition, rift-basin normal faulting in an environment of rapid sedimentation would take on aspects of growth faulting. The lack of marker horizons and uncertain paleogeographic configuration of the "Ocoee basin" makes identification of such faults unlikely in an area where outcrop is limited.

Geological evidence in favor of the proposed fault-conduit system consists of: a) the localization of minor sulfide occurrences in the area in a linear belt along strike with Ducktown, which would presumably be the result of fault control; and b) the restricted occurrence of the only known evidence of igneous activity in the Great Smoky Group - the amphibolite bodies - to this same linear belt; and c) the regional paleo-tectonic environment during latest Precambrian time.

On a plot of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ (Fig. 17) Ducktown galena and "whole ore" lead isotope ratios form a line with a slope corresponding to a Pb-Pb isochron age of 1529 m.y. The large 2σ uncertainty in the isochron age shown on Figure 17 is a reflection of the shallow slope of the isochron (this problem is discussed in Chapter 2). Rocks older than about 1.3 b.y. are unknown in the southern Appalachians. The provenance of rocks now in the Gren-

Figure 16. A model for the origin of the ores at Ducktown. Base metals and sulfur as well as mafic igneous material are shown using a deep fault zone as a conduit. Heat from the rising material sets up a circulating hydrothermal cell in enclosing sediments, which leaches metals - especially lead - and some sulfide and contributes to the growing sulfide deposit. Seawater sulfate may also have been involved.

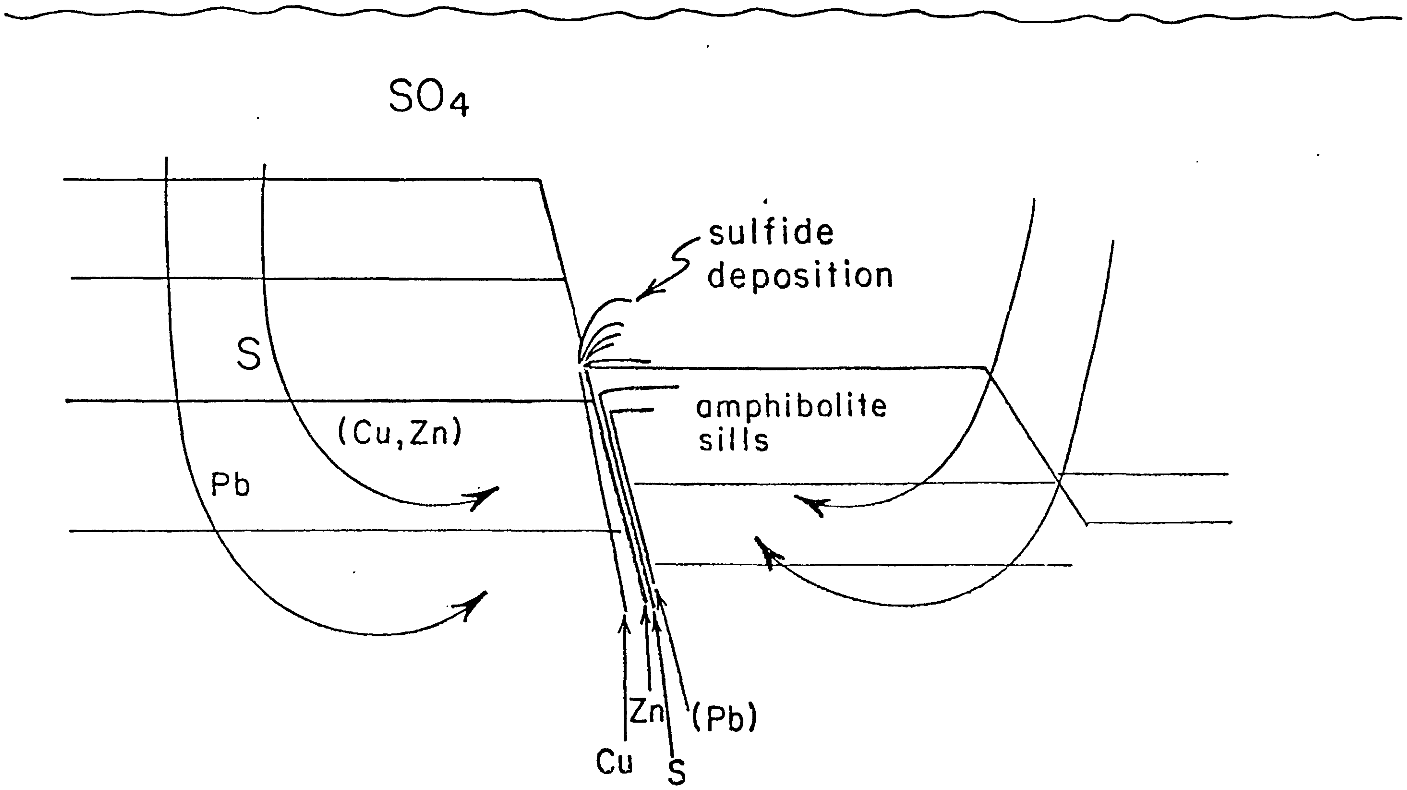
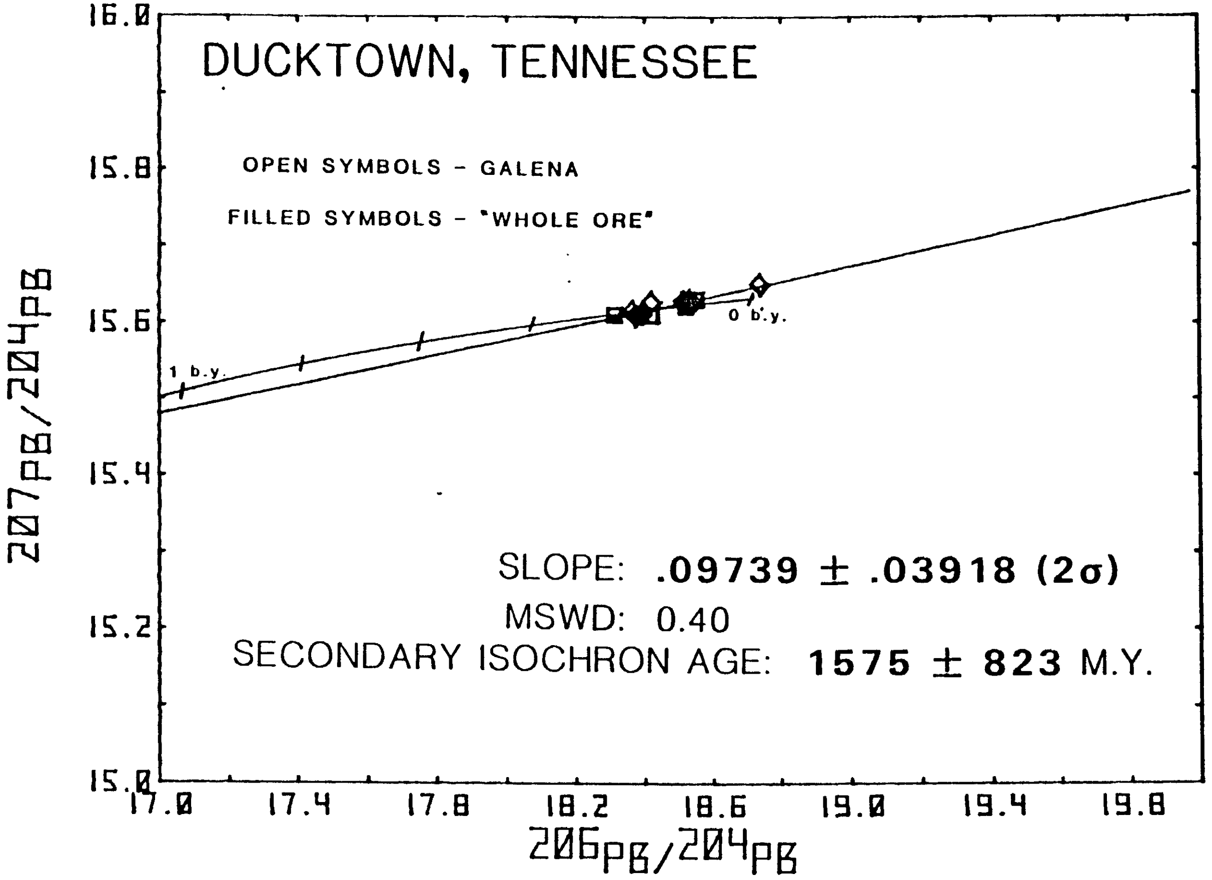

SO4
sulfide
deposition
S
(Cu,Zn)
Pb
amphibolite
sills
Zn
(Pb)
Cu
S

Figure 17. Pb-Pb isochron regressions through Ducktown and Blue Ridge ore lead isotope data.


DUCKTOWN, TENNESSEE
OPEN SYMBOLS – GALENA
FILLED SYMBOLS – "WHOLE ORE"
1 b.y.
0 b.y.
SLOPE: .09739 ± .03918 (2σ)
MSWD: 0.40
SECONDARY ISOCHRON AGE: 1575 ± 823 M.Y.
16.0
15.8
15.6
15.4
15.2
15.0
17.0
17.4
17.8
18.2
18.6
19.0
19.4
19.8
206PB/204PB
207PB/204PB

ville-age province - some of which, at least, are presumably metasediments - is unknown. The line defined by Ducktown lead isotope ratios could be a reflection of an older component in the sediments of the Great Smoky Group or it could be without any age implication and simply represent a mixing line between a relatively unradiogenic source of lead, such as that proposed in the model discussed above, and a highly radiogenic source such as the enclosing clastic sedimentary sequence.

Regression calculations that include the Payne prospect galena yield a line with a slope corresponding to a Pb/Pb isochron age of about 1800 m.y. Both numbers are compatible with the derivation of the bulk of the lead in the ores from the enclosing sedimentary pile. As mentioned earlier in this section, the trend defined by Ducktown lead isotopes on a $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram (Fig. 13) is sub-parallel to the upper continental crustal growth curve of the plumbotectonics model (Doe and Zartman, 1979), which approximates a line at its radiogenic end.

Comparison of Ducktown with similar deposits

Sawkins (1976), described four main types of strata-bound sulfide deposits using as criteria the typical host rocks, metals present, and tectonic environments associated with well known districts worldwide. He classified

Ducktown as a Sullivan-type massive sulfide deposit.

Sullivan-type ores are characterized by: a) occurrence in very thick sequences composed largely of continentally-derived clastic sediments; b) little or no relationship to volcanism; c) well-defined mineral banding; and d) presence of significant amounts of lead (Sawkins, 1976). Ducktown ore lenses fit very well if only the first two criteria are considered. Lead is scarce at Ducktown and mineral banding is not a notable feature of the Ducktown deposits. Perhaps intensity and/or style of deformation at Ducktown destroyed any original banding that may have existed or discouraged its development during deformation and metamorphism.

Sawkins (1976) also cites Mount Isa, Australia, and the Rammelsberg and Meggen deposits of Germany as examples of Sullivan-type ores. Lead isotope compositions of galenas from Sullivan-type (Reynolds and Sinclair, 1971), and Mount Isa (Ostic _et al_., 1967; Richards, 1975), have model ages that approximate the ages of the deposits. Rammelsberg and Meggen galenas are somewhat radiogenic for their Middle Devonian age (Wedepohl _et al_., 1978), but not so much as at Ducktown. Lead from the German deposits does not have the range of isotope ratios found at Ducktown and their $^{208}Pb/^{204}Pb$ values fall to the high Th/U ratio side of Stacey and Kramer's (1975) growth curve, which may indicate a component of lead derived from a granulitic (low-

TABLE 5

Comparison of Ducktown ores with characteristic features of major sediment-hosted stratiform copper and lead-zinc deposits as outlined by Gustafson and Williams (1981). Information on the Mount Isa deposit is included separately for comparison.

Feature	Copper deposits	Lead-zinc deposits	Mount Isa	Ducktown
Major metals	Cu; few have mineable Pb or Zn	Pb, Zn; few have mineable Cu	Cu; Pb-Zn (separate mineralization?)	Cu-Zn; Pb was recovered locally in supergene zone
Iron	low Fe	variable	10.5% as py + cpy; highest in Gustafson & Williams' review	ores average 60% po, 30% py, 4% cpy, 2% mg
Silver	variable	variable; more common than in Cu ores	Cu ores low	trace
Cobalt	important in some	No	in higher grade, siliceous Cu ore	trace
Barite	minor in some	important	No	No
Rhenium & Molybdenum	anomalous concentrations; recovered in some	No	No	MoS_2 in Mary-Polk ore body

TABLE 5 (CONT.)

Feature	Copper deposits	Lead-zinc deposits	Mount Isa	Ducktown
Age	<2000 m.y.	<2000 m.y.	Middle Proterozoic (≈1650 m.y.)	Late Proterozoic (640 - 690 m.y.)
Tectonic setting	Most in fault-controlled, intracratonic sedimentary basins.	Same as Cu	Fault-controlled intracratonic basin	Rift basin
Red bed association	Most in sequences containing red beds	Less common	No; hosted by siliceous dolomite	Flysch-like sediments; red beds not known
Post-early-diagenetic permeability	Favorable (i.e. permeable)	Apparently unfavorable	(Fracture controlled)	Probably favorable
Evidence of evaporites/ aridity	Many	Many	Yes	None known; minor anhydrite gangue
Volcanics	No	No	Abundant thin tuff beds	None known; amphibolite (sills) locally
Organics	Yes	Yes	Yes	Pockets of methane gas in Calloway; abundant graphite

TABLE 5 (CONT.)

Feature	Copper deposits	Lead-zinc deposits	Mount Isa	Ducktown
Ore structure	Disseminated	Massive (some disseminated)	Disseminated	Massive
Zonation	Cu mineral zonation in some	Subtle variations in Pb/Zn ratios	Yes, but may be separate mineralization	Central ore bodies contain less Cu, Zn, more mg, py. See Magee (1968) for individual lenses
Important Cu minerals	bn, cc, cpy	None	cpy	cpy
S isotopes				
1. range	Wide (>30^{o}/oo)	Limited (<30^{o}/oo)	Limited (Pb-Zn ore)	Limited (10^{o}/oo)
2. shape of frequency distribution curve	Flat or strongly skewed	Peaked	Peaked	Slightly skewed
3. average $\delta^{34}S$	Strongly negative to strongly positive	Either about 0^{o}/oo or strongly positive	Strongly positive	4^{o}/oo (somewhat positive
Pb isotopes	Insufficient data	"Conformable" to very radiogenic; may be uniform throughout deposit or have a wide range	"Conformable"	Radiogenic; relatively wide range

TABLE 5 (CONT.)

Feature	Copper deposits	Lead-zinc deposits	Mount Isa	Ducktown
Metamorphism	None to greenschist	Low, except for Sullivan and Broken Hill	Lower greenschist	Amphibolite

er crustal) source (Wedepohl et al., 1978). In all of these deposits galena is a major ore mineral.

Because of the very thick clastic sequences associated with Sullivan-type massive sulfides, Sawkins (1976), envisioned their tectonic environment as continental margin or tension-related intracontinental troughs. Such great thicknesses of sedimentary material represent relatively long periods of subsidence or very rapid subsidence and sedimentation. This scenario is consistent with the rift basin envisioned as the environment of deposition of the Ocoee Supergroup (Odom and Fullagar, 1973; Rankin, 1975), in which Ducktown sulfides were deposited (Gair and Slack, 1980).

Hutchinson (1980), included Ducktown in his "Kieslager" - or "Besshi" - type exhalative volcanogenic group of massive sulfide deposits. Kieslager-type ores are characterized by Cu-Zn (Au) mineralization in unstable subsiding basins with thick sedimentary sequences of greywackes and volcanoclastic rocks and tholeiitic volcanic and plutonic rocks. Hutchinson (1980), envisions the plate tectonics setting of Kieslager-type deposits as fore-arc trough or trench environments above the subduction zone at converging plate boundaries.

Metagreywacke certainly is a major feature of the stratigraphic sequence at Ducktown, and the presence of amphibolite may indicate that basaltic rocks played a role in the formation of the ores, but the small volume and restricted occurrence of mafic material and of igneous activity in general in the Ducktown area and the absence of igneous activity in the western Blue Ridge does not resemble the situation observed in the Besshi deposits, Japan (Kanehira and Tatsumi, 1970), or in the deposits of the Amphibolite Belt, Namibia (Goldberg, 1976), which are also cited by Hutchinson (1980), as examples of Kieslager-type ores. The plate tectonics setting of ore deposits is an important element of Hutchinson's (1980), classification system. As has been mentioned numerous times, the late Precambrian sediments of the Blue Ridge and, presumably, the stratabound deposits they enclose are thought to be related to the rifting associated with the opening of the Iapetus Ocean. This hypothesis is not consistent with the convergent boundary envisioned for the Kieslager-type deposit environment. Furthermore, Hutchinson's inference that Ducktown is a time-transgressive, tectonic correlative of the cupriferous pyrite deposits of the Eastern Townships, Quebec (Cambro-Ordovician), and the Ming-Rambler deposits, Newfoundland (Ordovician), is unsupported. Pyritic Cu-Zn deposits in the Eastern Townships occur in a felsic to magic volcanic suite containing abundant soda-granite (Sauve _et_ _al_., 1972), which were thrust westward during the Taconic orogeny. The sequence is generally thought to represent arc volcanism associated with convergent plate margins (Osberg, 1978; Schenk, 1978). The Ming-Rambler deposits occur within a tholeiitic to calc-alkaline transitional zone of an island arc sequence of Newfoundland's Central Volcanic Belt (Ruitenberg, 1976; Kean, et al., 1981). Neither of these tectonic environments or stratigraphic sequences is comparable to that of Ocoee Supergroup sediments.

The tectonic setting and host rock lithologies of Ducktown mineralization do not compare favorably with those of well known volcanogenic exhalative deposits. Neither, however, do the overall features of Ducktown ores match those of sediment-hosted stratiform deposits. In Table 5, Ducktown is compared with characteristic features of major stratiform copper and lead-zinc (not including Mississippi Valley-type) deposits, described in a recent review by Gustafson and Williams (1981). Information from the Mount Isa, Queensland, deposit is given separately because, like Ducktown, many of its features diverge significantly from characteristics observed in other sediment-hosted stratiform deposits (Gustafson and Williams, 1981).

There are striking differences between Ducktown and the sediment-hosted deposits. Ducktown ore bodies are primarily iron sulfide deposits. In contrast, Mt. Isa, with 10.5% iron as pyrite and chalcopyrite, has the highest iron content of the deposits considered by Gustafson and Williams (1981). Those authors state that few, if any, sediment-hosted stratiform deposits are associated with active continental margins. Ducktown, however, is thought to have formed in a rift basin near a divergent margin. An association with red bed sequences is an ubiquitous feature of sediment-hosted copper deposits. Although the primary oxidation state of Great Smoky Group sediments can not be stated with certainty, flysch-like sediments are not usually associated with red beds. Similarly, evaporite deposits or other evidence of an arid climate are commonly found in proximity to sediment-hosted stratiform ores. No such evidence is known in the Ocoee Supergroup, although a minor amount of anhydrite occurs as gangue at Ducktown. Gustafson and Williams (1981), point out that all of the copper deposits are disseminated ores and that, except for Mt. Isa, they are not generally of economic importance unless they contain bornite and chalcocite in addition to chalcopyrite. Evaluation of the effects that deformation and metamorphism may have had upon the ore structure and sulfide mineralogy of Ducktown ores is difficult. Chalcopyrite is usually the predominant copper mineral, however, is unaltered, iron-rich sulfide deposits as it is at Ducktown. Sulfur isotope patterns of Ducktown sulfides also differ substantially from those of sediment-hosted copper deposits. No large scale isotopic homogenization occurred at Ducktown, so the difference is probably a significant primary feature.

The conclusion drawn from this comparative exercise is that Ducktown does not belong to the class of sediment-hosted stratiform deposits described by Gustafson and Williams (1981).

Those considerations, along with lead and sulfur isotope evidence, support a deep fault-controlled hydrothermal cell model in that it is one way to generate a deposit with characteristics of volcanogenic exhalative ores in an overwhelmingly sedimentary environment.

6. RECONNAISSANCE SURVEY OF LEAD AND SULFUR ISOTOPES IN OTHER BLUE RIDGE SULFIDE DEPOSITS

Lead and Sulfur in Stratabound Massive Sulfides

The results of lead isotope analyses of galenas from the Fontana district, North Carolina, and the Great Gossan Lead, Virginia, are shown in table 6 and figure 18. The Fontana district contains generally conformable lenses of pyrite with minor copper in the Great Smoky Group of western North Carolina (Espenshade, 1963; Gair and Slack, 1979). The Great Gossan Lead of southwestern Virginia lies on the eastern flank of the Grenville-age core of the Blue Ridge in the upper Precambrian(?) Ashe Formation (Stose and Stose, 1957; Rankin, 1970).

The analyses of galena from each of these deposits do not reveal whether their lead isotope patterns are similar to that found in Ducktown. Like Ducktown, however, they are highly radiogenic for their presumed late Precambrian age of formation.

The Gossan Lead galenas have a ^{206}Pb/^{204}Pb ratio similar to Ducktown group II galenas (Fig. 18), but have slightly lower ^{207}Pb/^{204}Pb. The latter may be partly due to a contribution of lead by the relatively abundant amphibolite associated with the district (Stose and Stose, 1957; Henry *et al*., 1979) which Rankin (1970) and Rankin *et al*. (1973) recognized as mafic volcanic rocks.

Galena seems to be more common in the deposits of the Gossan Lead district than at Ducktown. Henry *et al*. (1979) report that it is ubiquitous in trace amounts, usually as anhedral inclusions in pyrrhotite, chalcopyrite, and sphalerite, and locally exceeds 3 percent, usually in Zn-rich zones. Pyrite is rare in Gossan Lead lenses; pyrrhotite is the main iron sulfide, generally constituting over 90 percent of total sulfide in ore zones. The same authors present abundant textural evidence for the metamorphism and deformation of the ore bodies.

As at Ducktown, a metamorphic origin of at least some of the galena in the Gossan Lead is a posssibility, espeecially for the trace amounts forming inclusions in other sulfide minerals. Evidence for recrystallization is found in the growth of galena in pressure shadows reported by Henry *et al*. (1979)

A single $\delta^{34}S$ determination on pyrrhotite from the Gossan Lead has a value of +8.08 $^{o}/oo$, somewhat higher than found at Ducktown in this limited study, but within the range reported by Mauger (1972).

Sulfide bodies in the Fontana district of western North Carolina lie conformably in the metasediments of the Great Smoky Group. The lenses are dominated by pyrrhotite

TABLE 6

Lead and sulfur isotope ratios from some other Blue Ridge sulfide deposits. Abbreviations as in Table 4. "py,L" and "py,R" after sample number indicate that leachate and residue of an HCl leach of pyrite were analyzed.

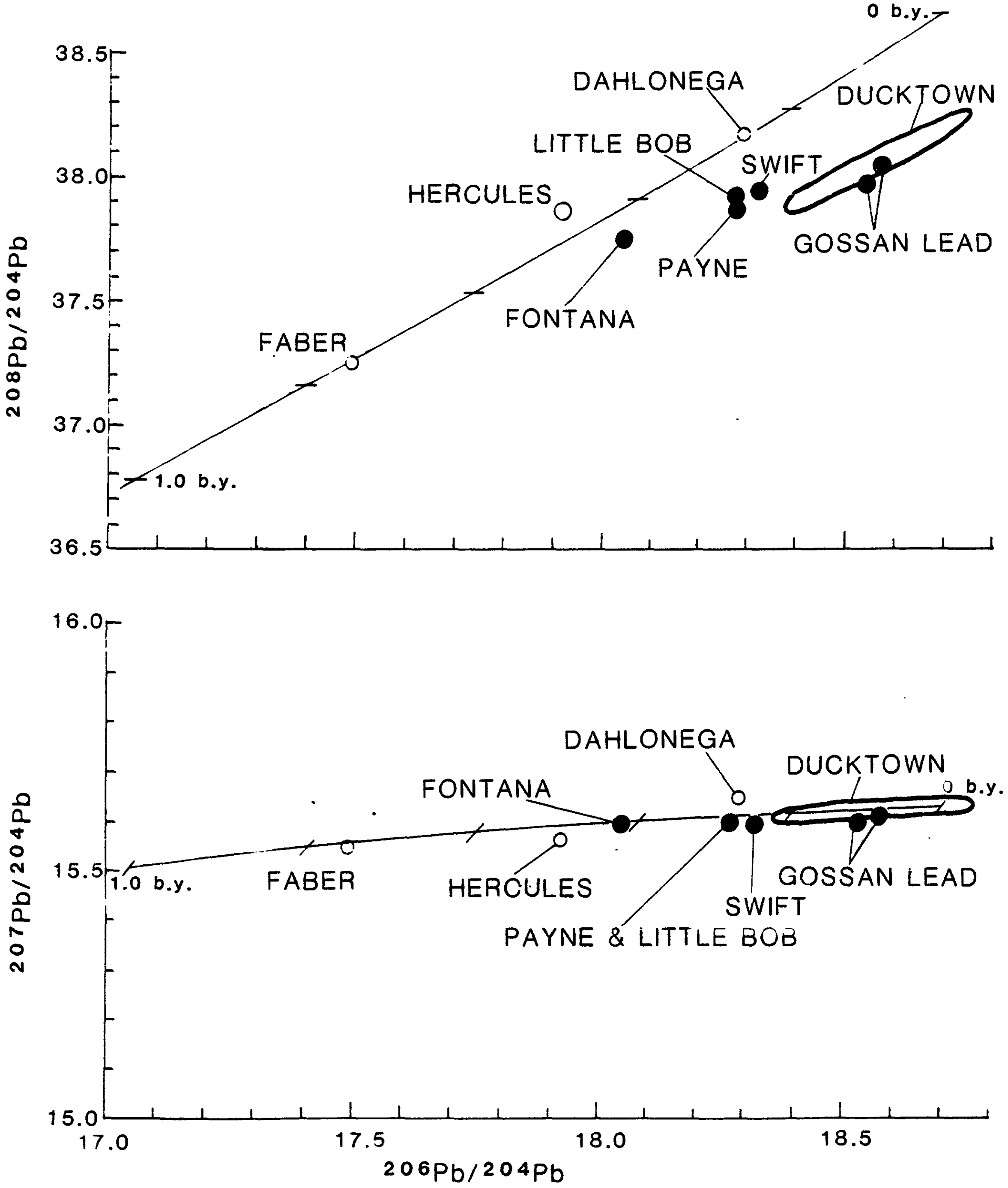
Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	$\delta^{34}S_{py}$	$\delta^{34}S_{po}$	$\delta^{34}S_{sp}$	$\delta^{34}S_{gn}$
<u>Stratabound sulfide deposits</u>							
Adams mine, Fontana district, North Carolina							
BS-10101	18.047	15.591	37.754		6.87		4.81
Gossan Lead, Virginia							
715	18.540	15.597	37.971		8.08		
JRC-474	18.583	15.602	38.059				
JRC-846	18.579	15.607	38.065				
Swift mine, Paulding County, Georgia							
BS-30101				3.65			
(py,L)	19.161	15.672	38.955				
(py,R)	18.321	15.589	37.947				
Little Bob mine, Paulding County, Georgia							
BS-30201	18.274	15.594	37.919	7.42		6.75	

TABLE 6 (CONT.)

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	$\delta^{34}S_{py}$	$\delta^{34}S_{po}$	$\delta^{34}S_{sp}$	$\delta^{34}S_{gn}$
Ore Knob, North Carolina							
BS-10301				5.84	6.46		
BS-10302				8.65	8.95		
Culhowee mine, North Carolina							
BS-10201				10.97			
<u>Vein deposits</u>							
Dahlonega district, Georgia							
*Battle Branch	18.293	15.646	38.176				
Faber mine, Virginia							
#--	17.496	15.546	37.240				
Hercules mine, North Carolina (In Inner Piedmont, near Brevard Zone)							
#--	17.924	15.564	37.860				

* Doe and Zartman, 1979; # Kish and Feiss, 1982

Figure 18. Lead isotope ratio diagrams showing values of galenas from Blue Ridge sulfide deposits. The point representing the Swift deposit, Georgia, is not a galena, but a pyrite residue analysis (Table 6). The Hercules deposit is actually in the Inner Piedmont belt close to the Brevard Zone. Stratabound sulfide deposits ● ; Vein deposits ○ . The two points shown for the Gossan Lead district represent three analyses (Table 6).


0 b.y.
38.5
38.0
37.5
37.0
36.5
208Pb/204Pb
DAHLONEGA
DUCKTOWN
LITTLE BOB
SWIFT
HERCULES
GOSSAN LEAD
PAYNE
FONTANA
FABER
1.0 b.y.
16.0
15.5
15.0
207Pb/204Pb
DAHLONEGA
DUCKTOWN
0 b.y.
FONTANA
FABER
HERCULES
GOSSAN LEAD
SWIFT
PAYNE & LITTLE BOB
1.0 b.y.
17.0
17.5
18.0
18.5
206Pb/204Pb

and/or pyrite with minor amounts of Cu (±Zn) (Espenshade, 1963). A galena from the Adams mine has lead isotope ratios that are much less radiogenic than those from Ducktown and the Gossan Lead (Fig. 18). Its ^{207}Pb/^{204}Pb and ^{206}Pb/^{204}Pb ratios appear to lie conformably on the Stacey and Kramers (1975) average growth curve and have a model age of 417 m.y. (using Stacey and Kramers' parameters), which is in relatively good agreement with the age of Blue Ridge regional metamorphism. Intrusive rocks of approximately the same age are known in the eastern Blue Ridge, but not in the western section in which the Fontana district is located. On the basis of the data presented here, determination of whether the model age of the Fontana galena has some real age significance is not possible. Lead isotope ratios of K-feldspar in two eastern Blue Ridge Paleozoic intrusives (Kish and Feiss, 1982), however, are much more radiogenic than the Fontana falena (Fig. 21).

Sulfur isotope analyses from the same sample (Table 6) also fall within the range of those found at Ducktown (Mauger, 1972; this study, Table 4).

The Swift and Little Bob deposits are stratabound, massive pyritic Cu-Zn ores in the Wedowee Group of west-central Georgia (Cook, 1970). Geologic relationships of the southernmost Appalachians are to be discussed in a later section, and the locations of these deposits are shown in figure 37.

The Wedowee Group has been correlated with the upper Precambrian(?) Ashe-Alligator Back sequence of the eastern Blue Ridge (Hurst, 1973). Lead isotope ratios of a Little Bob galena and the HCl-insoluble fraction of pyrite from Swift (Table 6) seem to fit the pattern of Blue Ridge ratios (Fig. 18). The Little Bob galena lead isotope composition is indistinguishable from that of the Payne prospect in the western Blue Ridge. Sulfur isotope values of minerals from Swift and Little Bob (Table 6) fall within the range found at Ducktown.

Lead in Blue Ridge Vein Deposits

Table 6 and Figure 18 also show lead isotope ratios obtained from galenas from vein and poorly-known sulfide occurrences in and near the Blue Ridge province. Doe and Zartman (1979) reported an analysis from the Battle Branch vein in the Dahlonega gold mining district, Georgia (described by Pardee and Park, 1948), that has slightly higher $^{207}Pb/^{204}Pb$ than Blue Ridge massive sulfide deposits, and significantly higher $^{208}Pb/^{204}Pb$. Dahlonega veins occur in the eastern Blue Ridge where Paleozoic plutonism is relatively common, and the vien mineralization may be related to this later event, or to regional metamorphism.

Kish and Feiss (1982) reported lead isotopic analyses of galenas from the poorly-known Hercules mine, North Carolina (actually in the Inner Piedmont), and Faber mine, Virginia. Both deposits contain lead that is substantially less radiogenic than any other Blue Ridge galena. The Faber mine galena has uranogenic lead ratios similar to those found in a Grenville-age pegmatitic K-feldspar (Fig. 18). Faber is reportedly found in quartz veins in late Precambrian metasediments of the eastern Blue Ridge (Kish and Feiss, 1982). Hercules is in the Inner Piedmont province close to the Brevard Zone and the Grandfather Mountain Window (Bryant and Reed, 1970). Both veins may have derived at least some of their lead from underlying Grenville-age basement rocks.

7. WHOLE-ROCK U-TH-PB SYSTEMATICS IN MOUNT ROGERS FORMATION RHYOLITES

The Mount Roger Formation on the northwest limb of the Blue Ridge anticlinorium consists, for the most part, of a subaerially erupted bimodal suite of basalt and rhyolite in which basalt predominates (Rankin, 1975). It has been interpreted as the extrusive equivalent of late Precambrian plutonic rocks of the eastern Blue Ridge, which together make up the Crossnore plutonic-volcanic group (CPVG). Igneous activity which formed the CPVG is presumably related to late Precambrian rifting and the opening of the Iapetus ocean (Odom and Fullagar, 1973; Rankin, 1975).

U-Pb zircon analyses of felsic volcanic rocks of the Mount Rogers Formation give an apparent age of about 820 m.y. (Rankin *et al.*, 1969), but this seems to have been affected by inherited zircons and the CPVG appears to have formed approximately 690 m.y. ago (Odom and Fullagar, 1971, 1982). In the syngenetic rift basin model massive sulfide bodies of the Blue Ridge would have formed during this same interval.

Analyses of U-Th-Pb whole-rock and lead in K-feldspar from the Whitetop Mountain, Virginia, center of rhyolitic volcanism in the Mount Rogers Formation were made to test whether isotope systematics of the volcanic suite are similar to those in the Ducktown ore bodies and other Blue Ridge massive sulfides.

Results

Table 7 shows the results of U-Th-Pb whole-rock and lead in K-feldspar isotope analyses from rhyolites of the Mount Rogers Formation from Whitetop Mountain, Virginia. Lead isotope compositions define a wide range of ^{206}Pb-, ^{207}Pb-, and ^{208}Pb/^{204}Pb ratios: 17.64 - 19.57, 15.57 - 15.69, and 37.84 - 39.62, respectively. As is shown in Figure 19 uranogenic lead ratios form a line which has a slope corresponding to a Pb-Pb isochron age of about 640 m.y., which agrees well with the age range of CPVG rocks reported by Odom and Fullagar (1982).

The least radiogenic lead found is in K-feldspar from sample MR-106 (Table 7). Its ^{207}Pb/^{204}Pb and ^{206}Pb/^{204}Pb ratios are similar to those found in a K-feldspar from a Grenville-age granitic pegmatite (GG-101, Table 7), but the ^{208}Pb/^{204}Pb ratios of the two are dissimilar. The Mount Rogers K-feldspar has a more radiogenic ^{208}Pb component. The similarity of the uranogenic lead ratios of the Mount Rogers and basement K-feldspar suggests that these ratios in sample MR-106 may be representative of the ratios at the time of eruption of the Mount Rogers rhyo-

TABLE 7

Lead isotope ratios and U, Th and Pb concentrations of whole-rock (WR) and K-feldspar (KF) from Mount Rogers Formation rhyolites and of a Grenville-age granitic pegmatite. Also included are results from a mafic dike which crosscuts basement gneiss and may be of Mount Rogers age, and from two Paleozoics intrusives in the Blue Ridge province reported by Kish and Feiss (1982).

Sample no.	Type	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Pb	U	Th	$\frac{^{238}U}{^{204}Pb}$	$\frac{^{232}Th}{^{238}U}$	$\frac{^{232}Th}{^{204}Pb}$
					(-----	ppm	-----)			
Mount Rogers Formation										
MR-101	WR	17.929	15.596	38.112	100	4.40	17.8	2.76	4.18	11.5
MR-102	KF KF-L	18.353 18.821	15.623 15.643	38.323 38.744						
MR-102	WR	19.570	15.695	39.623	30.1	8.21	33.7	17.9	4.24	75.8
MR-103	KF	18.511	15.624	38.507						
MR-104	WR	19.380	15.685	40.606	13.1	3.73	19.4	18.9	5.37	101.4
MR-106	KF	17.640	15.576	37.841						
MR-106	WR	18.217	15.612	38.982	8.39	.847	7.41	6.44	9.04	58.2
Grenville-age granitic pegmatite										
GG-101	KF	17.563	15.561	36.855						

TABLE 7 (CONT.)

Sample no.	Type	$\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}}$	$\frac{^{207}\mathrm{Pb}}{^{204}\mathrm{Pb}}$	$\frac{^{208}\mathrm{Pb}}{^{204}\mathrm{Pb}}$	Pb	U	Th	$\frac{^{238}\mathrm{U}}{^{204}\mathrm{Pb}}$	$\frac{^{232}\mathrm{Th}}{^{238}\mathrm{U}}$	$\frac{^{232}\mathrm{Th}}{^{204}\mathrm{Pb}}$
					(-----	ppm	-----)			
<u>Greenstone dike (of Mount Rogers age?)</u>										
GG-103	WR	18.514	15.626	38.406	--	.522	2.50	--	4.82	--
<u>Paleozoic intrusions</u>										
*Whiteside	KF	18.418	15.632	38.278						
*Spruce Pine pegmatite	KF	18.403	15.638	38.242						

* Data from Kish and Feiss (1982)

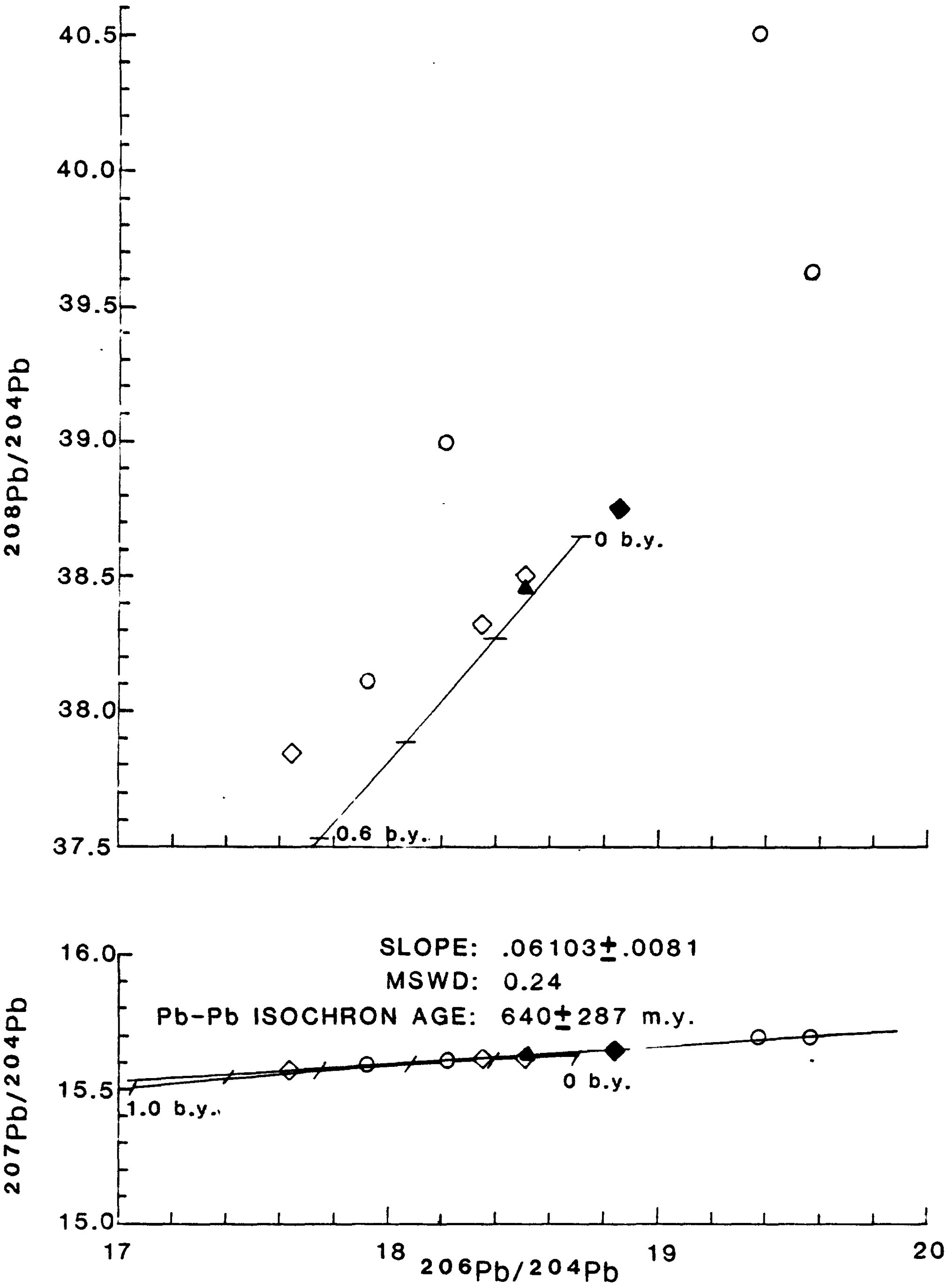
lites. The high $^{208}Pb/^{204}Pb$ ratio may reflect derivation from a relatively thorium-rich source.

Odom and Fullagar (1982) interpret the inherited zircon fraction in CPVG rocks to be derived from Grenville-age rocks. That lead in Mount Rogers Formation volcanics is at least partly derived from the same source seems reasonable. The lead isotopic character of the volcanics at the time of their formation could have been similar to that of an underlying low U/Pb (cratonized ?), Grenville-age basement. Whole-rock analysis of MR-106 shows that the rock is enriched in thorium relative to lead and supports the derivation of "excess" ^{208}Pb from a thorium-rich source, which may well have been granulitic basement rocks.

The lead isotope ratios of basement rocks in the southern Appalachian Blue Ridge is represented by GG-101, the only high-precision analysis currently available. There is probably a range of lead isotope ratios in these rocks of which, it is hoped, the analysis reported here is representative.

The regression on Figure 19 includes an analysis of a mafic dike (GG-103, Table 7) which crosscuts Grenville-age gneisses in the same outcrop as GG-101. Inclusion of the greenstone data in the Mount Rogers regression has a negligeable effect on the results, and supports the interpretation of the dike as part of the feeder system of Mount Rogers volcanics.

Figure 19. Lead isotope ratio diagrams showing results from Mount Rogers Formation rhyolites. Analysis of a greenstone dike which cuts Grenville-age gneisses and may be of Mount Rogers' age is also included. ○ whole-rock; ◇ K-feldspar residue; ◆ K-feldspar leach; ▲ greenstone dike whole-rock.


208Pb/204Pb
40.5
40.0
39.5
39.0
38.5
38.0
37.5
0 b.y.
0.6 b.y.
207Pb/204Pb
16.0
15.5
15.0
SLOPE: .06103±.0081
MSWD: 0.24
Pb-Pb ISOCHRON AGE: 640±287 m.y.
0 b.y.
1.0 b.y.
17
18
19
20
206Pb/204Pb

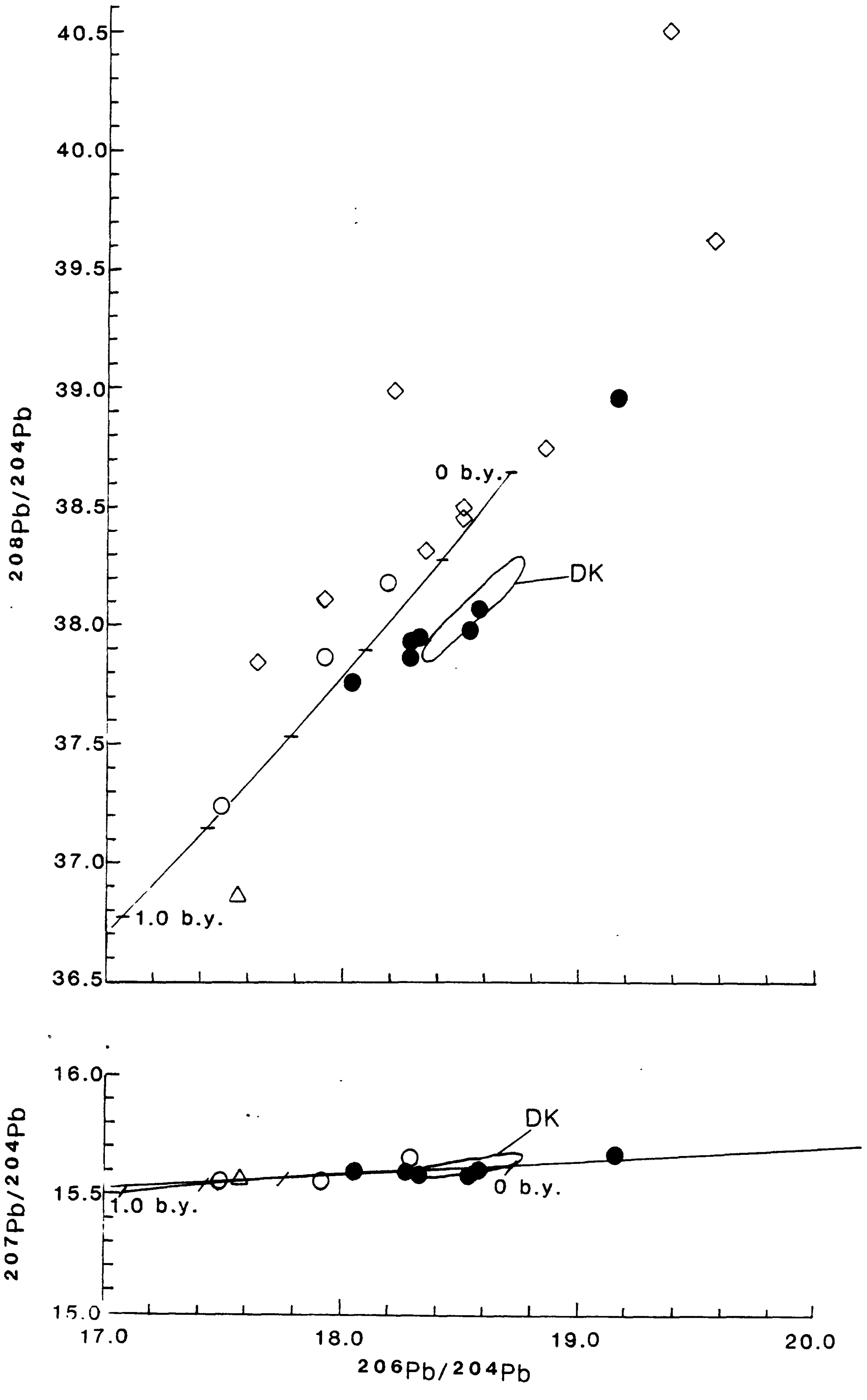
Comparison of Mount Rogers with Blue Ridge Massive Sulfide Isotope Systematics

Figure 20 shows the Mount Rogers isotope data together with those from Blue Ridge sulfide deposits. On a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram the trends formed by the data sets are quite distinct, but intersect at about the range of Ducktown group II galenas. If, as argued in the preceeding section, lead in MR-106 is representative of the original composition of the felsic component of Mount Rogers volcanism, then lead in the Ducktown deposits could not have derived from an isotopically similar source. Projection of the Ducktown data back to the $^{206}Pb/^{204}Pb$ ratio of MR-106 indicates a corresponding, substantially lower $^{207}Pb/^{204}Pb$ ratio for Ducktown source material. This difference precludes association of the ore with the rhyolitic phase of Mount Rogers volcanism. On a $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram the isotopic patterns of the two data sets are completely different, effectively eliminating significant contribution of lead to Ducktown from a Mount Rogers-like source.

Doe _et_ _al_. (1982) have recently reported that basalts and rhyolites from the bimodal Yellowstone Plateau volcanic field are isotopically dissimilar, indicating different sources for the two rock types with little cross-contamination. The fit of the mafic "feeder" dike (GG-103, Table

Figure 20. Mount Rogers lead isotope data together with lead isotope ratios of Blue Ridge sulfide deposits. For clarity, Mount Rogers data is represented only by the linear regression through the points on the uranogenic lead diagram. The analysis of a Grenville-age K-feldspar (△) is also included for comparison. ◇ Mount Rogers Formation analyses (^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb diagram only); ● stratabound sulfide deposits; ○ vein deposits. Sulfide data points as identified in figure 18.

123


208Pb/204Pb
40.5
40.0
39.5
39.0
38.5
38.0
37.5
37.0
36.5
0 b.y.
1.0 b.y.
DK
207Pb/204Pb
16.0
15.5
15.0
DK
0 b.y.
1.0 b.y.
17.0
18.0
19.0
20.0
206Pb/204Pb

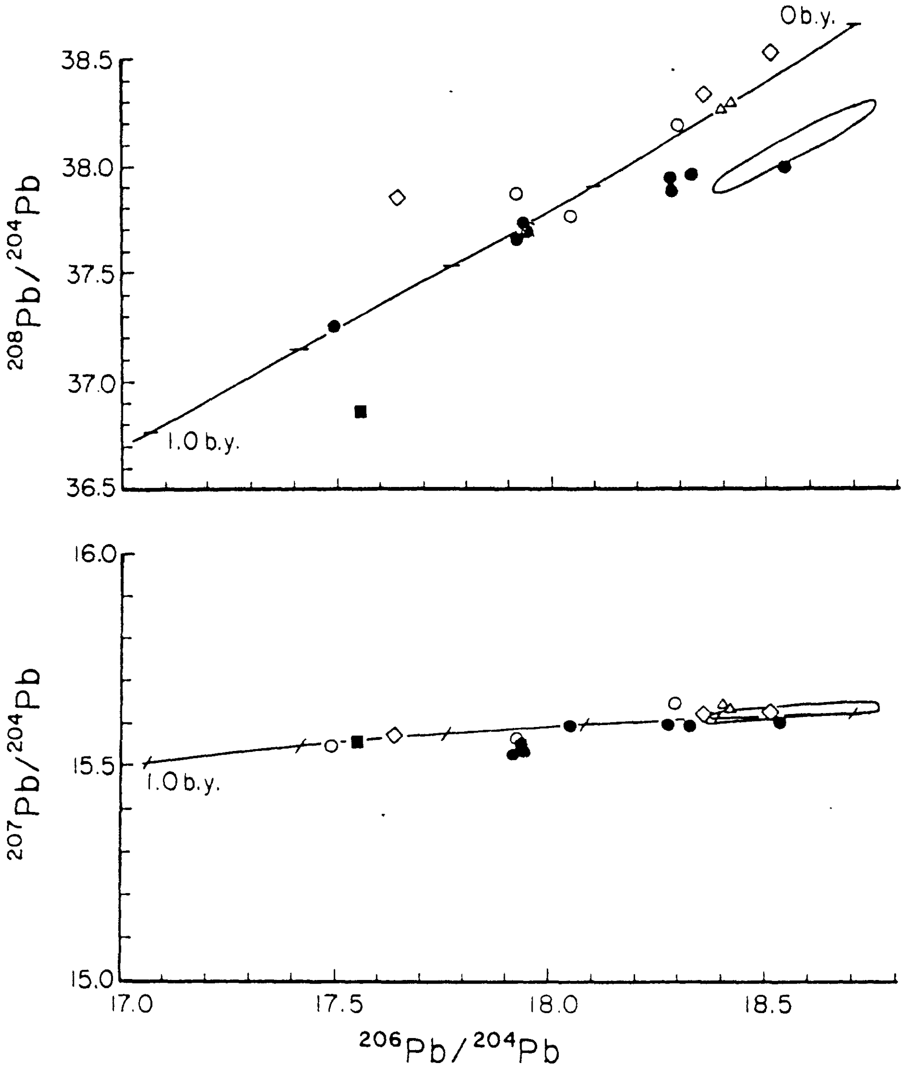
7) to the rhyolite regression suggests that this may not be the case for Mount Rogers Formation basalts and rhyolites.

Kish and Feiss (1982) reported K-feldspar lead isotopic analyses from two Blue Ridge Paleozoic plutons (Table 7). Figure 21 shows that these also have ^{207}Pb/^{204}Pb and ^{206}Pb/^{204}Pb ratios similar to those in Ducktown ores, but also have distinct values of ^{208}Pb/^{204}Pb. Isotopically similar intrusions could not have contributed substantially to lead in Ducktown or other Blue Ridge massive sulfide deposits. If the lead isotopic characteristics of the Mount Rogers rhyolites and of the two Paleozoic plutons are representative, the two major periods of felsic igneous activity recognized in the Blue Ridge could not have contributed to lead in massive sulfide bodies of the region. This is consistent with a sedimentary source for the major portion of lead in the bodies.

Galena from the Faber mine has uranogenic lead isotope ratios (Kish and Feiss, 1982) similar to those found in Grenville-age K-feldspar (Fig. 21), suggesting a basement source of lead in this deposit. As in the least radiogenic Mount Rogers K-feldspar, galena from the Faber mine has a high ^{208}Pb/^{204}Pb ratio compared to the basement K-feldspar, again indicating thorium enrichment in the source rock.

Lead isotope ratios of galenas from the Hercules

Figure 21. Comparison of Blue Ridge galena lead isotope ratios with those of K-feldspar in igneous rocks. Grenville-age granitic pegmatite ■ ; Mount Rogers Formation rhyolites ◇ ; Paleozoic plutons △ (from Kish and Feiss, 1982). Sulfide deposit data (● , ○) as in figure 18. Also included in this figure are galena data from Stone Hill, Alabama, and whole-ore dat from Pyriton, Alabama, which will be discussed in Chapter 11.


0 b.y.
38.5
38.0
37.5
37.0
36.5
1.0 b.y.
$^{208}Pb/^{204}Pb$
16.0
15.5
15.0
1.0 b.y.
$^{207}Pb/^{204}Pb$
17.0
17.5
18.0
18.5
$^{206}Pb/^{204}Pb$

deposit, North Carolina (Kish and Feiss, 1982), the Battle Branch vein, Georgia (Doe and Zartman, 1979), and the Adams mine in the Fontana massive sulfide district lie in the range between "Grenville-derived" lead and lead in Ducktown, the Gossan Lead, and the Paleozoic plutons. Lead in these deposits may be a mixture of lead from two or more of the various possible sources. Figure 21 also illustrates that Blue Ridge igneous K-feldspars and vein deposit galenas (except for Faber) are enriched in ^{208}Pb relative to galena in stratabound deposits, an indication of the relative thorium-enrichment of the sources of igneous and vein deposit lead.

8. SULFIDE DEPOSITS IN THE PIEDMONT

The Piedmont geologic province occupies the area southeast of the Blue Ridge and continues under the Coastal Plain, which is probably underlain by Piedmont-type rocks throughout its subaerial extent. The Piedmont is generally subdivided into northeast-southwest trending belts (Fig. 22) which display more or less distinct variations in lithology, structure, and metamorphic grades. Significant stratabound sulfide deposits are confined largely to the central Virginia plutonic-volcanic belt (CVPV) and to the Carolina volcanic slate belt. The CVPV also contains the quartz vein deposits of the Virginia gold-pyrite belt; the latter is host to Virgilina (Cu) district vein mineralization. Most of the massive sulfide deposits are polymetallic (Zn-Pb-Cu ± Ag,Au) with pyrite as the dominant iron sulfide.

Deposits in the Haile-Brewer area of the South Carolina slate belt are associated with massive pyritic bodies, but are important for their disseminated gold content. The base metal content of these deposits is typically insignificant.

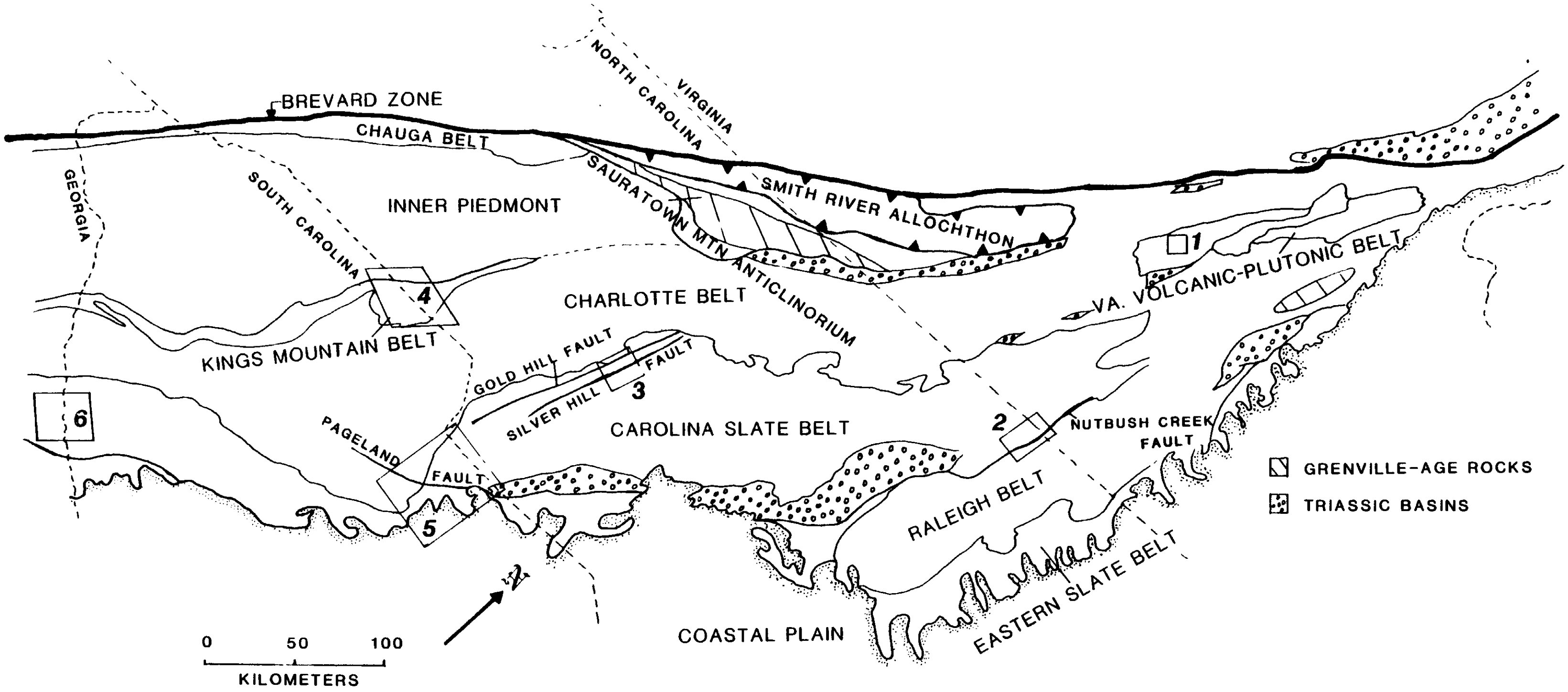
The Kings Mountain belt does not contain significant massive sulfide mineralization but has been important for its gossan iron (Moss, 1981), gold (Pardee and Park, 1948;

Figure 22. Index map of the Piedmont province in Virginia and the Carolinas showing the locations of sulfide deposits discussed in text:

1. Mineral district, Virginia (23);
2. Hamme tungsten district, North Carolina (55);
3. Cid and Gold Hill districts, North Carolina (34);
4. Kings Creek area, North and South Carolina (41);
5. Haile-Brewer area, South Carolina (48); and
6. Lincolnton-McCormick district, Georgia and South Carolina.

Numbers in parentheses refer to figures in which the area is shown in greater detail.

PART III. PIEDMONT STRATABOUND (MASSIVE) SULFIDE DEPOSITS


BREVARD ZONE
CHAUGA BELT
INNER PIEDMONT
NORTH CAROLINA
VIRGINIA
SOUTH CAROLINA
GEORGIA
SMITH RIVER ALLOCHTHON
SAURATOWN MTN ANTICLINORIUM
CHARLOTTE BELT
KINGS MOUNTAIN BELT
GOLD HILL FAULT
SILVER HILL FAULT
CAROLINA SLATE BELT
PAGELAND FAULT
VA. VOLCANIC-PLUTONIC BELT
NUTBUSH CREEK FAULT
RALEIGH BELT
EASTERN SLATE BELT
COASTAL PLAIN
1
2
3
4
5
6
N
0
50
100
KILOMETERS
GRENVILLE-AGE ROCKS
TRIASSIC BASINS

Butler, 1981), stratabound barite (Brobst, 1958; Sharp and Hornig, 1981), and a variety of non-metallic mineral commodities (Horton and Butler, 1977, 1981).

The deposits considered from the northwest Georgia and northern Alabama Piedmont are stratabound sulfides occurring in a variety of settings. Although they occur in the Piedmont physiographic province, these deposits are generally considered to be in the southernmost extension of the Blue Ridge geologic province. The deposits are included with Piedmont sulfide deposits on the basis of isotopic regularities which may or may not have significance.

Many of the Piedmont stratabound sulfide deposits have in the past been mined for base and/or precious metals. Currently, however, deposits interpreted as alteration zones associated with mineralization are more economically significant. Kyanite is mined in the mineralized belt of the central Virginia volcanic-plutonic belt and near the Lincolnton-McCormick district, Georgia. Sericite is recovered at the Haile mine, South Carolina. Although not mined, kyanite quartzites support topographic highs in the Kings Mountain belt. Pyrophyllite is an important resource in the central North Carolina slate belt.

9. MINERAL DISTRICT, VIRGINIA

The Mineral district of Louisa County, Virginia, is located in the Chopawamsic Formation of the Central Virginia volcanic-plutonic belt (CVVP) of probable early Cambrian age (Pavlides, 1981). In the vicinity of the Mineral district massive sulfide deposits the Chopawamsic consists largely of amphibolite, quartz-sericite-biotite schist, sericitic-pyrite quartzite, and quartz-sericite phyllite (Feuer, 1977; Gair, 1978; Pavlides _et al_., 1982). Some of the schists appear to have derived from fragmental volcanic rocks. The sulfides and altered chemical sediments are found in a suite of felsic, intermediate, and basic metavolcanic rocks with island-arc calc-alkaline to tholeiitic chemical affinities (Southwick _et al_., 1971; Pavlides, 1981; Pavlides _et al_., 1982) which interfinger with metapellites. The rocks have been metamorphosed to at least the garnet-staurolite grade of the amphibolite facies in the vicinity of Mineral.

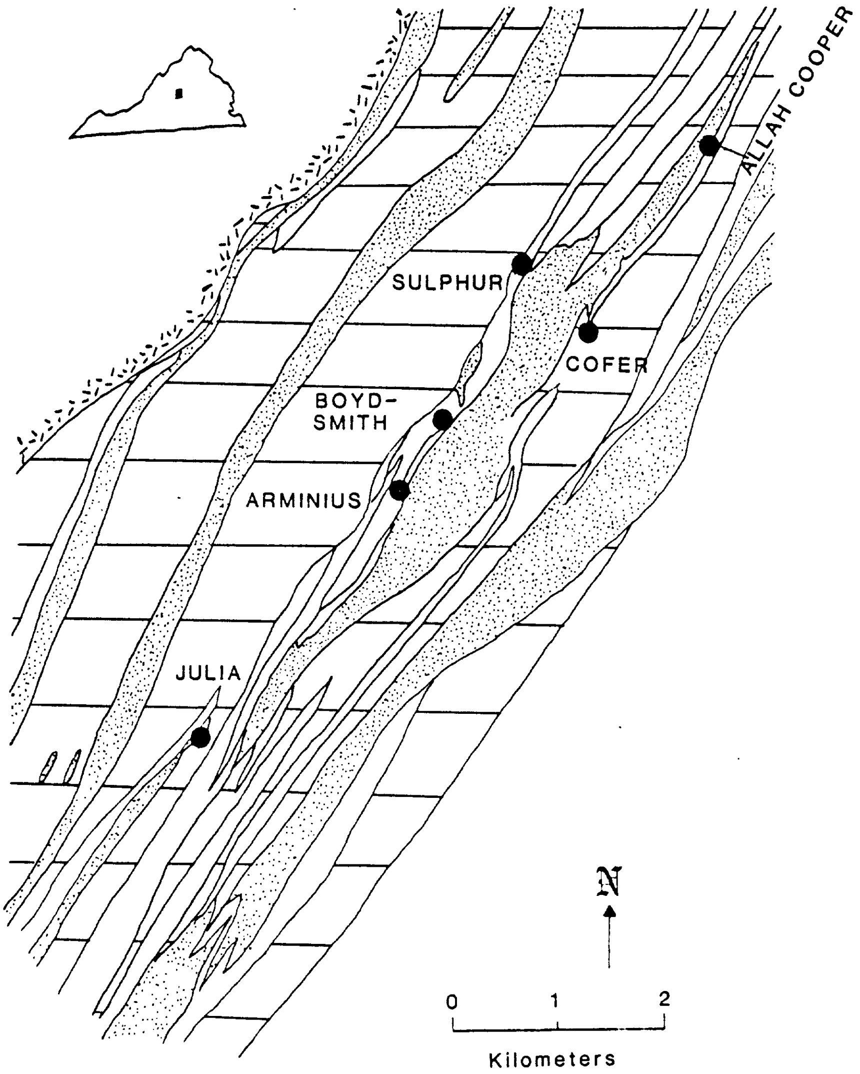
Pavlides (1981) interprets the CVVp as having formed as an island arc during Cambrian time over a west-dipping subduction zone, with a marginal basin to the west of the arc. Gair and Slack (1980) and Pavlides (1981) speculate that the CVVP may be allochthonous with westward transport occurring during the early Paleozoic, before deposition of the Ordovician Quantico Formation. Aspects of the geologic setting and sulfide deposits of the Mineral district have been presented in Gair (1978), Craig (1980) and Pavlides *et al*. (1982).

Description of the Ore Bodies

The massive sulfide bodies of the Mineral district seem to lie of two sub-parallel trends (Fig. 23). On the east are the Allah Cooper and Cofer lenses. Sulphur, Boyd-Smith, and Arminius are the main lenses in the western trend. Drilling proves that Sulphur and Boyd-Smith are connected at depth. The Julia body is geographically in the western trend, but there is no apparent connection with Arminius, the next mine to the north, and there are some structural complications in between.

The three western ore bodies were largely mined out by early miners. The Sulphur lense was a very large pyritic body, containing low base metal values overall but appreciable Cu as chalcopyrite. The connected Boyd-Smith body had a slightly higher base metal content, but was predominantly pyritic. No connection is known between Boyd-Smith and the Arminius lense. Arminius has a higher Zn-Pb content than other western trend deposits and Cox *et al*. (1979) note that it contains more magnetite than other

Figure 23. Geologic map of the Mineral district, Virginia, showing locations of massive sulfide bodies. Stippled areas are dominated by amphibolite. Areas marked by horizontal lines are dominated by sericitic quartzites, quartz-sericite schists, and quartz-biotite shists. After Feuer (1977) and Gair (1978).


ALLAH COOPER
SULPHUR
COFER
BOYD-
SMITH
ARMINIUS
JULIA
N
0
1
2
Kilometers

district lenses. The footwall of the western trend has been called and "accessory mineral schist" because of its high accessory mineral content which includes garnet, staurolite, magnetite, kyanite, and chloritoid and has been interpreted as metamorphosed chemical sediments (Pavlides _et_ _al_., 1982). The hanging wall consists of (turbiditic ?) metasediments interfingered with amphibolite.

The Julia mine is in a thick massive sulfide body high in Zn-Pb-Cu (Ag-Au). An extensive zone of sulfide veinlets rich in sphalerite, galena and pyrite with minor local chalcopyrite below the massive sulfide may constitute a feeder zone (Pavlides _et_ _al_., 1982), but lead isotope evidence (discussed below) seems to argue against it.

The Cofer and Allah Cooper deposits constitute the eastern trend and are generally higher in base metal content than the Sulphur-Boyd-Smith-Arminius trend.

Results of Lead Isotope Studies

Doe and Zartman (1979) reported the lead isotopic ratios found in a galena from the Arminius ore body (Table 8). That analysis is supplemented here by eight additional analyses of galena from five Mineral massive sulfide lenses and three analyses of veinlet occurrences from the Julia deposit.

The nine analyses from massive sulfide lenses (Table 8) form a coherent data set showing little variation in isotopic composition. $^{206}Pb/^{204}Pb$ ratios vary by about two time maximum analytical error (0.1%) when the slightly different Allah Cooper ratio is included. When that value is excluded the variation approximates analytical arror. The variation in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ for all nine analyses is about 0.1%. Galena lead isotopic uniformity is characteristic of volcanic exhalative sulfide deposits (Doe and Zartman, 1979).

Galenas from cross-cutting veinlets of sphalerite and galena, and from coarse galena cubes in open spaces from a single core drilled in the Julia deposit (d.d.h. CV80-86) have a wider range of $^{206}Pb/^{204}Pb$ ratios than the massive lenses, although $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ retain uniformity. The $^{206}Pb/^{204}Pb$ ratios are generally more radiogenic than those found in massive ore, indicating the local addition of a ^{206}Pb-rich component. This addition may have occurred during metamorphic remobilization.

The growth of at least two of these galenas must have occurred during or after the waning stages of deformation. Sericitic quartzite at 1729' and 1961' of core CV80-86 contains relatively coarse cubes of galena which show no evidence of deformational effects. At 1729' the galena cube grew into a vug in the sericitic quartzite, which is lined with well-terminated quartz crystals. Such features

TABLE 8

Galena lead isotope ratios from five Mineral district, Virginia, stratabound sulfide bodies. Model ages were calculated using the parameters of Stacey and Kramers (1975).

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Model age (m.y.)
Galena in massive sulfide lenses				
Arminius ore body				
U58A-620	18.208	15.642	38.121	398
*76-BD2	18.205	15.643	38.121	422
Cofer ore body				
PS-02001	18.219	15.642	38.126	390
PS-02002	18.219	15.641	38.116	388
PS-02003	18.221	15.652	38.146	408
#Cofer	18.226	15.653	38.181	407
Allah Cooper ore body				
PS-03001	18.248	15.651	38.155	387
Julia ore body				
101J-860	18.206	15.638	38.106	393
Sulphur ore body				
27S-542	18.218	15.637	38.109	381
"Disseminated" galena				
Julia ore body (all sample numbers have prefix CV-80)				
-86-1611	18.261	15.642	38.129	359

TABLE 8 (CONT.)

Sample no.	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Model age (m.y.)
"Disseminated" galena (continued)				
Julia ore body				
-86-1729	18.294	15.645	38.149	340
-86-1961	18.222	15.638	38.123	380

---

* Doe and Zartman (1979)

\# Courtesy of B.R. Doe (U.S. Geological Survey, Reston); triple-filament analysis by M.H. Delevaux (U.S. Geological Survey, Denver).

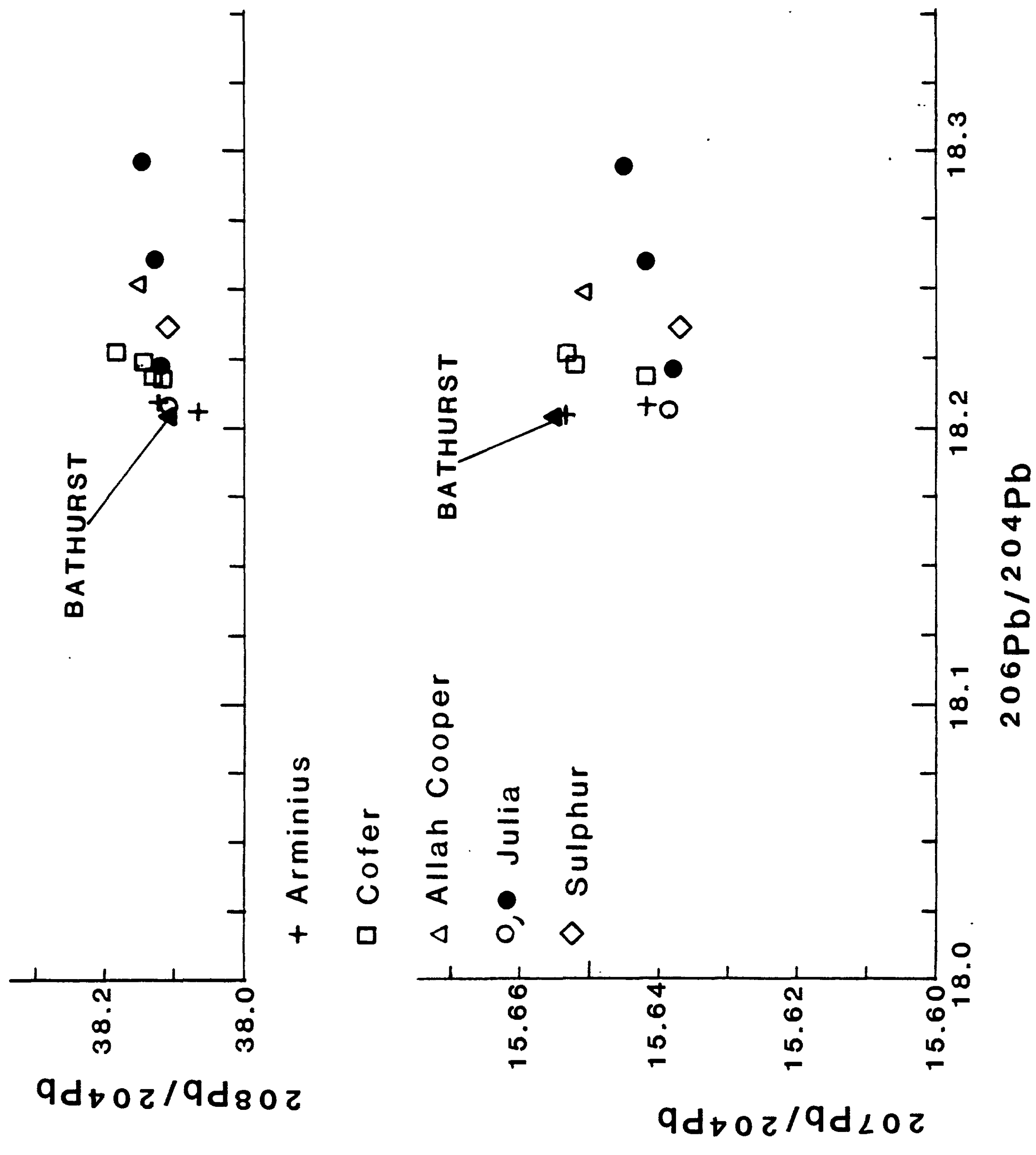
do not usually survive deformation or metamorphism.

The $^{206}Pb/^{204}Pb$ ratio of the disseminated galena does not seem to follow a regular progression of increasing ^{206}Pb in any direction along the core, and, in fact, that ratio in the galena described above at 1961' falls within the range found in massive sulfide lenses.

The radiogenic character and variability of $^{206}Pb/^{204}Pb$ ratios in the veinlet galenas, along with the coherency of $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios with those of galenas in massive lenses, suggests that these galenas formed after main-stage mineralization and that a component of radiogenic ^{206}Pb was locally introduced. The textures of the disseminated galenas strongly indicates late- or post-deformation growth and so may be the result of remobilization accompanied by metamorphic fluids which carried radiogenic lead. This interpretation is more compatable with observations from similar massive sulfides than one in which the sphalerite-galena veinlets represent a "feeder zone". Where such a zone has been observed in comparable deposits it is usually Cu-rich and Pb-Zn-poor (see recent review articles by Hutchinson, 1980; Franklin *et al.*, 1981; and others).

Lead in massive ore at Mineral is strikingly similar to that found at Bathurst, New Brunswick (Fig. 24). Bathurst ores are in Middle Ordovician metavolcanic and metasedimentary strata (Ruittenberg, 1976). The Mineral

Figure 24. Lead isotope ratio diagrams showing galena lead isotope ratios from the Mineral district, Virginia, and from Bathurst, New Brunswick (Stacey *et al.*, 1969). Please note the expansion of the ^{207}Pb/^{204}Pb scale. Julia: ○ galena in massive ore; ● galena in d.d.h. CV80-56 (see text for discussion).


208Pb/204Pb
38.2
38.0
207Pb/204Pb
15.66
15.64
15.62
15.60
206Pb/204Pb
18.0
18.1
18.2
18.3
BATHURST
BATHURST
+ Arminius
□ Cofer
△ Allah Cooper
○, ● Julia
◇ Sulphur

district lies in similar rocks of Cambrian(?) age (Pavlides, 1981). The isotopic character of lead in Mineral and Bathurst galenas place both close to but above the "average orogene" curve of Doe and Zartman's (1979) plumbotectonics model (see Fig. 7). Deposits of this type are most often submarine exhalative massive sulfide bodies in volcanic island arc environments, which in previous models were known as "single stage" or "conformable" leads. Indication of greater than average contribution by upper continental material to the lead in Mineral and Bathurst ores is the high $^{207}Pb/^{204}Pb$ ratios which cause the data points to plot above an average growth curve on a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram (Fig. 24). Doe and Zartman (1979) suggested that this indicates ensialic arc volcanism.

The model age calculated from $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios yields a reasonable (within about 50 m.y.) age of about 400 m.y. for Ordovician Bathurst galenas. The same ratios give model ages that are as much as 150 m.y. too young for mineralization at Mineral, however, if Pavlides' (1981) age of about 550 m.y. is correct for the Chopawamsic Formation. This difference indicates that the source(s) of lead at Mineral was enriched in uranium relative to lead compared to "average orogene" environments. As will be shown, this is true of all Piedmont massive sulfide deposits considered in this study.

Doe and Stacey (1974) and many other authors have observed that many of the world's major ore deposits are conformable with respect to lead evolution model curves. They also pointed out that a deposit with lead ratios similar to a major producer within the same district has a greater likelihood of economic potential. Bathurst and Mineral certainly are not in the same district and are probably not even the same age, but it may be worth repeating Doe and Zartman's (1979) observation that one of the more promising areas in the southern Piedmont - Mineral - resembles Bathurst in the composition of the ores and their host rocks, as well as in their lead isotopic signatures.

Results of Sulfur Isotope Studies

Ninety three sulfur isotope analyses of sulfides from five ore bodies (Table 9) were made to determine the characteristics of $\delta^{34}S$ variation at Mineral. The total range of observed $\delta^{34}S$ in all deposits is 12 $^{o}/oo$. A pyrite sample from Julia (51J-400) and one from Arminius (U62A-1264), however, have $\delta^{34}S$ values that are substantially lower than those found in all other sulfides analyzed and may represent an input of sedimentary pyrite or some other "contaminant". Disregarding those two pyrites, the total range for 91 sulfide samples is about 7 $^{o}/oo$, from

TABLE 9

Sulfur isotope ratios of sulfide minerals from Mineral district, Virginia, ore bodies.

Footage	$\delta^{34}S_{py}$	$\delta^{34}S_{cpy}$	$\delta^{34}S_{sp}$	$\delta^{34}S_{gn}$	Sample description
Julia ore body					
d.d.h. CV80-86					
1668		8.25	8.16	6.11	sp+cpy±gn in ser-qtzte
1729	9.36		8.60	7.64	py in qtz-bio schist; gn±sp in ser-qtzte
1961				6.51	1.5 cm gn cube in vug lined with well-terminated qtz crystals
d.d.h. 51J					
240.5	9.49		8.56		py+sp±gn in schist
400	1.50				coarse-grained (c.g.) banded py
516.5	10.18		9.57		sp-rich zone
	9.45		8.67		py-rich zone
534	9.38				py in garnet-amph
611	10.45	9.86			massive sulfide (m.s.)
629	9.29	9.66			m.s.: top, near contact
	9.84				m.s.: middle of zone
844	10.40				py in amph (clast?) in qtzte
847	10.65				py along foliation
929	10.50		10.06	8.61	blebs and stringers of sp+gn+py
966.5	10.13		9.78		py+sp stringers

TABLE 9 (CONT.)

Footage	$\delta^{34}S_{py}$	$\delta^{34}S_{cpy}$	$\delta^{34}S_{sp}$	$\delta^{34}S_{gn}$	Sample description
<u>Julia ore body (cont.)</u>					
d.d.h. 52J					
696	8.98		8.28		py+sp in amph
753		9.63			blebs and bedded cpy+py in amph
776	9.49		9.00		m.s.
786	9.97		9.32		c.g. m.s.
797	10.32	9.58	9.30		m.s.
834.5	8.56				disseminated py in schist
d.d.h. 101J					
845	9.75		9.10		m.s.
860	9.94		9.25		m.s.
<u>Cofer ore body</u>					
d.d.h. CV79-78					
858	10.28				disseminated py in gneiss
1499	10.91				bedded py
1508	10.84		10.27		2.5 cm band of massive py+sp
1827	8.01		7.00		discrete stringers of py and sp
1913		9.32			disseminated sulfides in ser-qtz schist
d.d.h. CV73-2					
735	10.37		9.65		sub-m.s.
d.d.h. CV74-23					
443	9.95				py-rich layer in m.s.

TABLE 9 (CONT.)

Footage	$\delta^{34}S_{py}$	$\delta^{34}S_{cpy}$	$\delta^{34}S_{sp}$	$\delta^{34}S_{gn}$	Sample description
Cofer ore body (cont.)					
d.d.h. CV74-23 (cont.)					
477	8.63				sub-massive py+sp in schist
862	9.74		8.88	7.89	sp-gn-rich zone
d.d.h. CV74-22					
805	9.37		8.61	7.63	sp+gn+py in bands and blebs
809	9.43	9.21	8.38		py-rich layers in m.s.
824	9.12		8.42	7.02	blebs of sp+gn
825	10.00		9.17		sub-m.s.
827	9.88		9.12	7.76	blebs of sp+gn
Allah Cooper ore body					
PS-03001			12.08	11.10	m.s.
Arminius ore body					
d.d.h. U62A					
1227	10.19		9.46		m.s., py+sp
1248	10.32				m.s., py+mg
1261	10.69				c.g. m.s., py+mg
1264	4.67				c.g. massive py
d.d.h. 20A					
1545	9.85		9.09		m.s., py+sp+mg
1554	10.07				m.s., py+sp+mg
1573	11.16				massive py
Sulphur ore body					
d.d.h. 27S					
510	10.76				py in foliation

TABLE 9 (CONT.)

Footage	$\delta^{34}S_{py}$	$\delta^{34}S_{cpy}$	$\delta^{34}S_{sp}$	$\delta^{34}S_{gn}$	Sample description
Sulphur ore body (cont.)					
d.d.h. 27S (cont.)					
530	10.99				sub-massive py+mg
537	13.45				sub-massive py+mg
542	9.60		9.40	8.11	m.s., sp+py+gn+mg
545		9.23	($\delta^{34}S_{po}$ = 9.03)		disseminated po+cpy+mg in chlorite schist
d.d.h. CV80-88					
1407	11.65	10.57			sub-massive py+cpy
1417	11.98	11.87			sub-massive py+cpy

+6.51 to +13.45 with a mean value of 9.37 ± 1.53 (1σ).

Figure 25 is a histogram of all $\delta^{34}S$ data from Mineral. It shows a strong maximum between +9.0 and +10.0 °/oo. In subsequent figures the data is broken down by deposit (Fig. 26), and by mineral (Fig. 27). Figures 26 and 27 seem to show an increase in average $\delta^{34}S$, with the Julia and Cofer lenses containing the lightest sulfur (lower $\delta^{34}S$) and Arminius, Sulphur, and Allah Cooper sulfides containing progressively heavier sulfur. There are only two determinations from Allah Cooper, however, and the range of values from that lense are therefore poorly known. The mean values of $\delta^{34}S$ in the individual deposits (excluding the two low pyrite values) are: Julia = 9.26 ± 0.98 (N = 41); Cofer = 9.10 ± 1.06 (N = 28); Arminius = 10.10 ± 0.66 (N = 8); Sulphur = 10.55 ± 1.53 (N = 12); and Allah Cooper = 11.59 (N = 2). If the two analyses from Allah Cooper are representative, then average $\delta^{34}S$ ratios in that lens could be substantially higher than in other deposits. The difference in average $\delta^{34}S$ ratios may reflect the effects of different temperatures, pH, rock/water ratios, and/or oxygen fugacities on sulfur isotopic fractionation or may indicate slightly different source mixes. Higher magnetite content in the Arminius and Sulphur lenses may indicate that oxygen fugacity differences played a role in sulfur isotope variations relative to Julia and Cofer. The difference may also be partially

Figure 25. Frequency distribution diagram of sulfur isotope ratios of sulfides from Mineral district ore bodies.

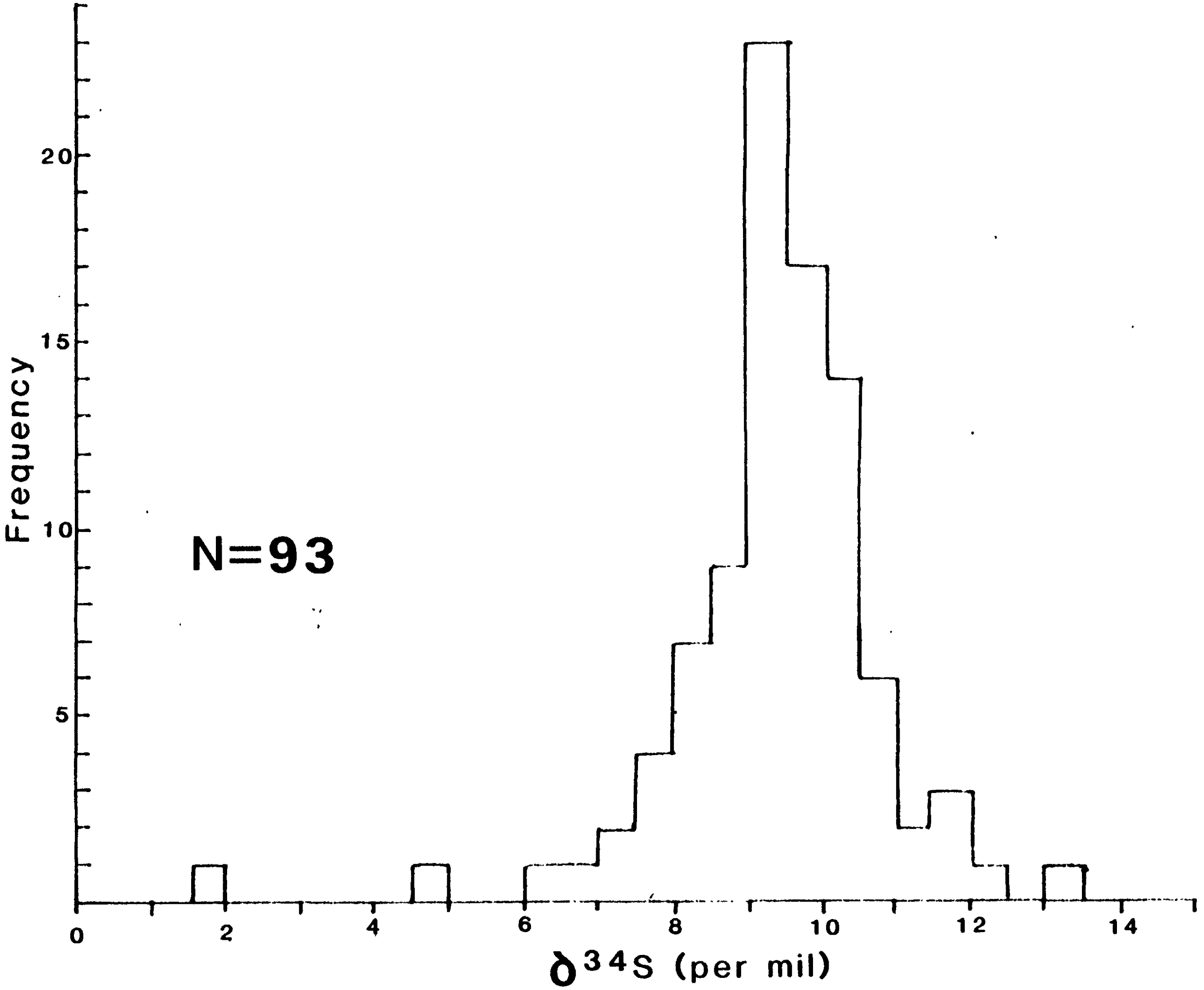
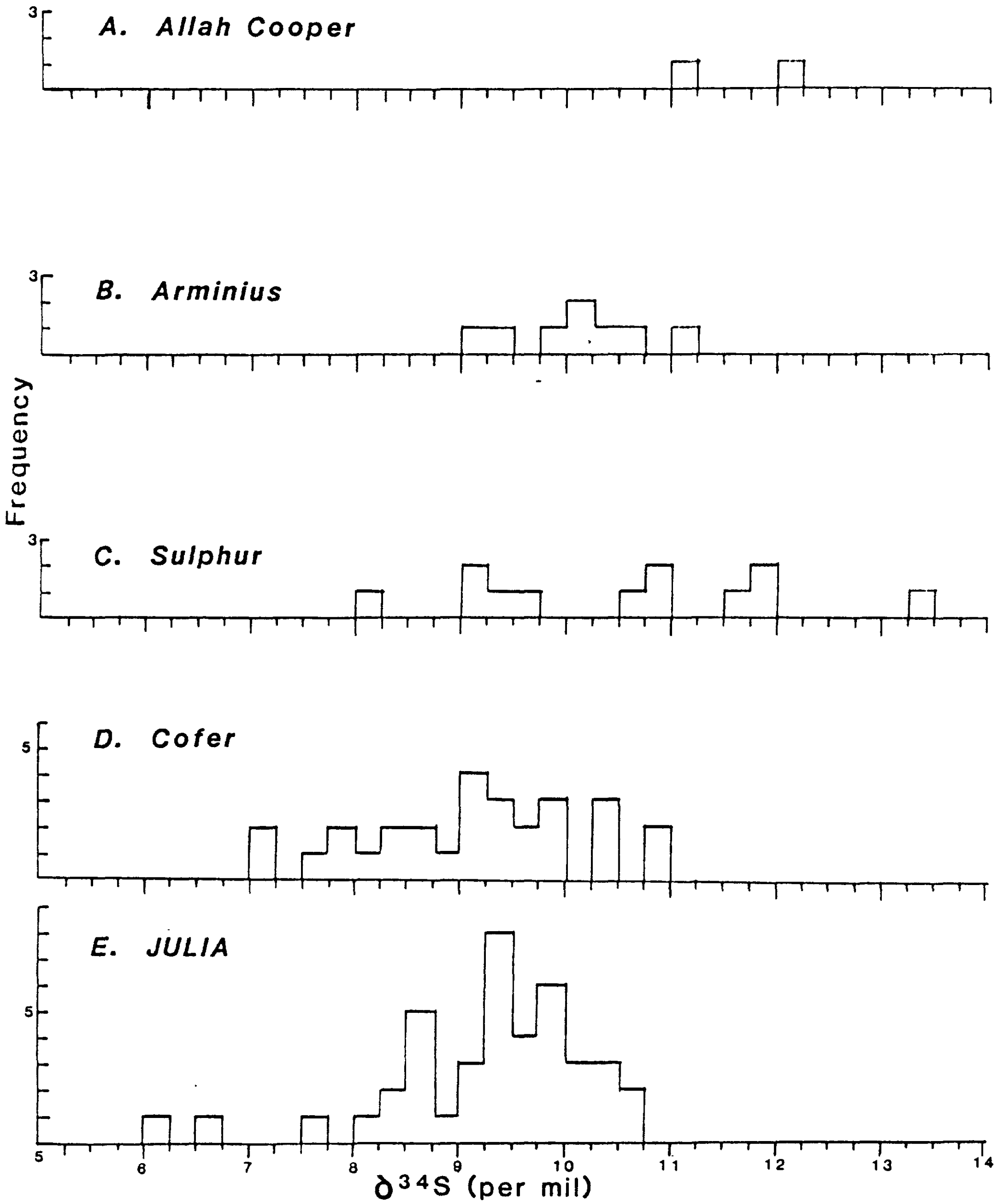

N=93
Frequency
0
5
10
15
20
0
2
4
6
8
10
12
14
δ34S (per mil)

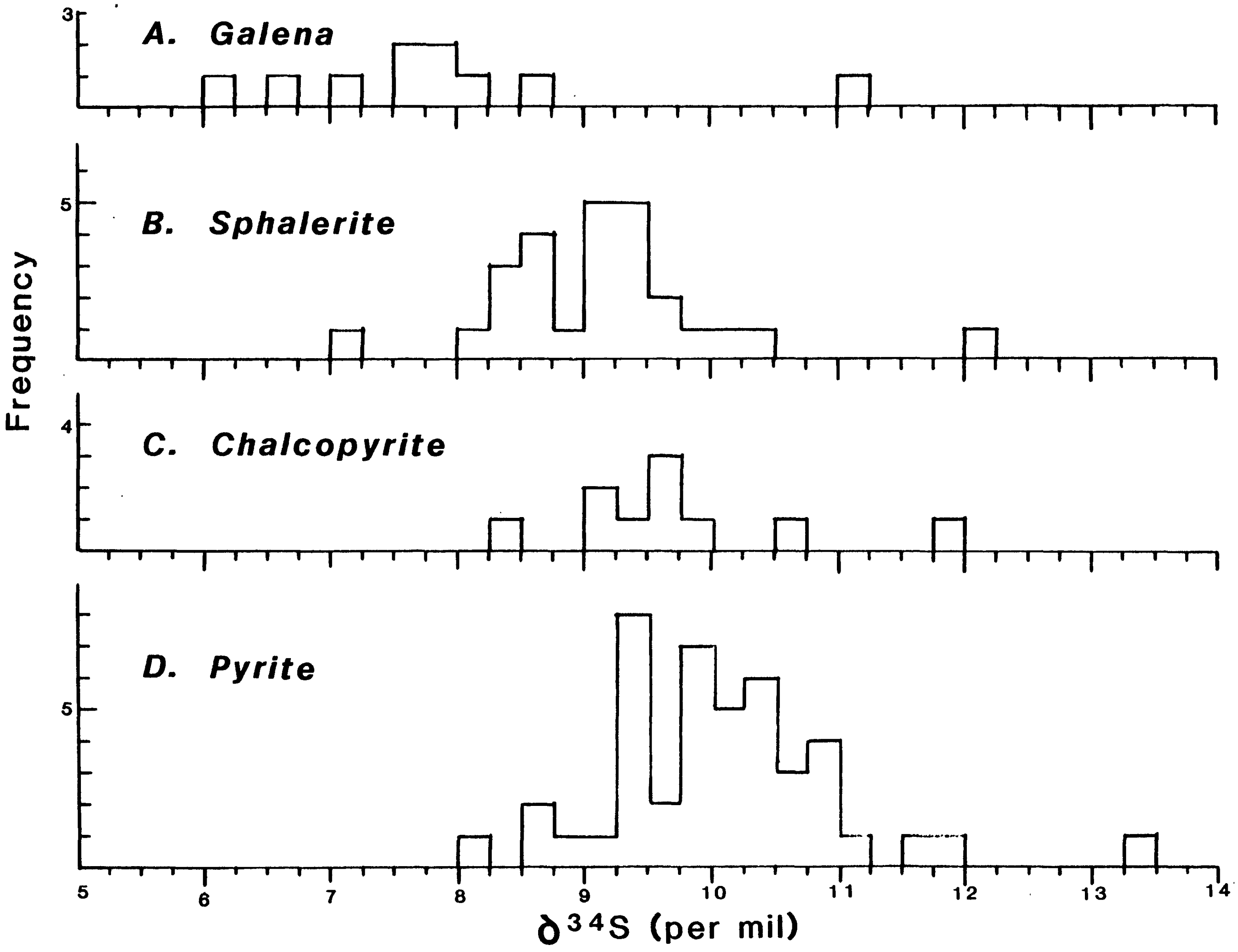
Figure 26. Frequency distribution diagrams of sulfur isotope ratios in individual Mineral district sulfide lenses.

154



3
A. Allah Cooper
3
B. Arminius
Frequency
3
C. Sulphur
5
D. Cofer
E. JULIA
5
5
6
7
8
9
10
11
12
13
14
δ34S (per mil)

Figure 27. Frequency distribution diagrams of individual sulfide minerals from the Mineral district.


A. Galena
B. Sphalerite
C. Chalcopyrite
D. Pyrite
Frequency
3
5
4
5
5
6
7
8
9
10
11
12
13
14
δ³⁴S (per mil)

attributable to different mineralogies effecting sulfur fractionation (Cofer and Julia have higher base metal content than Sulphur and Arminius).

Sulfides in the Julia deposit have the narrowest range of $\delta^{34}S$ values. The total range for pyrite, chalcopyrite, and sphalerite is about 2.5 $^{o}/oo$. Cofer and Sulphur appear to have a wider range for those same minerals. Data for Arminius and Allah Cooper are insufficient to establish a meaningful range. Six pyrites from Arminius massive ore, however, have a total range of about 1.3 $^{o}/oo$. In general the range of values observed in sulfides from massive ore is less than that in disseminated occurrences.

The average $\delta^{34}S$ value of about +9.4 $^{o}/oo$ for Mineral district sulfides translates to a $\delta^{34}S$ ratio of contemporaneous seawater sulfate of about +26.4 $^{o}/oo$ (see Ch. 3) which is compatible with the value of Cambrian seawater (Claypool _et_ _al_., 1980). Figure 28 compares Mineral sulfide sulfur isotope compositions with those observed in the Cambrian Mount Lyell and Roseberry deposits (Solomon _et_ _al_., 1969) and in the Ordovician Bathurst ores (Tupper, 1960; Lusk and Crocket, 1969; Lusk, 1972). The bimodal distribution at Bathurst is due to distinct sulfur isotope compositions in the northern and southern massive sulfide groups and is attributed to differnces in temperature of deposition by Lusk (1972).

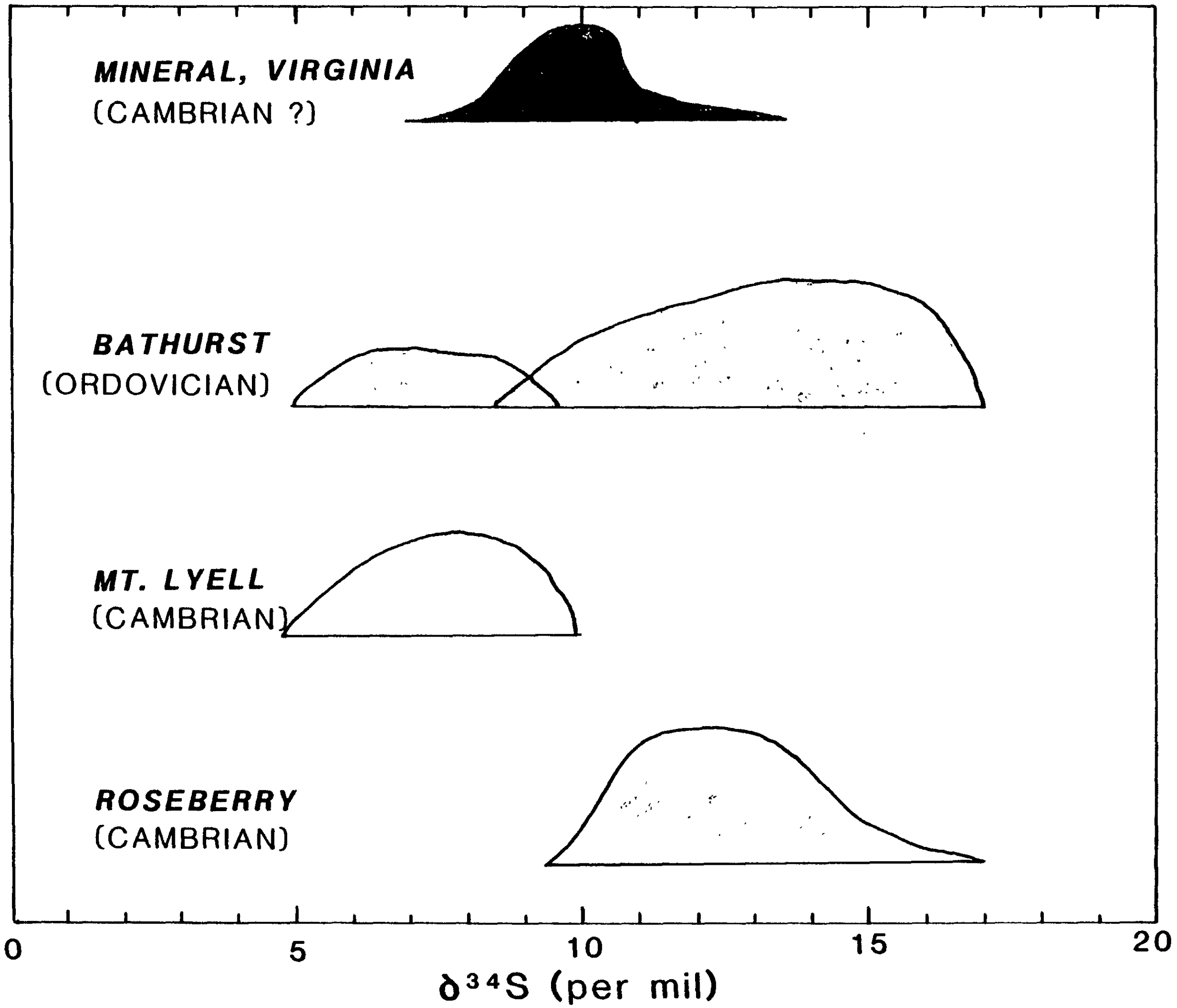
Figure 29 illustrates the results of isotope temperature calculations. The wide range (260° - 660°C) may indicate that equilibrium was not attained or was disturbed during metamorphism. There are several problems associated with equilibrium termperature determinations in metamorphosed sulfide deposits such as Mineral. Because original textures have been disturbed, primary paragenetic relationships are obscured so that selection of coprecipitated sulfides for temperature analysis becomes largely a matter of chance. The mean of all the temperature data is 425°C (±90) which closely matches the mean of data from massive ore alone: 418°C (±90). In fact, reducing the data to averages for each grouping of data (by deposit, by mineral pair within deposits, and the total averages) results in a tighter cluster of data with a mean of the means of 419°C (±33) which may be a closer estimate of the temperatures of deposition of the ores.

Although the range of temperatures may indicate that isotopic equilibrium was not attained or was disturbed, only one sample actually exhibits disequilibrium sulfur isotopic compositions: Julia sample 51J-629 (Table 9) has $\delta^{34}S_{py} < \delta^{34}S_{cpy}$.

Several volcanogenic massive sulfide deposits have been shown to have sulfur isotope compositions that vary systematically with stratigraphy. Generally, $\delta^{34}S$ decreases up-section, as in the Kuroko, Japan, Cyprus, and Raul, Peru deposits (summarized by Rye and Ohmoto, 1974, and Ohmoto and Rye, 1979). In the Shakanai, Japan, deposit there is a sharp decrease in $\delta^{34}S$ values at about the boundary between black ore (Pb-Zn-rich ore) and overlying chemical sediments (Kajiwara, 1971). Interestingly, Julia sample 51J-400 which has a much lower $\delta^{34}S_{py}$ value than other samples, occurs at about the boundary between possible metamorphosed chemical sediments ("accessory mineral schist") and structurally overlying biotite-sericite-quartz schist. If this sample is analogous to the similar sharp drop at Shakanai, it may be a facing indicator. Additional data are required to determine if the $\delta^{34}S$ value of the anomalous pyrite is a feature of the hydrothermal mineralizing system, or is a "contaminant" introduced through some unrelated process.

Possibly the difference in sulfur isotopic composition between the Cu-pyrite Sulfur and Arminius lenses and the Zn-Pb-rich Cofer and Julia depsoits is a lateral expression of the vertical pattern of upward-decreasing $\delta^{34}S$ observed in other systems. The lateral mineralogy change also follows that found vertically in other depsosits: Cu-pyrite-rich ("stringer" and "yellow" ore) in the lower reaches and Zn-Pb-rich ("black ore" = kuroko) in the upper section. If the lateral analogy is correct, then Sulphur-Arminius, with higher $\delta^{34}S$ values, would be more "proximal" and Julia-Cofer, which are generally lower in $\delta^{34}S$, are "distal". Lateral variations in $\delta^{34}S$ and in mineral-

Figure 28. Range and approximate frequency distribution of sulfur isotope ratios of Mineral district sulfides compared with those of the Cambrian Mount Lyell and Roseberry deposits (Solomon _et_ _al_., 1969), and of the Ordovician Bathurst deposits, New Brunswick (Tupper, 1960; Lusk and Crocket, 1969; Lusk, 1972).


MINERAL, VIRGINIA
(CAMBRIAN ?)
BATHURST
(ORDOVICIAN)
MT. LYELL
(CAMBRIAN)
ROSEBERRY
(CAMBRIAN)
0
5
10
15
20
δ³⁴S (per mil)

(6)

Figure 29. Sulfur isotope mineral pairs equilibrium temperatures frequency distribution diagram.

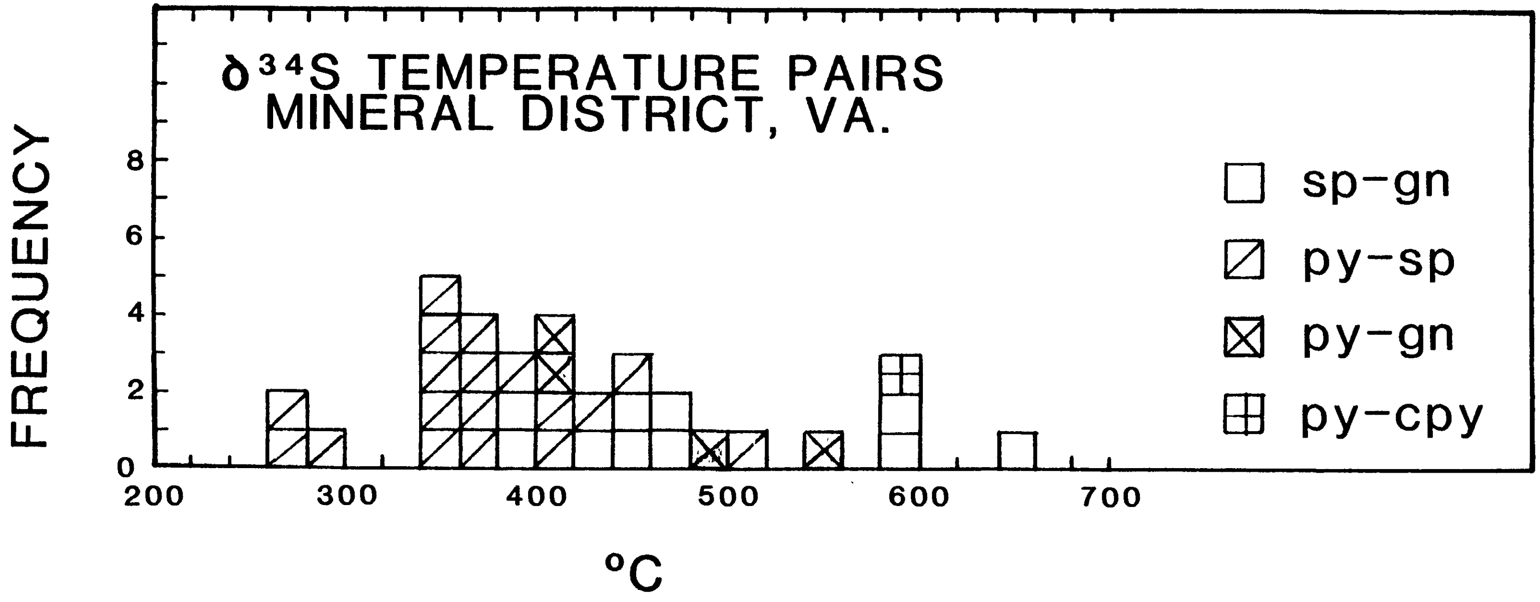

δ34S TEMPERATURE PAIRS
MINERAL DISTRICT, VA.
FREQUENCY
0
2
4
6
8
200
300
400
500
600
700
°C
□ sp-gn
▨ py-sp
☒ py-gn
⊞ py-cpy

Figure 30. Sulfur isotope variations in Julia cores 51J and 52J. Please note that A. (d.d.h. 51J) covers a substantially greater footage interval than B. (d.d.h. 52J).

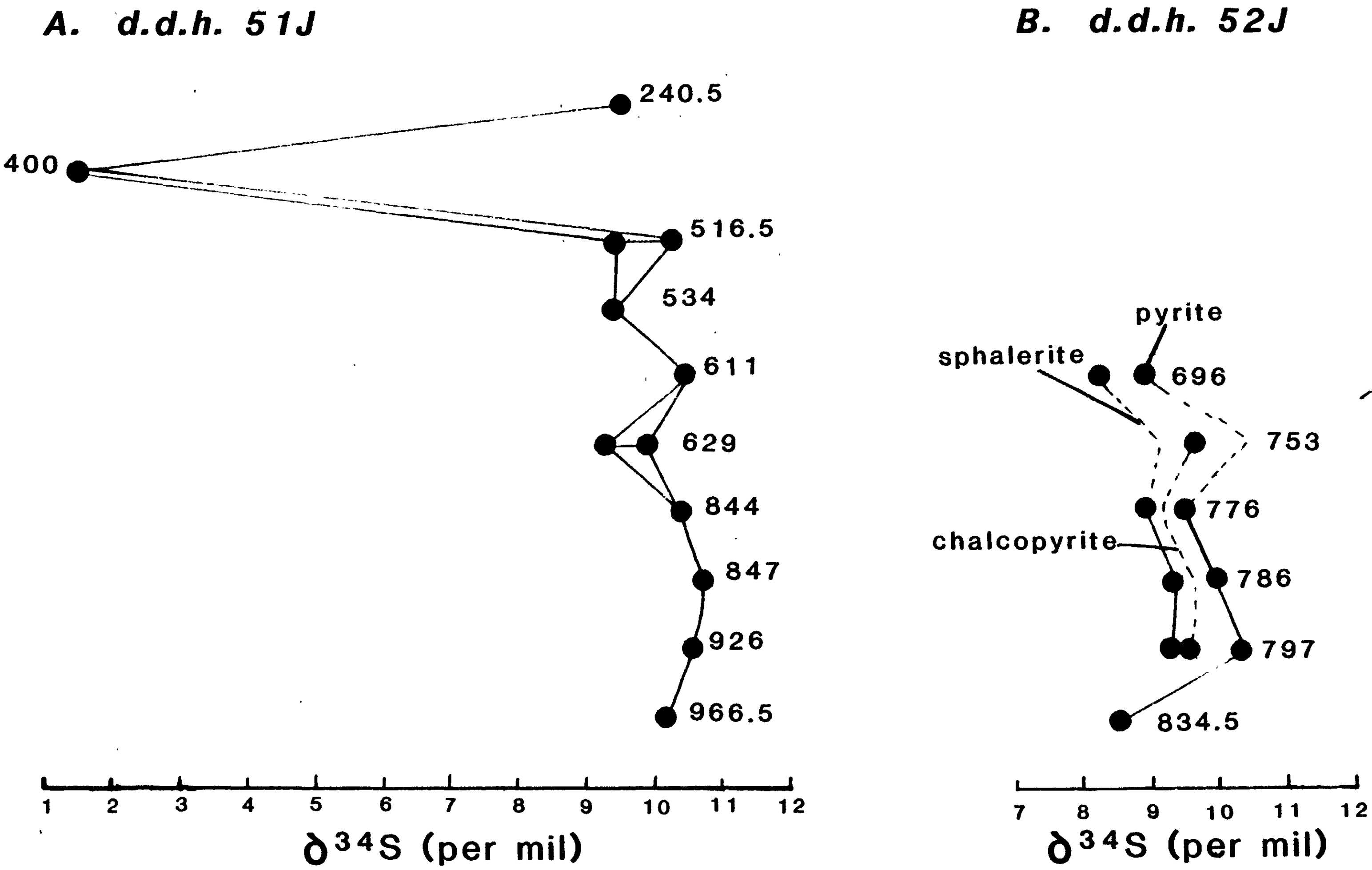
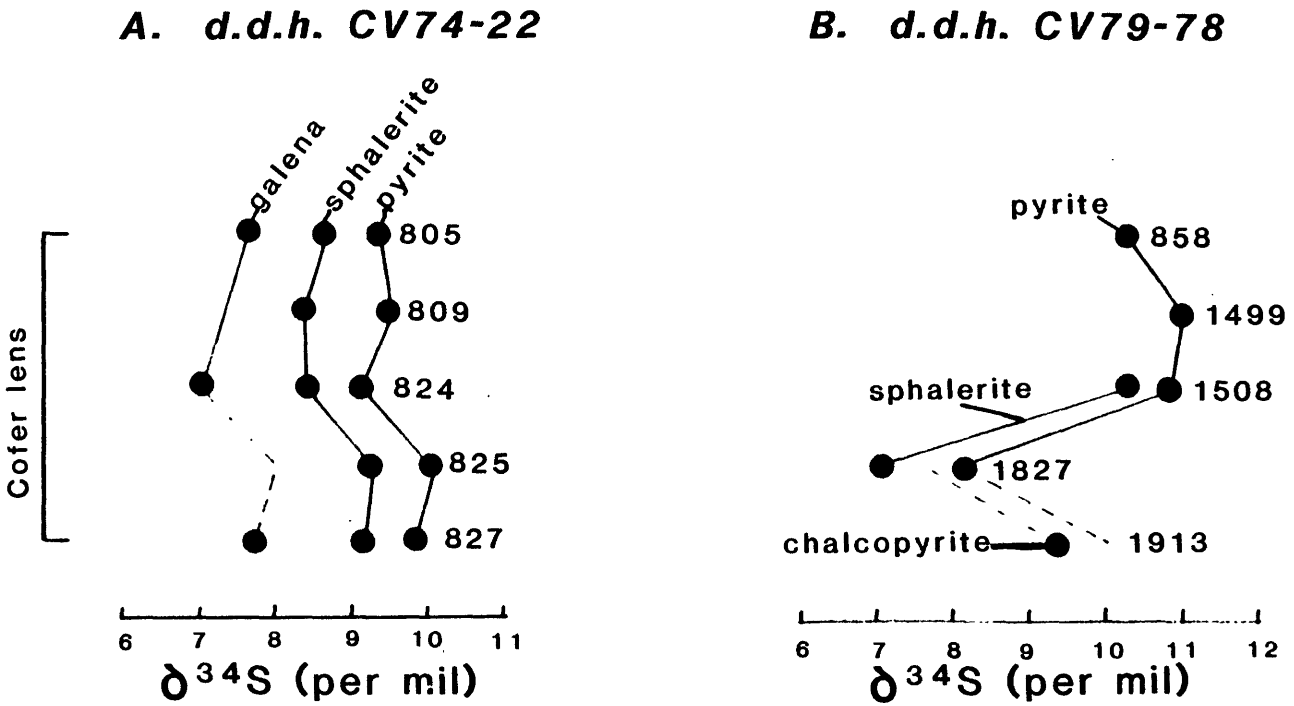

A. d.d.h. 51J
240.5
400
516.5
534
611
629
844
847
926
966.5
1
2
3
4
5
6
7
8
9
10
11
12
δ34S (per mil)
B. d.d.h. 52J
pyrite
sphalerite
696
753
776
chalcopyrite
786
797
834.5
7
8
9
10
11
12
δ34S (per mil)

Figure 31. Sulfur isotope variation in Cofer cores CV74-22 and CV79-78. Please note that A. (CV74-22) represents only the interval that is stratigraphically equivalent to the "Cofer lense" whereas B. (CV79-78) illustrates ratios from over 1000 feet of drill core.


A. d.d.h. CV74-22
galena
sphalerite
pyrite
805
809
824
825
827
Cofer lens
6
7
8
9
10
11
$\delta^{34}S$ (per mil)
B. d.d.h. CV79-78
pyrite
858
1499
sphalerite
1508
1827
chalcopyrite
1913
6
7
8
9
10
11
12
$\delta^{34}S$ (per mil)

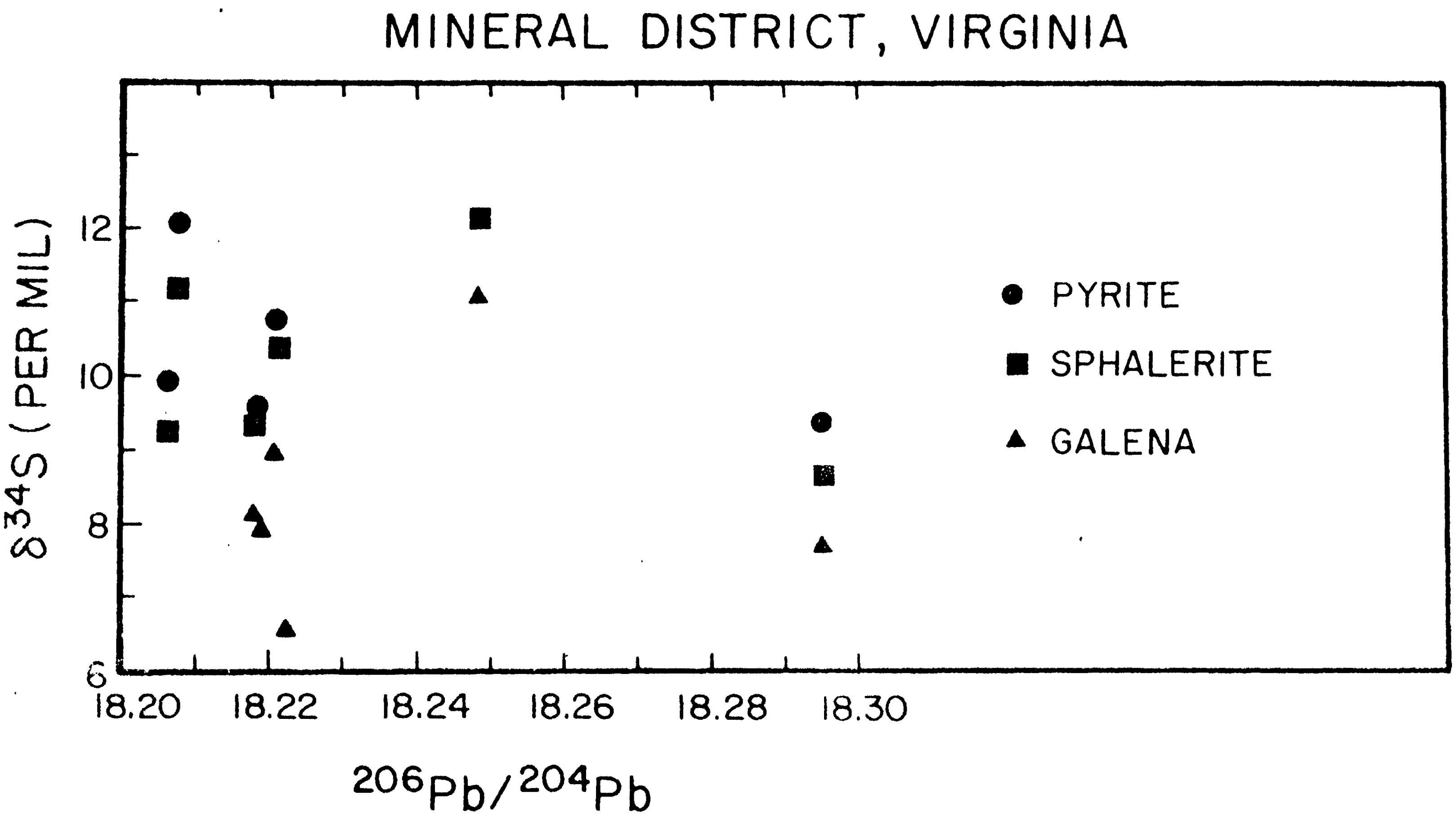

MINERAL DISTRICT, VIRGINIA
● PYRITE
■ SPHALERITE
▲ GALENA
$\delta^{34}S$ (PER MIL)
6
8
10
12
18.20
18.22
18.24
18.26
18.28
18.30
$^{206}Pb/^{204}Pb$

Figure 32. Sulfur isotope versus lead isotope ratios from Mineral district sulfides. Pyrite and sphalerite sulfur ratios are from samples for which galena lead isotope ratios were measured.

ogy are also observed in the Bathurst district (Lusk, 1972) and between the Mount Lyell and Roseberry deposits, Tasmania (Solomon et al., 1969).

Trends in individual Mineral district lenses are tenuous (Table 9). There seems to be a gross decrease in $\delta^{34}S$ up-core in Julia cores 51J and 52J (Fig. 30), which may indicate that Julia is right side up. Two Cofer cores, however, have opposing gross trends. $\delta^{34}S$ ratios increase upward in d.d.h. CV79-78, but decrease (in a very general fashion) up core in d.d.h. CV74-22 (Fig. 31). If these trends have significance, they indicate local overturned sections in the Cofer area. $\delta^{34}S$ values decrease up-section in two Arminius massive sulfide lenses (d.d.h. U62A and 20A), indicating that Arminius is probably right side up. A pyrite at the bottom of the lens in d.d.h. U62A has an anomalously low $\delta^{34}S$ value, which may be due to some "contaminant". Sulfur isotope data from the Sulphur deposit are ambiguous.

There does not appear to be any relationship between lead and sulfur isotopic compositions in Mineral district ores (Fig. 32).

Virginia Gold-Pyrite Belt

The Virginia gold-pyrite belt consists of numerous gold-bearing quartz veins and coincides in part with the strike belt of the Chopawamsic Formation. Because of the geographic coincidence of the mineralized quartz veins and several massive sulfide districts of the central Virginia plutonic-volcanic belt, there has been some speculation that there is a genetic relationship. Good _et al_. (1977) proposed that the gold deposits are related to volcanogenic sulfide mineralization and suggested that gold could be used as a guide to nearby massive sulfide deposits. Sweet (1980) has compiled available information about individual gold-pyrite belt occurrences.

Lead isotope compositions from the Whitehall and Mineral Ridge mines (Table 10) and from the Moss vein (Kish and Feiss, 1982) are quite distinct from each other as well as from lead in Mineral district galenas (Fig. 33). Galenas from the veins have lead that is radiogenic relative to Mineral and have a wide range of lead isotope ratios. The lead patterns and the evidence of the cross-cutting nature of the belt (Pavlides _et al_., 1982) indicates that it is younger than volcanogenic mineralization events of the area and perhaps is related to metamorphism.

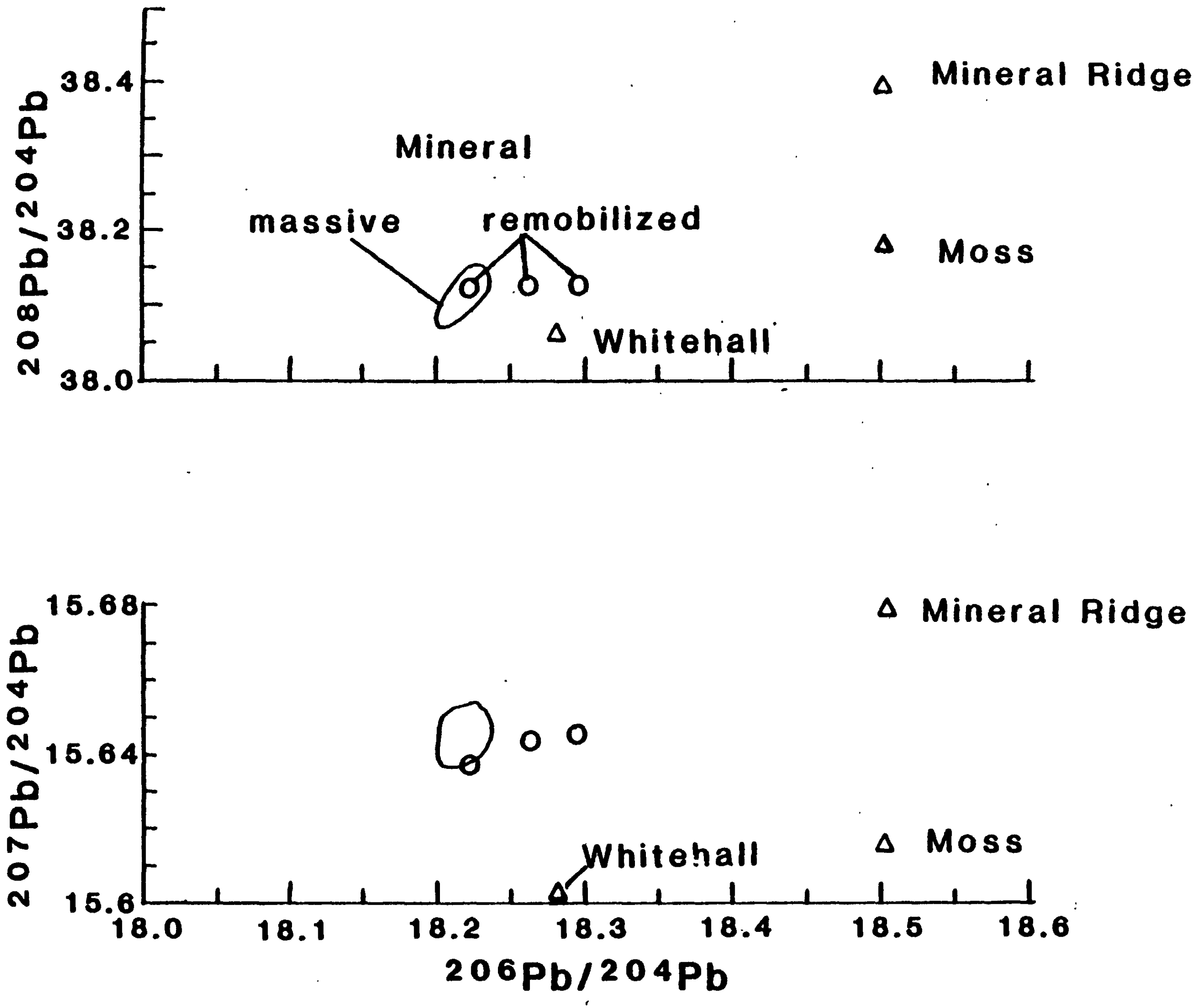
TABLE 10

Galena lead isotope ratios from some deposits of the Virginia gold-pyrite belt.

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$
Mineral Ridge			
USNMNH 10832	18.503	15.679	38.397
Whitehall mine			
USNMNH 79032	18.279	15.605	38.058
Moss mine*			
--	18.503	15.615	38.178

* data from Kish and Feiss (1982).

Figure 33. Lead isotope ratio diagrams illustrating ratios found in Virginia gold-pyrite belt galenas compared with those of the Mineral district. "Remobilized" refers to the galenas in Julia core CV80-86. Data from the Moss mine is from Kish and Feiss (1982).


208Pb/204Pb
38.4
38.2
38.0
Mineral Ridge
Mineral
massive
remobilized
Moss
Whitehall
207Pb/204Pb
15.68
15.64
15.6
Mineral Ridge
Whitehall
Moss
18.0
18.1
18.2
18.3
18.4
18.5
18.6
206Pb/204Pb

10. CAROLINA SLATE BELT POLYMETALLIC STRATABOUND SULFIDE DEPOSITS

The Carolina volcanic slate belt is a sequence of slightly metamorphosed (greenschist facies) volcanic and volcanoclastic rocks which extends from south-central Virginia to east-central Georgia. Stratigraphic, geochemical, and geophysical evidence argues against a direct relationship between the Carolina slate belt and the Virginia plutonic-volcanic belt (Gair _et_ _al_., 1980; Pavlides _et_ _al_., 1982). Radiometric ages from slate belt rocks suggest two distinct age provinces. From Virginia to central North Carolina, slate belt rocks give late Precambrian (660-680 m.y.) ages. The southern area is largely Cambrian in age and contains probable middle Cambrian trilobites (St. Jean, 1973).

In a review of available geochemical data Black (1980) found that slate belt metavolcanics have a strong mafic - felsic bimodal distribution with a dominant felsic component. He also found that discriminant analysis indicates a dominant calc-alkaline composition with continental margin volcanics characteristics. The proportion of calc-alkaline rock compositions appears to increase from the older northern part to the younger southern part of the slate belt, suggesting a maturing of the volcanics through time. Geochemical data also indicate that slate belt volcanics developed on a continental crust 20 to 25 km thick (Black, 1980). Glover et al. (1978) suggested that this crust was Grenville-age basement. Whitney et al. (1978), however, found that the southwesternmost extension of the Carolina slate belt contains metavolcanic and metavolcanoclastic rocks with island arc tholeiitic geochemical affinities. They suggested that this part of the slate belt developed over oceanic crust or a thin wedge of continental crust and represents a more "primitive" arc setting than that postulated for more northerly segments of the belt. Fullagar and Butler (1979) also argue that the eastern portion of the Piedmont, at least, must have developed over mafic crust. In another analysis of available geochemical data, Feiss (1982) pointed out that alteration of slate belt volcanics is pervasive and severely limits the usefulness of major element chemistry as indicators of tectonic and petrogenetic processes. He believes, however, that major element combined with immobile trace element chemistry supports the interpretation of the slate belt as a bimodal, calc-alkaline suite generated over a subduction zone.

Whitney et al. (1978) and numerous other authors have interpreted the Carolina slate belt as an ancient volcanic island arc. Long (1979), however, uses geophysical evidence to suggest a rift basin orogin for the belt. Black

(1980) pointed out that the dominance of felsic over mafic volcanism seems inconsistent with recent rift volcanics where the reverse relationship prevails. Glover *et al.* (1978) and Hatcher and Butler (1979) suggested that both models may be applicable in certain areas if a back-arc environment is used as a model.

Polymetallic exhalative volcanic sulfide deposits are associated with the younger, Cambrian slate belt rocks from central North Carolina to Georgia (Fig. 22). They are concentrated in two areas: The Cid and Gold Hill districts contain numerous individual deposits in the central North Carolina slate belt and several deposits comprising the Lincolnton-McCormick district are found at the southwestern extension of the slate belt in Georgia and South Carolina.

Massive pyritic lenses are associated with the gold deposits of the Haile-Brewer area in north central South Carolina. This area will be discussed in a later section.

Central North Carolina Slate Belt

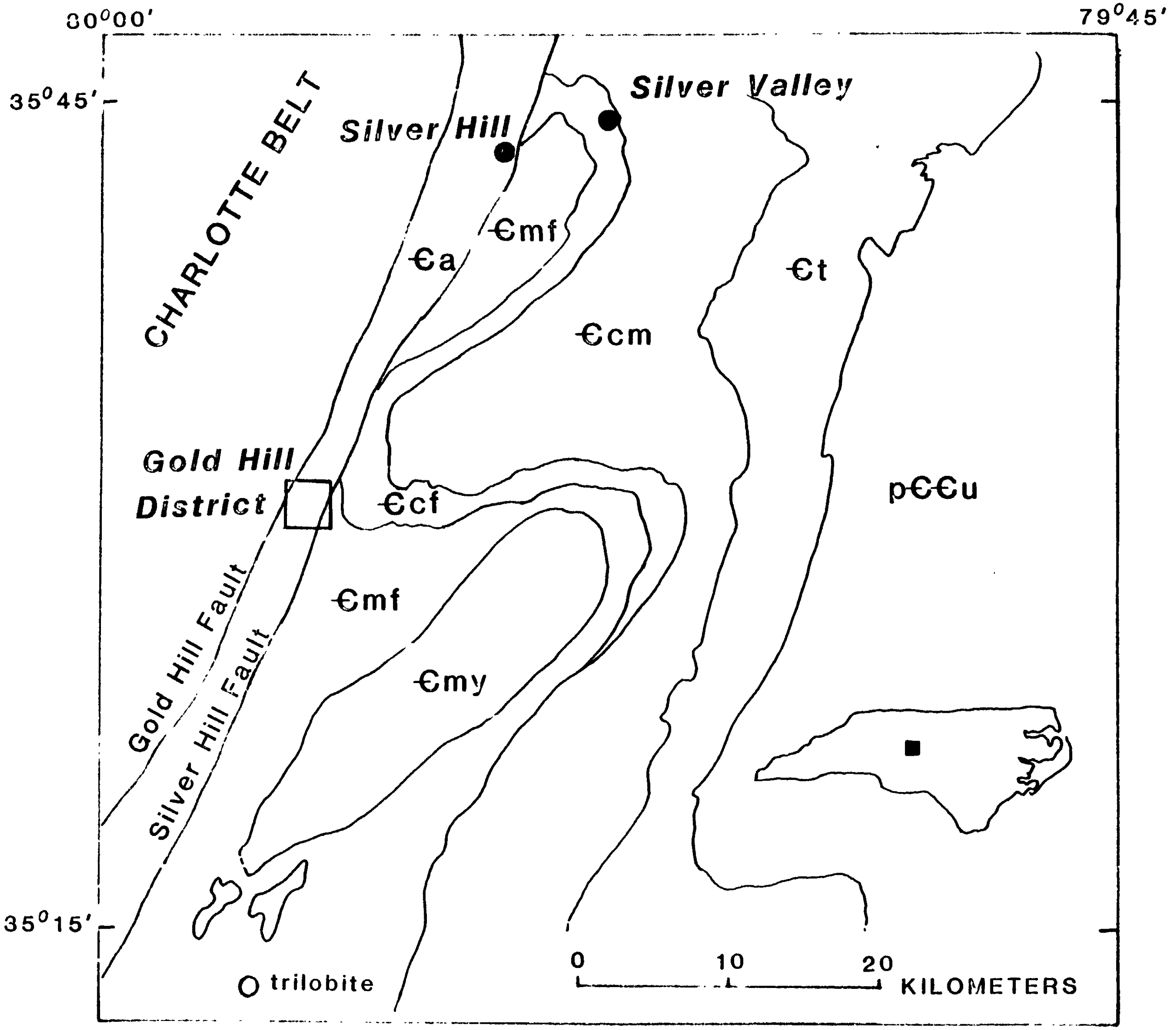
The geology of the area around the Cid and Gold Hill districts has been described by Seiders (1978), Seiders and Wright (1977), Stromquist and Sundelius (1969, 1975), Stromquist *et al.* (1971), and Sundelius (1970). Sulfide deposits of the two districts are found in or just east of the Gold Hill-Silver Hill fault zone which, in this area, is the boundary between the Carolina slate and Charlotte belts (Fig. 34). The stratigraphy within the fault zone is uncertain but the units southeast of the zone are believed to be represented. The Cid district straddles the Silver Hill fault and lies within the Cid Formation which consists of mudstone and mafic and felsic volcanic and volcanoclastic rocks (Stromquist and Sundelius, 1969; Seiders, 1978; Indorf, 1981). Trilobite segments found in the overlying Floyd Church Member of the Millingport Formation were assigned to the genus Parodoxides and are probably Middle Cambrian in age (St. Jean, 1973). Zircons from the underlying Uwharrie Formation felsic volcanic rocks define a cord with an upper intercept of 586 ± 10 m.y. (Wright and Seiders, 1980), which is in good agreement with a Rb-Sr whole-rock age of 554 ± 50 m.y. from the Uwharrie Formation (Hills and Butler, 1969; as recalculated by Seiders and Wright, 1977) and with the age of the trilobites. The stratigraphic position of the Gold Hill district is probably similar to that of the Cid district.

Indorf (1981, p. 1170) described the Silver Hill deposit (the largest in the Cid district), as "a stratiform deposit 15m wide, 5m thick, and at least 550m long, in chloritic argillite in a sequence of Cambrian andesitic to rhyolitic submarine pyroclastic-flow tuffs''. It is a Zn-Pb deposit with minor Cu and traces of arsenic, bismuth

Figure 34. Geologic map of the central North Carolina slate belt showing the locations of the Silver Hill and Silver Valley mines of the Cid district, and of the Gold Hill district. The trilobite locality of St. Jeans (1973) is also indicated. After Wright and Seiders (1980).

Explanation

Cambrian	€my	Yadkin member	Millingport Formation	€a Albermarle Group, undivided
	€mf	Floyd Church member		
	€cf	Flat Swamp member	Cid Formation	
	€cm	Mudstone member		
	€t	Tillery formation		
Cambrian and/or upper PreCambrian	p€€u	Uwharrie Formation		


80°00'
79°45'
35°45'
35°15'
CHARLOTTE BELT
Silver Hill
Silver Valley
€a
€mf
€t
€cm
Gold Hill District
€cf
p€€u
€mf
€my
Gold Hill Fault
Silver Hill Fault
O trilobite
0
10
20
KILOMETERS

and silver. Metamorphic textures are evident at microscopic scales in Cid district ores, but do not obscure macroscopic sedimentary textures in the ore (Indorf, 1981). The nearby Silver Valley deposit (Fig. 34) is generally similar to Silver Hill.

The Gold Hill district lies wholly within the Gold Hill-Silver Hill fault zone (Fig. 34). It is a mineralized belt over 3km long and 1 km wide in volcanoclastic rocks which generally show more evidence of shearing than those associated with Cid district lenses. Laney (1910) described two ore types at Gold Hill: (1) Unsilicified argillite with thinly interlaminated chalcopyrite and minor pyrite but little gold; and (2) a more thickly bedded auriferous pyrite and highly silicified cherty argillite zone rich in gold but poor in copper. Ballard and Clayton (1948) found a third type at the Union Copper Mine: Sphalerite-galena ore similar to that at Silver Hill. They reported that copper mineralization is concentrated near the middle of the ore zone while sphalerite predominates along strike. Union Copper was mined mainly for gold and copper. Between 1899 and 1906, $300,000 in gold and 5,000,000 pounds of copper is estimated to have been produced at Union Copper (Pardee and Park, 1948). The Silver Hill and Silver Valley mines, however, were mined for silver, zinc, and lead (some of which became Confederate bullets). The value of production from Silver Hill between 1838 and 1882 has been estimated at more than $1,000,000 (Pardee and Park, 1948).

Lead isotope ratios of galena from the Silver Hill and Silver Valley deposits are listed in Table 11. These include the data of Kish and Feiss, (1982). There is no difference between lead in massive and disseminated ores within the deposits, but there is a statistically significant difference between lead isotope ratios in Silver Valley massive ore and the Silver Hill deposit, with the latter containing slightly more radiogenic $^{206}Pb/^{204}Pb$ ratios. $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios from the two lenses do not vary significantly. The difference may be attributable to a slightly different mix of source materials contributing lead to the deposits.

There appears to be a tendency towards higher $^{206}Pb/^{204}Pb$ ratios in disseminated galena from the Silver Valley deposit relative to that in massive ore (Table 11). This suggests that a component of radiogenic ^{206}Pb was added to vein galenas, perhaps during metamorphic remobilization (Kish and Feiss, 1982).

Table 12 presents lead isotope compositions of galenas from four deposits of the Gold Hill district, North Carolina. The $^{206}Pb/^{204}Pb$ ratios of these galenas is significantly more radiogenic than those from the Cid district. There is also a tendency for higher $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios at Gold Hill. The difference in $^{206}Pb/$

TABLE 11

Galena lead isotope ratios from ore bodies in the Cid district, central North Carolina slate belt.

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Model age (m.y.)
Galena in massive sulfide				
Silver Hill ore body				
PS-10101	18.135	15.622	37.888	413
PS-10102	18.133	15.611	37.863	393
CQ-8*	18.133	15.622	37.886	414
CQ-10*	18.139	15.623	37.898	412
Silver Valley ore body				
PS-10302	18.107	15.615	37.867	420
CQ-11*	18.104	15.625	37.899	442
CQ-11B*	18.111	15.625	37.895	437
CQ-12*	18.107	15.627	37.911	444
Galena in quartz veins and disseminated occurrences				
Silver Hill				
PS-10107	18.138	15.616	37.874	399
Silver Valley				
PS-10301	18.114	15.601	37.843	387
CQ-13*	18.118	15.615	37.884	412
CQ-14B*	18.107	15.609	37.859	408
CQ-15*	18.128	15.618	37.881	410

* Data from Kish and Feiss (1982).

TABLE 12

Galena lead isotope ratios from the Gold Hill district, central North Carolina. The parameters of Stacey and Kramers (1975) were used for model age calculations.

Sample no.	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Model age (m.y.)
Galena in massive sulfide				
Union Copper mine				
PS-10204	18.222	15.622	37.915	348
Silver Shaft				
PS-10601	18.207	15.622	37.904	359
Galena in quartz veins and disseminated occurrences				
Union Copper				
PS-10207	18.216	15.618	37.908	345
PS-10211	18.151	15.607	37.876	371
CQ-6*	18.228	15.628	37.930	356
Southern Copper				
CQ-4*	18.210	15.639	37.962	391
CQ-5*	18.198	15.625	37.912	372
Troutman				
CQ-17*	18.185	15.632	37.935	396
Silver Shaft				
CQ-7B*	18.214	15.625	37.919	360
CQ-16*	18.215	15.632	37.935	373

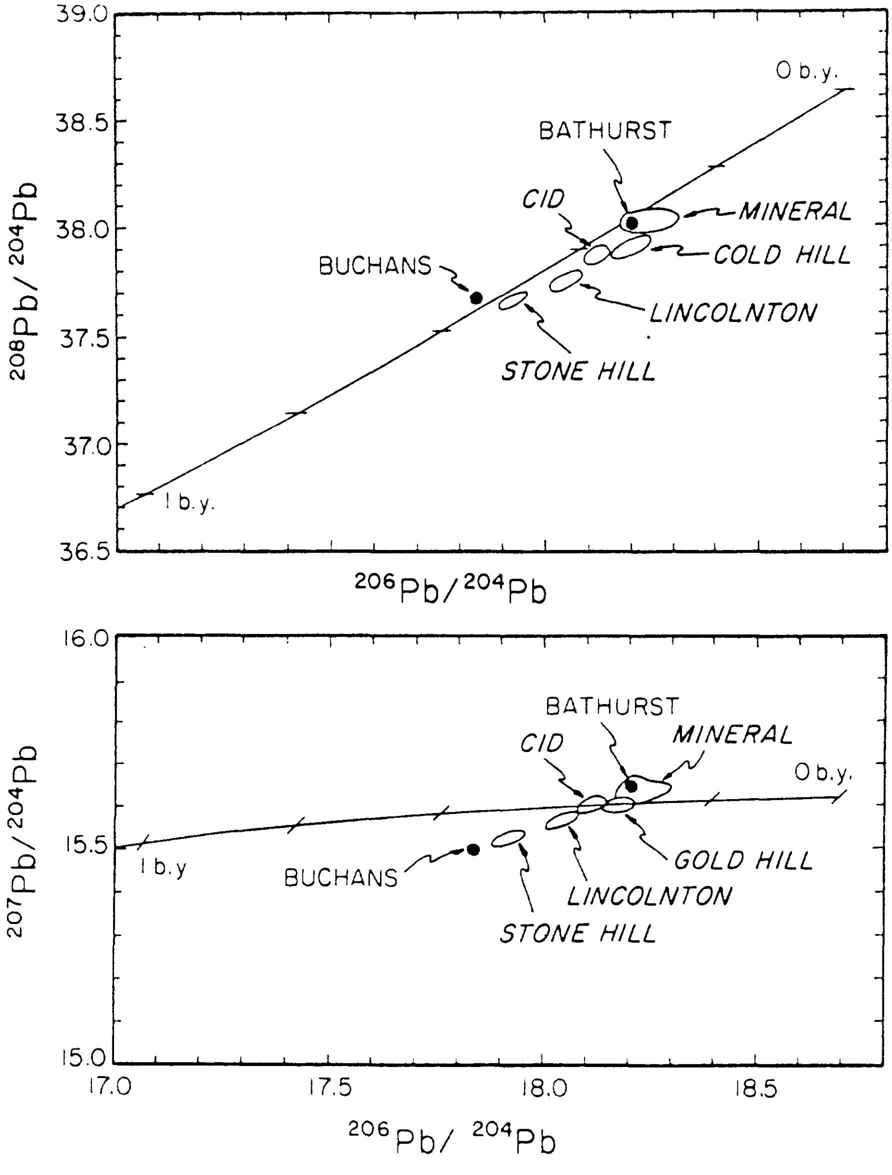
* Data from Kish and Feiss (1982)

^{204}Pb ratios between the two districts indicates a more radiogenic source of lead at Gold Hill. Lead is less common in Gold Hill ores and most of the galenas in Table 12 were found in quartz veins which may be metamorphic in origin. A radiogenic component possibly was added during metamorphic remobilization yielding more radiogenic lead (Kish and Feiss, 1982). Samples of Zn-Pb-rich massive ore from the Union Copper and Silver Shaft, however, have ratios indistinguishable from those found in many vein galenas (Table 12) suggesting that metamorphism had little effect on lead isotope composition.

Kish and Feiss (1982), proposed that lead in Cid and Gold Hill district sulfides was largely derived from the volcanic rocks of the underlying Uwharrie Formation. In their model, the radiogenic nature (relative to "model" Cambrian lead) of lead from both districts is accounted for by short-term growth in the volcanic pile.

Lead in the Cid and Gold Hill districts is less radiogenic than that in the Mineral district, Virginia (Fig. 35). Both the North Carolina and Virginia ores are in rocks of probable lower to middle Cambrian age, so the difference in lead ratios is probably not due to any significant difference in the ages of the ores. The lower ^{207}Pb/^{204}Pb ratios in the North Carolina galenas suggests that less upper continental material contributed lead to those deposits than was the case in Virginia. Deposits in rocks

Figure 35. Lead isotope ratio diagrams showing fields defined by Piedmont polymetallic massive sulfide district galena lead isotope ratios. Ratios from the Bathurst, New Brunswick, and Buchans, Newfoundland, deposits are included for comparison.


39.0
38.5
38.0
37.5
37.0
36.5
^{208}Pb/^{204}Pb
0 b.y.
1 b.y.
BATHURST
CID
MINERAL
COLD HILL
BUCHANS
LINCOLNTON
STONE HILL
^{206}Pb/^{204}Pb
16.0
15.5
15.0
^{207}Pb/^{204}Pb
BATHURST
MINERAL
CID
0 b.y.
1 b.y
BUCHANS
GOLD HILL
LINCOLNTON
STONE HILL
17.0
17.5
18.0
18.5
^{206}Pb/^{204}Pb

of similar age in the Lincolnton-McCormick district at the southwestern end of the Carolina slate belt contain lead that is still less radiogenic.

Lincolnton-McCormick district, Georgia and South Carolina

Carpenter *et al.*, (1982), found that Rb-Sr whole-rock and U-Pb zircon ages for the intrusive complex near Lincolnton, Georgia, and surrounding felsic volcanic units are in good agreement with ages from slate belt rocks in the area of the Cid and Gold Hill districts. The volcanic rocks of the central North Carolina slate belt have calc-alkaline geochemical characteristics (Seiders, 1978; Black, 1980), but those of the Lincolnton-McCormick area have island arc tholeiite affinities (Whitney *et al.*, 1978).

Carpenter (in Bell, Carpenter and Feiss, 1980), described mineralization in the Lincolnton-McCormick district as crosscutting and stratiform assemblages proximal to the felsic volcanic center represented by the so-called "Lincolnton metadacite". Mineralization was restricted to a quartz-sericite-rich pyroclastic sequence that developed adjacent to the volcanic center. A variety of mineralized assemblages are found in the district including stratiform barite deposits, manganiferous zones, and aluminosilicate alteration zones which are now represented by extensive kyanite (-andalusite-pyrophyllite) deposits. Sulfide mineralization includes pyrite-chalcopyrite "stringer" zones beneath exhaltive deposits and massive Zn-Pb-Cu and pyrite-quartz assemblages (Bell _et_ _al_., 1980).

Two lead isotope analyses of galenas from the Dorn and Magruder mines are presented in Table 13. Lead in these deposits is less radiogenic than that in central North Carolina and Mineral, Virginia, galenas (Fig. 35). Evidence cited above indicates that the volcanic rocks in the three areas are similar in age, so the differences in lead isotope composition are probably not a function of different times of mineralization. The relatively unradiogenic lead found in Lincolnton-McCormick district galenas suggests still less of an upper continental crustal lead component than in the other Piedmont massive sulfide districts considered so far, and supports Whitney _et_ _al_.'s (1978) conclusion that the Lincolnton area represents a more "primitive" island arc environment than other parts of the Carolina slate belt. Despite its relatively unradiogenic character, however, Lincolnton-McCormick lead resembles Mineral, Cid, and Gold Hill district lead in being too radiogenic relative to "model" Cambrian lead and therefore has model ages that are too young for the age of mineralization.

TABLE 13

Galena lead isotope ratios from the Lincolnton-McCormick district, Georgia and South Carolina. Model ages were calculated using the parameters of Stacey and Kramers (1975).

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Model age (m.y.)
Dorn mine, massive sulfide				
PS-20101	18.025	15.562	37.629	375
Magruder mine, disseminated sulfide				
PS-30101	18.077	15.581	37.696	374

Other slate belt deposits

Kish and Feiss (1982) reported three additional galena lead isotope ratios from deposits in the North Carolina slate belt, which are shown in Table 14. These are similar to ratios found in Gold Hill district deposits.

Sulfur isotopes in Carolina slate belt massive sulfides

A reconnaissance sulfur isotope survey of Carolina slate belt polymetallic massive sulfide deposits indicates a preponderance of ^{34}S-enriched sulfur (Table 15, Fig. 36). Sulfur in Cid and Gold Hill district sulfides appears to be slightly heavier than the average Mineral district, Virginia, values (see Fig. 25), and agrees well with the $\delta^{34}S$ value of Cambrian seawater sulfate. The $\delta^{34}S$ value of barite (= 27.0^{o}/oo) from the Lincolnton-McCormick district is in excellent agreement with Cambrian seawater sulfate, but the corresponding sulfide $\delta^{34}S$ ratios seem to be a little lower than predicted for seawater-derived sulfur. The proximity of these ores to the center of volcanic activity (Bell *et al*., 1980), suggests that a component of magmatic sulfur ($\delta^{34}S \simeq 0$) may be present in the sulfides resulting in relatively low values of $\delta^{34}S$.

TABLE 14

Galena lead isotope ratios from some other sulfide deposits of the North Carolina slate belt from Kish and Feiss (1982).

Sample no.	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Rocky River			
CQ-1	18.260	15.635	38.046
Moore mine, Blue Shaft			
CQ-2	18.244	15.642	37.958
CQ-3	18.247	15.646	37.971
Eldorado (Henderson) mine			
CQ-20	18.165	15.617	37.890

TABLE 15

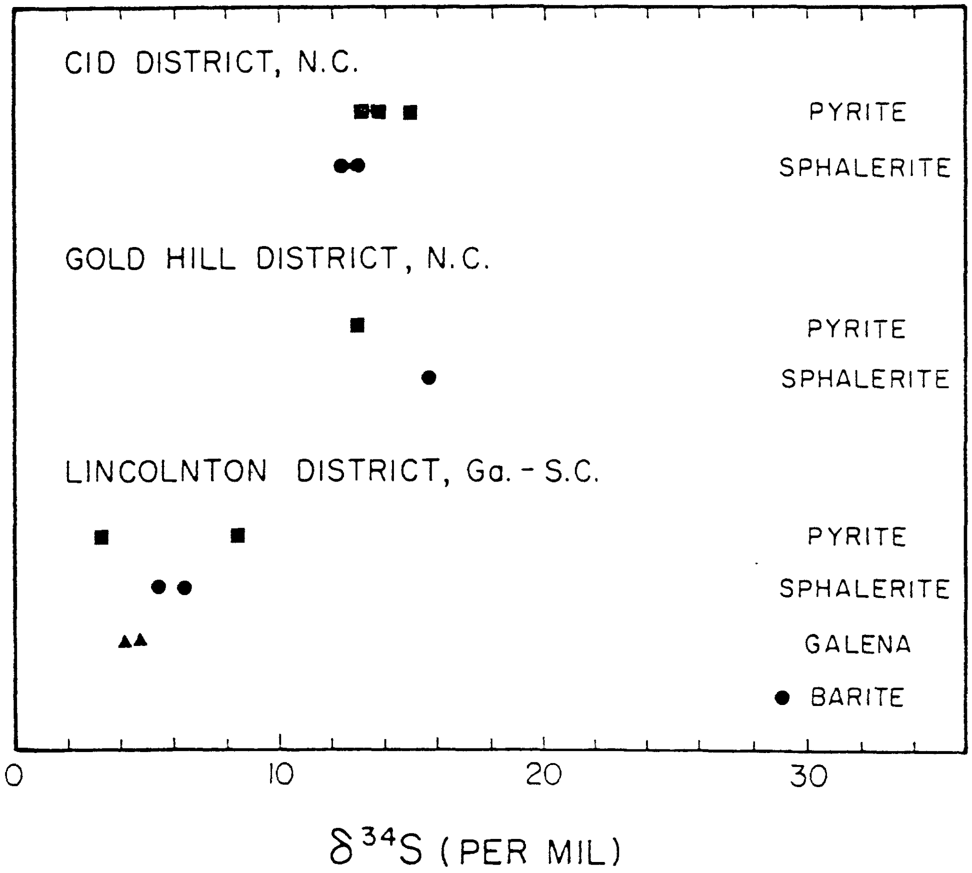
Sulfur isotope ratios of some sulfide minerals from Carolina slate belt polymetallic stratabound sulfide deposits. "Type" refers to massive (M) or disseminated (D) occurrence.

Sample no.	$\delta^{34}S_{py}$	$\delta^{34}S_{sp}$	$\delta^{34}S_{gn}$	$\delta^{34}S_{bar}$	Type
Cid district, North Carolina					
Silver Hill					
PS-10103	13.07				M
PS-10105	13.62				D
DK-65	14.95				M
DK-63	12.68				M
Silver Hill					
PS-10301		12.23			M
Gold Hill district, North Carolina					
Union Copper					
PS-10204	12.88				M
PS-10205		15.70			D
Lincolnton-McCormick district, Georgia and South Carolina					
Dorn deposit					
PS-20101		5.55	4.23		M
PS-20102	8.20				D
Magruder deposit					
PS-30101		6.44	4.79		D
Jennings deposit					
TC4-204-211	3.35				D

TABLE 15 (CONT.)

Sample no.	$\delta^{34}S_{py}$	$\delta^{34}S_{sp}$	$\delta^{34}S_{gn}$	$\delta^{34}S_{bar}$	Type
Lincolnton-McCormick district (continued)					
"Barite Hill"					
PS-21204	($\delta^{18}O_{bar}$ = 7.36^{o}/oo)			27.0	Massive barite

Figure 36. Sulfur isotope ratios in Carolina slate belt stratabound sulfide deposits.



CAROLINA SLATE BELT VOLCANOGENIC MASSIVE SULFIDE DISTRICTS

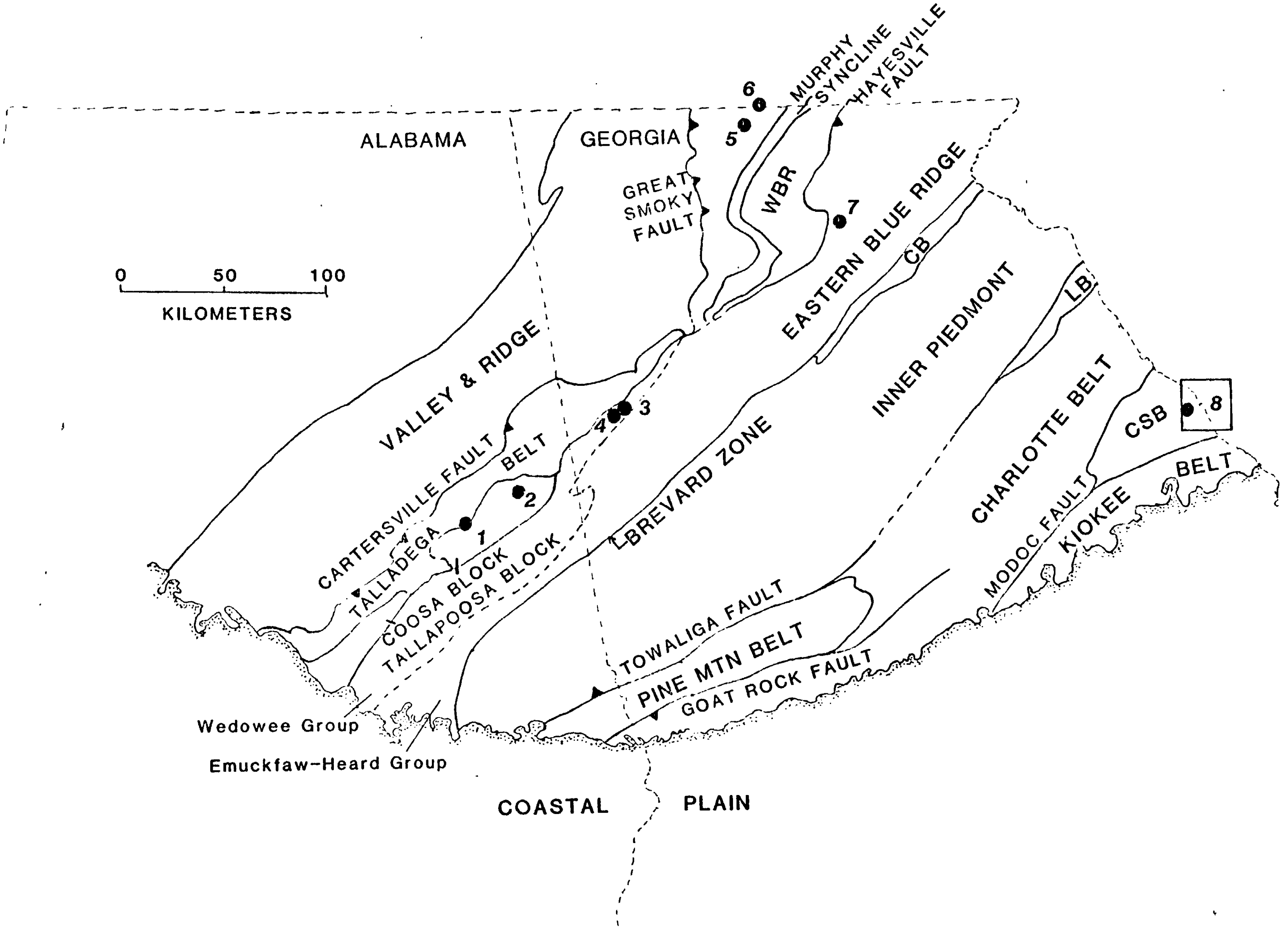
11. NORTHERN ALABAMA PIEDMONT

Geologic Relationships

The geology of the Alabama Piedmont northwest of the Brevard Zone ("Northern Alabama Piedmont" = NAP) has been summarized by Tull (1978) and Thomas et al. (1980). The NAP is generally subdivided into three major lithotectonic units (or blocks). These are the Talladega, Coosa, and Tallapoosa blocks (Fig. 37). The blocks correspond to metamorphic belts. The Talladega block comprises the lower greenschist facies Talladega belt and the Coosa and Tallapoosa blocks form the middle to upper amphibolite facies Ashland-Wedowee belt (Coosa = Ashland; Tallapoosa is part of the Wedowee belt). The two stratabound sulfide deposits sampled for lead isotope study, Pyriton and Stone Hill, are in the Talladega and Coosa blocks, respectively.

The Pyriton deposit occurs in the Hillabee greenstone, the uppermost stratigraphic unit in the Talladega belt. The stratigraphic interpretation of the Talladega by Tull (1978) and Tull and Stow (1982) indicates a Devonian age, based on a Devonian fossil assemblage found in the Jamison chert in the southwestern part of the belt. Russell (1978), however, found that zircons from a quartz dacit unit of the Hillabee

Figure 37. Index map of the Appalachians in Georgia and Alabama showing the locations of major lithotectonic units and of sulfide deposits (numbered). CSB - Carolina slate belt; LB - Lowndesville (= Kings Mountain belt ?) belt; WBR - Western Blue Ridge. 1. Pyriton; 2. Stone Hill; 3. Swift; 4. Little Bob; 5. Payne prospect; 6. Ducktown; 7. Dahlonega; 8. Lincolnton - McCormick district.


ALABAMA
GEORGIA
GREAT SMOKY FAULT
MURPHY SYNCLINE
HAYESVILLE FAULT
WBR
EASTERN BLUE RIDGE
CB
INNER PIEDMONT
LB
CHARLOTTE BELT
CSB
8
KIOKEE BELT
MODOC FAULT
VALLEY & RIDGE
CARTERSVILLE FAULT
TALLADEGA BELT
COOSA BLOCK
TALLAPOOSA BLOCK
BREVARD ZONE
TOWALIGA FAULT
PINE MTN BELT
GOAT ROCK FAULT
1
2
3
4
5
6
7
0
50
100
KILOMETERS
Wedowee Group
Emuckfaw-Heard Group
COASTAL
PLAIN

yielded nearly concordant U-Pb ages of about 450 m.y. Tull and Stow (1982), described the Hillabee as consisting of tholeiitic basalt containing 15% calc-alkalic quartz dacite near its base. Tull and Stow (1982) interpreted the Hillabee as a volcanic arc sequence developed over a thin continental crustal margin.

The Pyriton deposit is the largest and best known of the stratabound massive pyrite deposits within the Hillabee. It is a banded cupriferous pyrite ore with minor but ubiquitous sphalerite and rare galena and pyrrhotite. The enclosing rock is typical Hillabee tholeiitic (meta-) basalt (Stow and Tull, 1982).

The Stone Hill copper deposit is located in the Poe Bridge Mountain Group of the Ashland Supergroup in the northwest salient of the Coosa Block (Fig. 37). The boundary between the Talladega and Coosa block is the Hollins Line Fault. Tull (1978, p. 445) describes the Poe Bridge Mountain Group as "a distinctive sequence of interlayered, coarse-grained, graphitic feldspathic mica schists, quartzites, and amphibolites, presumably derived from a thick volcanic protholith."

The relationship of the three tectonic blocks of the NAP to each other and to the rest of the Appalachian system is a subject of controversy. The Hollins Line Fault separating the Talladega and Coosa Blocks has been interpreted as a steep metamorphic gradient across a normal stratigraphic succession with only local faulting (Neathery and Reynolds, 1973). More recently Tull (1978), has recognized the Hollins Line as a major tectonic feature which juxtaposes distinct rock sequences. Although there are discrepencies, fossil and isotopic evidence (discussed above), places age constraints on the Talladega Group. The Coosa Block, however, does not contain any known intrusives or other rocks amenable to common age-determination techniques capable of "seeing through" metamorphism. The Coosa Block (Ashland belt), is separated from the Tallapoosa Block (Wedowee belt), by the Goodwater-Enitachopco Fault system. Neathery and Reynolds (1973), suggested that the Poe Bridge Mountain and Wedowee Groups are correlative across the fault, but Tull (1978), disagrees. The Tallapoosa contains numerous intrusions including the batholith-size Elkahatchee Quartz (meta-) Diorite which has yielded a U-Pb zircon age of 516 m.y. and a Rb-Sr whole-rock age of 490 ± 26 m.y. (Russell, 1978).

The Coosa Block does not appear to extend north of the Alabama-Georgia border. The Talladega Block appears to terminate near Cartersville, Georgia. Part of the Tallapoosa Block continues into Georgia and has been correlated with the Ashe-Alligator Back sequence of the eastern Blue Ridge of North Carolina (Hurst, 1973). Thomas _et al_.,

(1980) believe that this part of the Tallapoosa is correlative with the Coosa Block sequence. If this scenario is correct, the age of Coosa-Tallapoosa rocks is late Precambrian, coeval with the clastic sedimentary sequences of the Blue Ridge.

Espenshade (1963), and Whittington (1980), described the Stone Hill copper deposit as conformable massive and disseminated sulfides in amphibolite. Whittington (1980), noted that mineralization is restricted to an amphibole-bearing quartz-muscovite schist lense enclosed within the amphiholite. He interpreted this as a felsic volcanic layer in the mafic unit which has ocean-floor tholeiitic basalt geochemical affinities. The ore consists of pyrrhotite with minor chalcopyrite and traces of sphalerite, pyrite, and galena.

From the above discussions it may seem as though sulfide deposits of the NAP would more logically be considered with those of the Blue Ridge. NAP ores resemble Ducktown-type ores mineralogically and in inferred tectonic setting more than they do Piedmont massive sulfide deposits. They are included in this section for the purpose of discussion of isotopic relationships which may or may not be coincidental. Given the ambiguous nature of geologic relationships at the southern end of the Appalachians, consideration of the possibilities seems reasonable. The

Alabama ores are unambiguously associated with (mafic) volcanic rocks, a situation that does not obtain in many Ducktown-type deposits in the Blue Ridge.

Results of lead isotope studies

Two galenas from Zn-Pb-rich pods in Stone Hill massive ore were analyzed for lead isotope composition. Additionally, whole-rock and "whole-ore" U, Th, and Pb concentrations and lead isotope compositions were determined for a sample of amphibolite from Stone Hill and of Pyriton ore. The results are tabulated in Table 16.

Galena from Stone Hill has the least radiogenic combination of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios found in this study. This result is not surprising given the proposed late Precambrian(?) age of the ore and host rocks. A large discrepancy exists, however, between the proposed age and the lead model age, which is a reflection of lead isotope compositions that are much too radiogenic for a late Precambrian ore.

The problem is compounded by $^{206}Pb/^{204}Pb$ ratios that are too high, whereas $^{207}Pb/^{204}Pb$ ratios are low. Amphibolite with tholeiitic chemical affinities and zones of hydrothermal alteration encloses the sulfide-bearing felsic unit (Whittington, 1980). A thermal cell circulating through the mafic material should be reflected in the lead

TABLE 16

Galena (gn) and whole-rock (WR) lead isotope ratios and whole-rock U, Th and Pb concentrations of ore and rocks of the Stone Hill and Pyriton deposits, Alabama.

Sample no.	Type	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Pb	U	Th	$\frac{^{238}U}{^{204}Pb}$	$\frac{^{232}Th}{^{238}U}$	$\frac{^{232}Th}{^{204}Pb}$	Model age (m.y.)
					(----ppm-----)						
Pyriton											
BS-40101	WR	17.933	15.550	37.722	185	.464	.582	0.156	1.30	0.203	421
Stone Hill											
MO-3	gn	17.919	15.525	37.644							380
MO-9	gn	17.942	15.532	37.670							377
DK-60	WR	19.170	15.636	38.602	1.15	.166	.506	9.28	3.15	29.2	

Sample no.	$\delta^{34}S_{py}$	$\delta^{34}S_{po}$
Pyriton		
BS-40101	3.24	
Stone Hill		
DK-61		5.70

isotopic composition - and it apparently is, in the low $^{207}Pb/^{204}Pb$ ratios. A very thick pile of schist, stratigraphically below the volcanic sequence containing the deposit, has been interpreted as upper Precambrian clastic sediments (Tull, 1978). Such sediments could very well have a high U/Pb ratio. A significant contribution of lead by the sedimentary pile to the mineralizing hydrothermal cell would provide a highly radiogenic source, which, when modified by a component from mafic volcanics could produce the observed ratios. The ^{207}Pb contribution from a highly radiogenic source would have been minimal because the production of ^{207}Pb from the decay of parent ^{235}U was low by late Precambrian time. It would, therefore, have had a minimal diluting effect when mixed with lead from other sources. This model is more compatible with a submarine hot spring, perhaps in a rift zone, than with volcanic exhalative origin in an orogenic arc, and is more consistent with the relative scarcity of igneous protoliths in the Coosa Block (Tull, 1978).

Comparison of the Stone Hill galena data with ratios obtained from the Silurian (?) Buchans deposit of central Newfoundland is revealing (Fig. 36). The Buchans data are thought to represent substantial contributions of oceanic mantle lead (Doe and Zartman, 1979). If this is the case, the comparison indicates that although Stone Hill is enclosed in mafic volcanic rock, significant non-oceanic lead is present that results in more radiogenic lead in a late Precambrian(?) galena than in a Silurian ore.

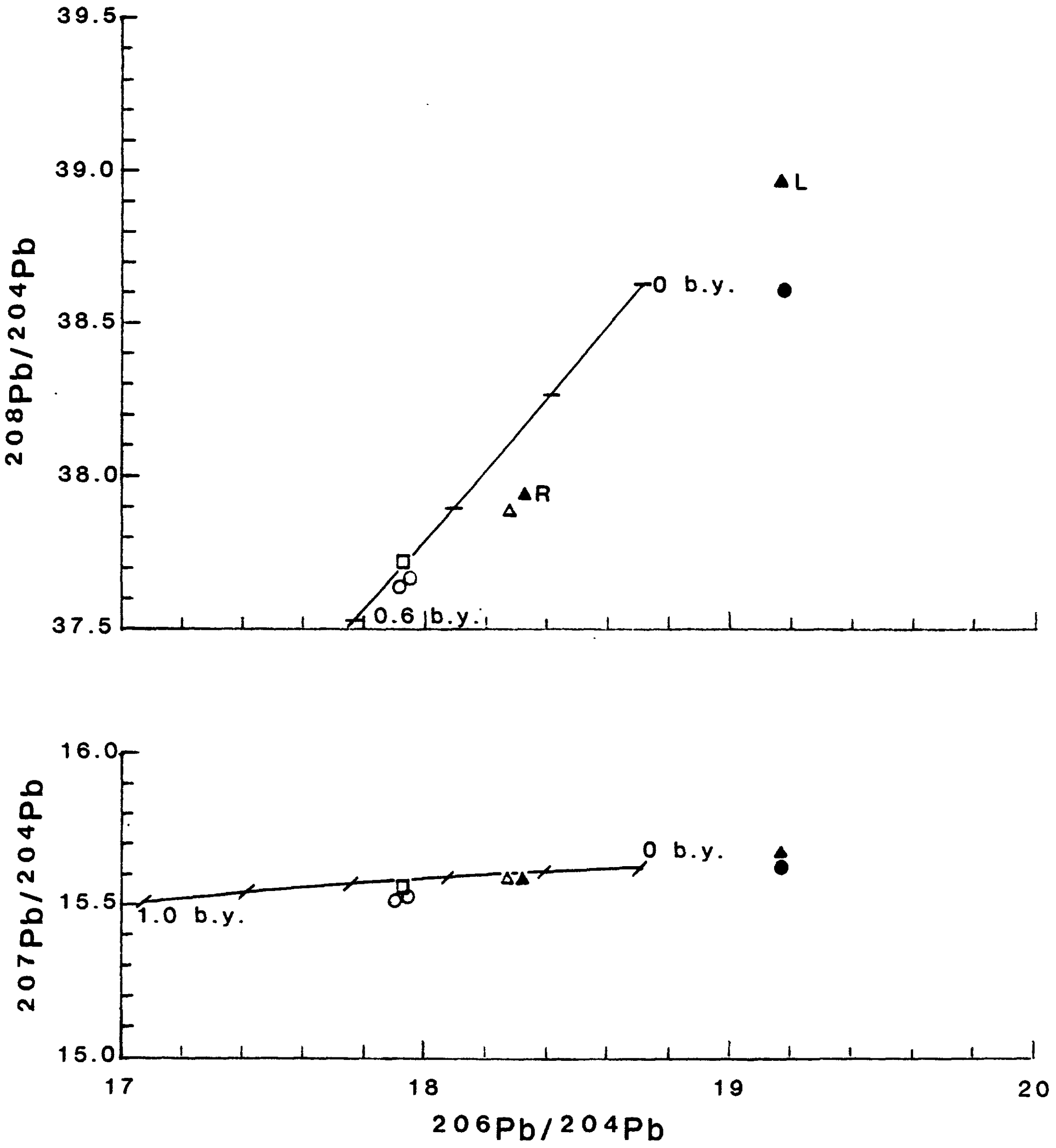
The isotopic composition of lead in a "whole-ore" sample from Pyriton is similar to that in Stone Hill Table 16). Pyriton lead may have slightly higher $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios. Using the concentrations of U, Th, and Pb in the ore (Table 16) to correct for lead isotope growth from radioactive decay since the Devonian and since late Precambrian time does not significantly alter any of the ratios because of the low U/Pb and Th/Pb ratios.

The similarity between lead in Stone Hill and Pyriton may be coincidental or it may have some genetic implications. One possibility is that the mafic igneous activity represented by Poe Bridge Mountain amphibolites and by the Hillabee greenstone is the same event, which has undergone subsequent tectonic complications and differential metamorphism. If this is the case then Neathery and Reynolds' (1973) suggestion of stratigraphic correlation across the Hollins Line Fault would be at least partially correct. Further work is needed to clarify field, age, and isotopic relationships, however, before the lead isotopic similarity between Stone Hill and Pyriton can be interpreted with confidence.

Whole-rock analysis of amphibolite from Stone Hill shows low U, Th, and Pb concentrations (Table 16) which is typical of mafic rocks. The isotopic composition of lead in the sample is radiogenic due to in situ decay of uranium and thorium (Fig. 38). If we assume closed system behavior of U, Th, and Pb since the time of original deposition and if the lead isotopic composition of galena from Stone Hill is assumed to represent the original isotopic composition of the rock, we can make age calculations for the amphibolite similar to those applied to U-Th-Pb zircon systems. U-Pb ages for such calculations are too old and highly discordant: $^{206}Pb/^{238}U \simeq 815$ m.y.; $^{207}Pb/^{235}U \simeq 990$ m.y.; $^{207}Pb/^{206}Pb \simeq 1400$ m.y. This discordance is probably an effect of uranium redistribution, probably during metamorphism. The $^{208}Pb/^{232}Th$ age ($\simeq 650$ m.y.), however, is a reasonable late Precambrian age and falls within the age range of late Precambrian igneous activity in the Blue Ridge of North Carolina and Virginia (Odom and Fullagar, 1982). This single determination from a highly metamorphosed rock does not clarify the actual age of the system, but may indicate that an investigation of Th-Pb systematics in the Coosa Block could prove fruitful.

A regression through the Stone Hill amphibolite and galena lead isotope compositions has a slope of 0.0868 ± 0.0137 (2σ). Calculations of secondary isochron ages (using Stacey and Kramers' (1975) model) yields a source age of about 1.1 b.y. when 400 m.y. (lower Devonian) is used as an age of mineralization. When the latter is increased to 600 m.y., the lower intercept is about 920 m.y. These figures may indicate the influence of Grenville-age basement rocks on the system. The low $^{207}Pb/^{204}Pb$ ratios, however, indicate that a significant portion of the lead had a long-term history of low U/Pb ratios.

Figure 38. Lead isotope ratio diagrams illustrating ratios of galenas (○) and amphibolite (●) from Stone Hill, Alabama, and whole-ore analysis (□) from Pyriton, Alabama. Stone Hill occurs in an amphibolite unit of the Ashland Supergroup and Pyriton lies within the Hillabee greenstone in the Talladega belt. The Little Bob (△) and Swift (▲) mines occur in the Wedowee Supergroup in Georgia, which may be partially correlative with the Ashland. Pyrite was the mineral analyzed from Swift, as HCl-soluble (L) and -insoluble (R) fractions.


39.5
39.0
38.5
38.0
37.5
208Pb/204Pb
L
R
0 b.y.
0.6 b.y.
16.0
15.5
15.0
207Pb/204Pb
0 b.y.
1.0 b.y.
17
18
19
20
206Pb/204Pb

12. A MODEL FOR THE PATTERN OF LEAD ISOTOPES IN PIEDMONT POLYMETALLIC STRATABOUND SULFIDE DEPOSITS

In the samples analyzed from the massive sulfide deposits of the central Virginia plutonic-volcanic belt, the Carolina slate belt, and Stone Hill, Alabama, galena is a significant constituent. Metamorphic effects are not usually discernable in the isotope ratios of deposits containing significant amounts of lead, especially when a relatively short time interval (100 to 200 m.y. for the Virginia and slate belt deposits) separates deposition from metamorphism. Therefore, the consistently young model ages observed in these deposits are probably not an effect of metamorphism but of radiogenic lead contributed by upper continental material in decreasingly ensialic arc volcanism from northeast to southwest.

As illustrated in figure 39, a plot of $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ values obtained for Piedmont massive sulfide deposits defines a line with a slope of 0.3987 which, using the parameters of Stacey and Kramers (1975) and assuming an age of mineralization of 550 m.y., corresponds to a secondary isochron age of 3.7 ± 0.25 b.y. (2σ). The line cannot actually be an isochron, by definition, if the points include deposits of differing ages and so may be

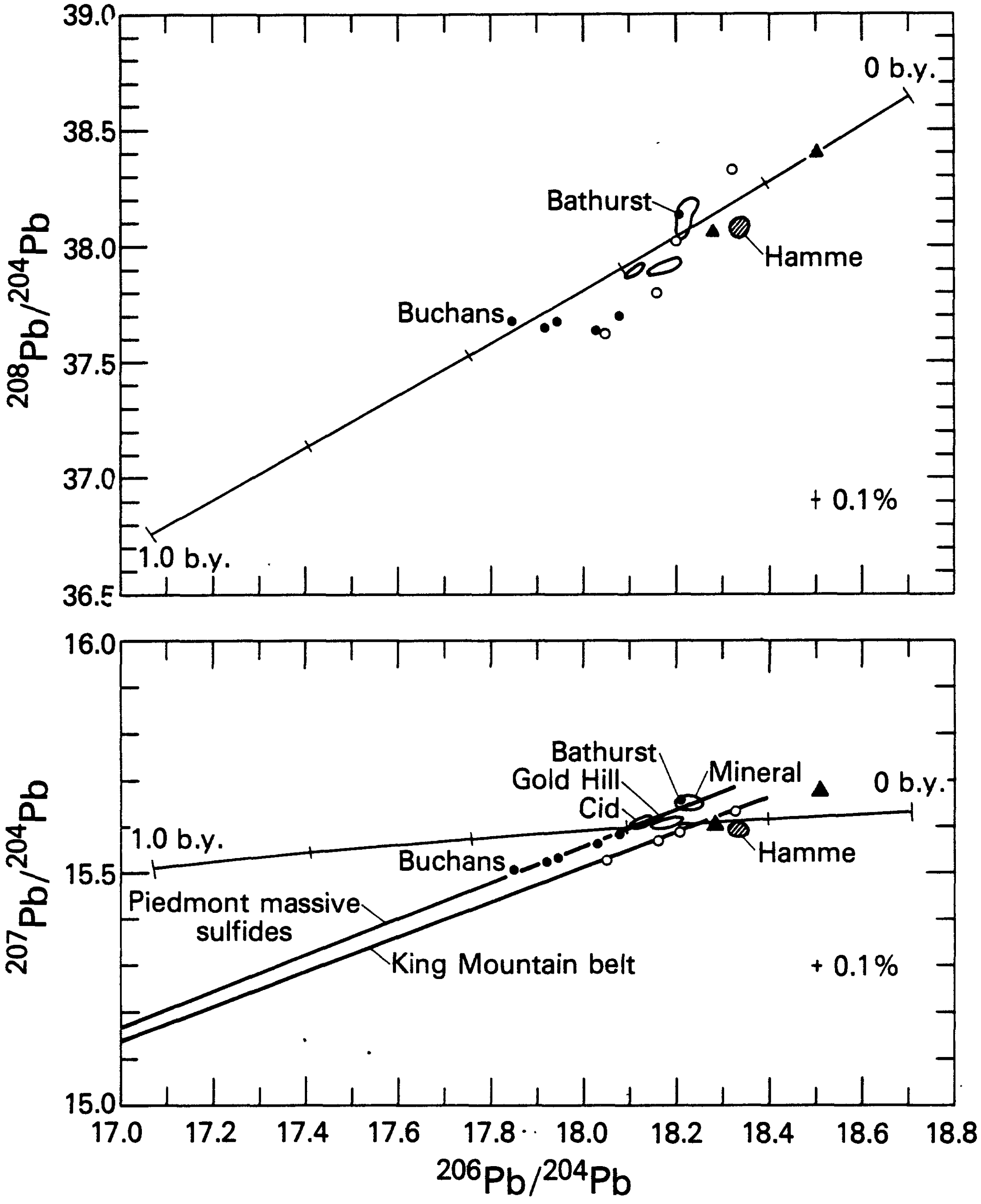

39.0
38.5
38.0
37.5
37.0
36.5
$^{208}Pb/^{204}Pb$
0 b.y.
Bathurst
Hamme
Buchans
+ 0.1%
1.0 b.y.
16.0
15.5
15.0
$^{207}Pb/^{204}Pb$
Bathurst
Gold Hill
Mineral
Cid
0 b.y.
1.0 b.y.
Buchans
Hamme
Piedmont massive sulfides
King Mountain belt
+ 0.1%
17.0
17.2
17.4
17.6
17.8
18.0
18.2
18.4
18.6
18.8
$^{206}Pb/^{204}Pb$

Figure 39. Secondary isochron regressions through lead isotope compositions of Mineral district, Carolina slate belt, and Stone Hill, Alabama, galenas and through the Kings Mountain belt data (○). Data points from the Lincolnton - McCormick district and Stone Hill are represented by ● . Galena lead isotope ratios from the Hamme tungsten district and the Virginia gold-pyrite belt (▲) are also shown.

more properly referred to as an apparent or "pseudo-isochron". There are two possibilities: The line may be fortuitous, or it may be reflective of a real relationship between deposits of the Piedmont.

Accepting a late Precambrian age for the Stone Hill deposit makes the lead isotopic composition of its galena highly anomalous, with a model age discrepancy much greater than those of slate belt and Mineral leads. In this case the line is probably fortuitous. The same applies if the lead isotopic composition has been affected by metamorphic processes. Most intriguing, however, is that galena analyzed from Buchans, Newfoundland (Doe and Zartman, 1979), which was not used in regression calculations, also falls on the line (Fig. 39).

If the line reflects a real relationship between sources of lead of the various deposits, then an upper Precambrian Stone Hill deposit is difficult to accept. U/Pb ratios were calculated for the observed lead isotopic compositions (Table 17) from the 3.7 b.y. event of Stacey and Kramers (1975), assuming a mineralization age of 500 m.y. for all the Piedmont massive sulfides. The U/Pb ratios decrease from northeast (Mineral, Virginia), to southwest (Stone Hill, Alabama). A possible explanation for the pattern is a source of regional dimensions with homogeneous average lead isotope composition and a low U/Pb value, such as depleted lower crust or mantle, mixing with vary-

TABLE 17

$^{238}U/^{204}Pb$ (μ) calculated for galena lead isotope ratios of Piedmont massive sulfide deposits. μ was calculated from the 3.7 X 10^9-yr differentiation event of Stacey and Kramers (1975) and assumed a minimum age of mineralization of 500 m.y. for all deposits.

District/ mine	μ	Comment
Mineral	10.2	Massive ore
Cid		
Silver Hill	10.1	Massive ore
Silver Valley	10.0	Massive ore
Gold Hill		
Union Copper	10.2	Massive ore
Silver Shaft	10.2	Massive ore
Lincolnton-McCormick		
Dorn	9.89	
Magruder	9.97	
Stone Hill	9.77	Sample MO-9
	9.74	Sample MO-3

ing amounts of continental crustal material which has higher average U/Pb ratios. At the time of ore formation such a source would have had a lead isotope ratio which would plot on the trend defined by Piedmont massive sulfide galena lead. Contamination of lead from the low U/Pb source area by varying amounts of orogenically mixed upper crustal lead would produce the steep slope of the apparent isochron. The decrease of galena lead isotope ratios from northeast to southwest indicates a decreasing contribution of upper crustal lead to the ore-forming systems.

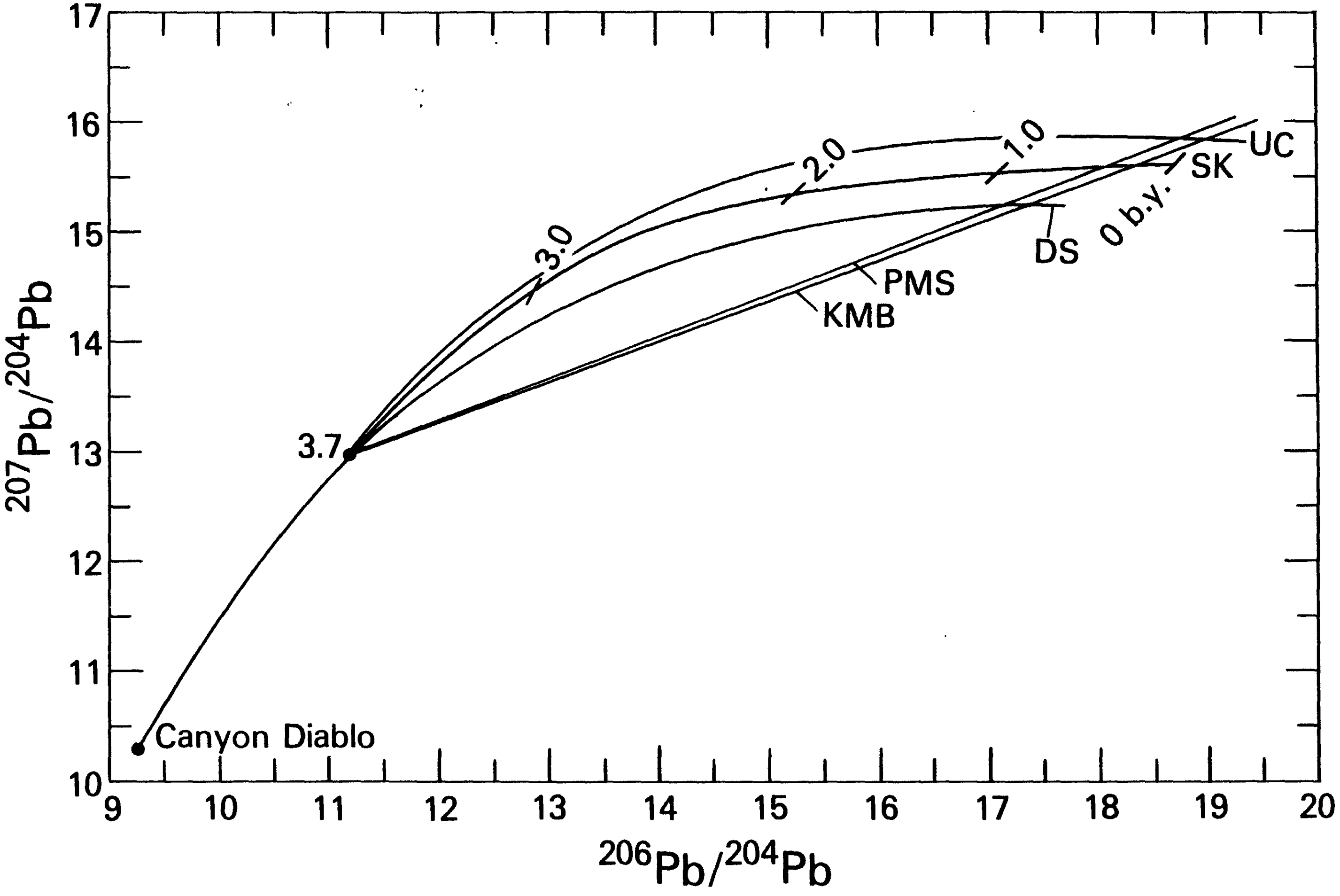
All of the galenas analyzed from Piedmont massive sulfide deposits yield model lead ages that are too young for their known or presumed ages of formation. In order for all model lead ages to come out young, there must have been an intermediate event(s) between 3.7 b.y. and the age of mineralization that added uranium relative to lead for all source rocks. High U/Pb ratios are inherent in upper continental crustal rocks (Doe and Zartman, 1979). In the hypothetical U/Pb depleted source area this may have been one or more discrete events of uranium gain/lead loss or a continuous process of U/Pb increase, analogous to the model proposed by Cumming and Richards (1975), for that part of the earth as a whole which contributed to ore formation. Tatsumoto (1978), proposed that U/Pb in the mantle has been steadily increasing due to deep earth differentiation processes. Secular increase in U/Pb ratios in depleted lower continental crustal rocks have not been observed. Doe and Zartman (1979), reported that U/Pb ratios in lower crust regimes generally appear to decrease.

Figure 40 diagramatically illustrates the evolution of lead in a U/Pb-depleted source (DS) which has undergone continuous increase in U/Pb since 3.7 b.y. ""UC" in figure 42 represents an average evolution curve for lead in upper continental material contributing to lead in the sulfide deposits. ""UC" also is represented as having been continuously enriched in uranium relative to lead.

U/Pb values calculated for a minimum age of 500 m.y. (Table 17) reflect the enrichment necessary to produce the observed lead isotope compositions. Stacey and Kramers' (1975), average lead evolution curve (SK on figure 42) has U/Pb = 9.74 from 3.7 b.y. to the present. The same value is necessary to produce the lowest ^{206}Pb/^{204}Pb ratio observed (Stone Hill, Alabama), in a system that remained closed with respect to uranium and lead from 3.7 b.y. to 500 m.y. The low ^{207}Pb/^{204}Pb ratio, however, indicates a source with U/Pb substantially less than 9.74 during much of its early history when ^{207}Pb was being produced at a greater rate from the decay of ^{235}U.

On a ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb diagram (Fig. 35) the Mineral district and Carolina slate belt massive sulfides form a consistent trend and show the same decrease to the southwest in ^{208}Pb as is seen in ^{207}Pb and ^{206}Pb.

Figure 40. Diagramatic illustration of the evolution of lead in a U/Pb-depleted source area which has undergone continuous increase in U/Pb since 3.7 b.y. (DS). UC is an upper continental crustal growth curve which has also had an increase in U/Pb. SK is the Stacey and Kramers (1975) average growth curve.


17
16
15
14
13
12
11
10
9
10
11
12
13
14
15
16
17
18
19
20
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$
Canyon Diablo
3.7
3.0
2.0
1.0
0 b.y.
UC
SK
DS
PMS
KMB

Stone Hill, however, deviates slightly from this trend. This indicates that the source of lead at Stone Hill had a different Th/U ratio than the source(s) of the Virginia and slate belt ores. The general decrease in $^{208}Pb/^{204}Pb$ from northeast to southwest indicates that the depleted source also had a low Th/U ratio.

Large scale isotopic uniformity, however, is not observed in crustal rocks and recently evidence has been accumulating for both large and small scale inhomogeneity in the mantle (see e.g. Dawson _et_ _al_., 1980; Dupre and Allegre, 1980). The linearity observed in much of the lead isotope data from young oceanic volcanics suggests that the inhomogeneities are non-random (Tatsumoto, 1978). An apparent isotopic homogeneity may be achieved through the averaging effects of sampling large columes of similar material during partial melting or hydrothermal cell circulation, much as mixing of crustal components (upper and lower continental crust and mantle) produces an average lead evolution curve in Doe and Zartman's (1979) plumbotectonics model.

A widespread and long-lived depleted source region is also indicated by the preponderance of relatively primitive initial $^{87}Sr/^{86}Sr$ ratios in plutonic rocks of all ages in the southern Piedmont (Fullagar, 1971; Fullagar and Butler, 1979), and by the ^{18}O depletion found in post-orogenic granites of the Carolina slate and Charlotte belts (Wenner, 1981).

Vitrac et al., (1981), also found that lead in K-feldspars from Hercynian (Alleghanian) granitic plutons around the North Atlantic basin have an averaged trend with a slope which corresponds to a secondary isochron age of about 3.8 b.y. This may also be attributable to mixing of the depleted source(s) with upper crustal material. If so, it indicates that the depleted source(s) was active over a very large area and had remarkably uniform average lead isotope composition.

The validity of the 3.7 b.y. trend in the southern Appalachians is reinforced by the occurrence of a second, albeit less well documented, linear regression giving similar results for galenas from Kings Mountain belt deposits.

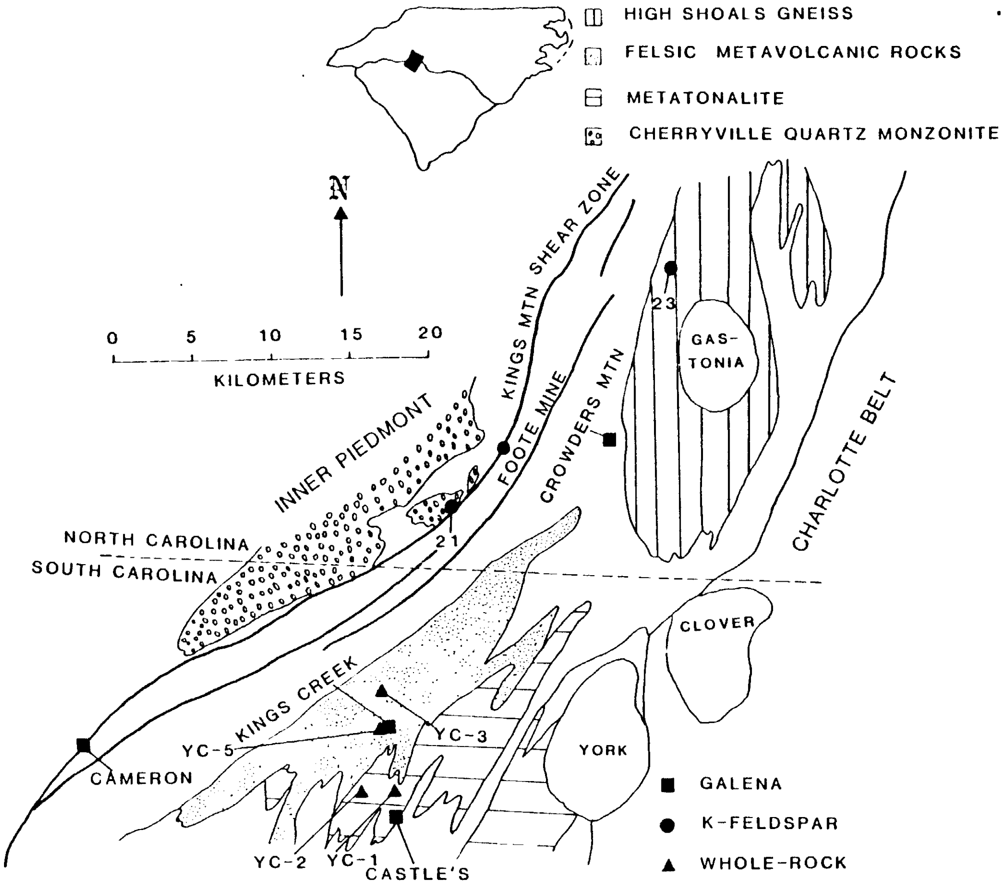
13. THE KINGS MOUNTAIN BELT AND THE PIEDMONT MODEL

The Kings Mountain belt of King (1955) is a problematical area of distinctive stratigraphy including metamorphosed quartzites, conglomerates, and marble as well as metavolcanic and plutonic units. It has been variously interpreted as a synclinal infolding of younger rocks (Overstreet and Bell, 1965; Hatcher, 1972), a cataclastic zone (Griffin, 1971) and as a large north-plunging antiform (Horton and Butler, 1977, 1981). It is not known to contain significant sulfide mineralization, but it is notable for the variety of its mineral deposits (Horton and Butler, 1977, 1981).

The Kings Mountain belt (KMB) lies between the Inner Piedmont on the northwest and the Charlotte belt on the southeast (Fig. 41). The flanking belts have been generally raised to a higher metamorphic grade than the KMB, which contains a zone of greenschist to epidote-amphibolite facies metamorphism (Horton, 1981a; Gregory, 1981).

Horton (1981a and b) showed that the Kings Mountain shear zone separating the Inner Piedmont and KMB is a profound discontinuity. Lithologies and structural styles differ across the shear zone. Metamorphic isograds are truncated at the boundary. Horton (1981b) and Milton (1981)

Figure 41. Geologic map of the Kings Mountain belt showing sample locations. 21 and 23 are APL81-21 and APL81-23, respectively, on table 19. The more or less circular areas are the York, Clover, and Gastonia late orogenic plutons. After Horton (1981a).


HIGH SHOALS GNEISS
FELSIC METAVOLCANIC ROCKS
METATONALITE
CHERRYVILLE QUARTZ MONZONITE
N
0
5
10
15
20
KILOMETERS
INNER PIEDMONT
KINGS MTN SHEAR ZONE
FOOTE MINE
CROWDERS MTN
21
23
GAS-TONIA
CHARLOTTE BELT
NORTH CAROLINA
SOUTH CAROLINA
CLOVER
YORK
KINGS CREEK
YC-5
YC-3
YC-2
YC-1
CASTLE'S
CAMERON
GALENA
K-FELDSPAR
WHOLE-ROCK

noted that the boundary of the KMB and the Charlotte belt is arbitrary in certain areas and that lithologies in the two are similar. They suggested that the belts are sedimentary and volcanic-plutonic parts of the same terrain. Milton (1980), noted the similarities between the Kings Mountain and Carolina slate belts and proposed that the Charlotte belt is the plutonic core of the flanking sequences.

Age relationships in the Kings Mountain belt

Horton and Butler (1977), and Horton (1981a), interpret the stratigraphy of the western portion of the Kings Mountain belt as a sequence of dacitic to andesitic metavolcanic rocks interlayered with and grading upward into quartz-sericite schist. The schist is believed to be mixed sedimentary and altered pyroclastic material (Horton, 1981a). This sequence grades vertically into predominantly metasedimentary rocks, including high-alumina quartzite and quartz-pebble conglomerates.

The metavolcanic sequences are intruded by biotite metatonalite, interpreted by Murphy and Butler (1981), as shallow sills and plugs intruding their own volcanic ejecta. Horton (1981a), reported that preliminary U-Pb zircon data indicates a late Precambrian age for the metatonalite. Other igneous rocks of the lower sequence include metamorphosed trondhjemite, gabbro and diorite.

Horton (1981a, p. 10), describes the "High Shoals" gneiss as a "coarse-grained, porphyritic, gneissic biotite granite or granitic gneiss that occupies an area of batholithic size within the Kings Mountain belt". Although there has been some speculation that the "High Shoals" is a Grenville-age gneiss and that the Kings Mountain belt occupies a position analagous to the Pine Mountain belt of Georgia and Alabama (which contains Grenville-age gneisses), paleomagnetic data indicates a post-Taconic age (Brown and Barton, 1980).

Two magnetic and size fractions of zircon from the "High Shoals" give concordant U-Pb ages of about 320 m.y. (Table 18, Fig. 42). This age puts the "High Shoals" in the range of ages found in late orogenic plutons (±300 m.y.) of the southern Appalachians. The late orogenic York and Clover plutons (Fig. 41) are unfoliated, as is the Gastonia pluton which is wholly enclosed by the "High Shoals".

Three magnetic and size fractions of zircon from the "schist of Kings Creek" (Murphy and Butler, 1981), and one from the metatonalite (Table 18), indicate a complex history. The smallest size fraction from schist unit (YC-5c-325) is essentially concordant and indicates an age of about 470 m.y. (Table 18, Fig. 43). Magnetic and non-magnetic splits of a larger size fraction, however, are dis-

TABLE 18

Results of U-Pb analyses of zircons from the Kings Mountain belt, North and South Carolina. NM = non-magnetic fraction; M = magnetic fraction. Mesh size in parentheses (+ = "greater than"; - = "less than").

Sample no.	Pb	U	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$
	(---ppm---)		(------------atom percent--------)				(------age (m.y.)------)		
"High Shoals" gneiss*									
K77-27 (+100)NM	59.8	1129	0.0107	84.25	4.606	11.13	325	325	321
(-325)M	18.3	289	0.2117	72.92	6.943	19.93	319	319	317
"Schist of Kings Creek"#									
YC-5(-325)	32.7	280	0/3657	61.77	8.795	29.07	465	466	471
YC-5 (-200, +250) NM	18.7	176	0.7791	47.87	13.88	37.47	263	269	316
M	31.9	324	0.1780	66.95	6.558	26.31	453	476	586
Metatonalite#									
YC-1	43.6	421	0.0115	76.05	4.769	19.17	563	575	623

* Lead isotope composition of K-feldspar (APL81-23, Table 20) used for common lead correction.

\# Isotope composition of Kings Creek barite mine galena (Table 19) used as correction.

Figure 42. Concordia diagram for "High Shoals" gneiss zircons. Sample numbers as in table 18.

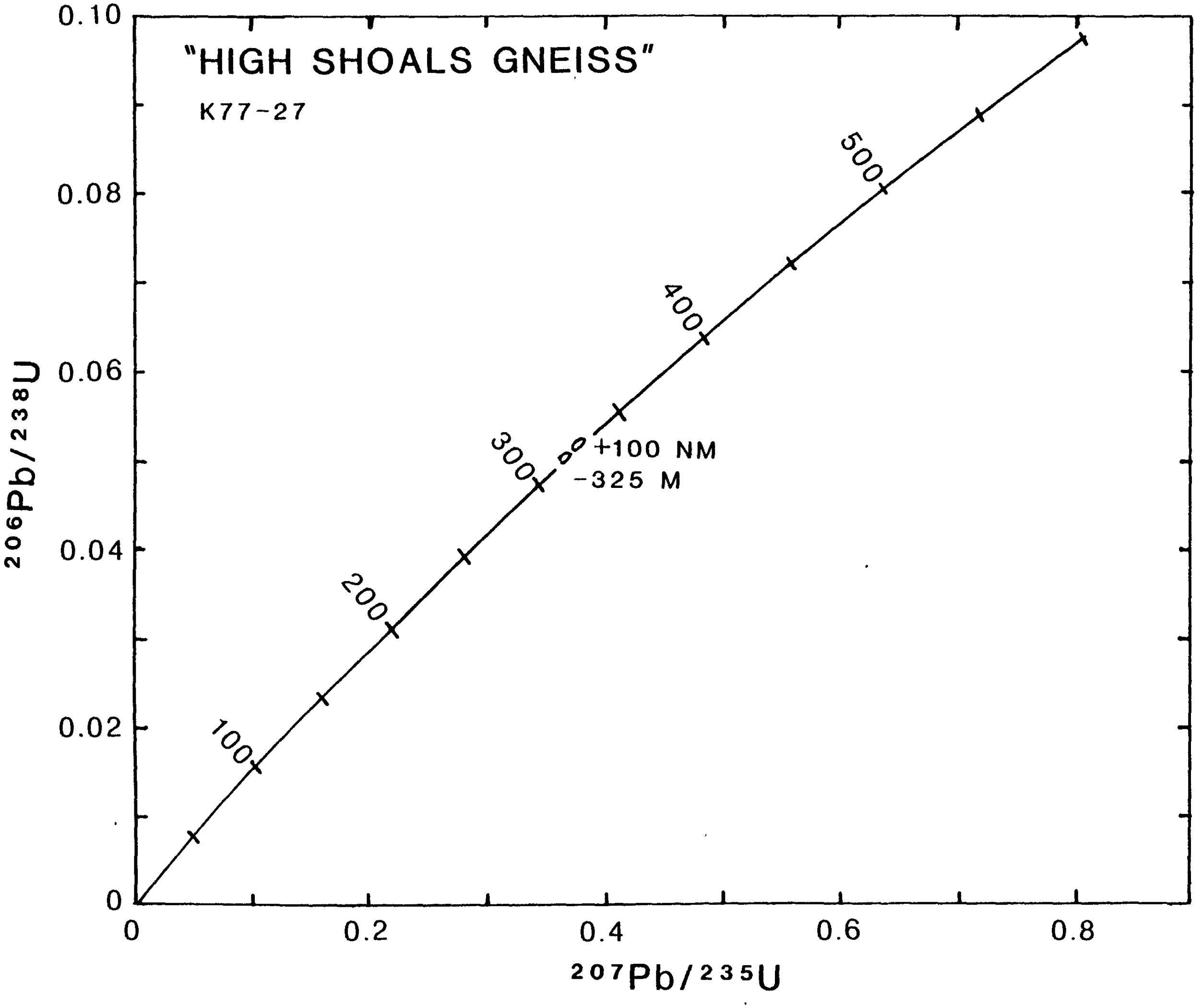
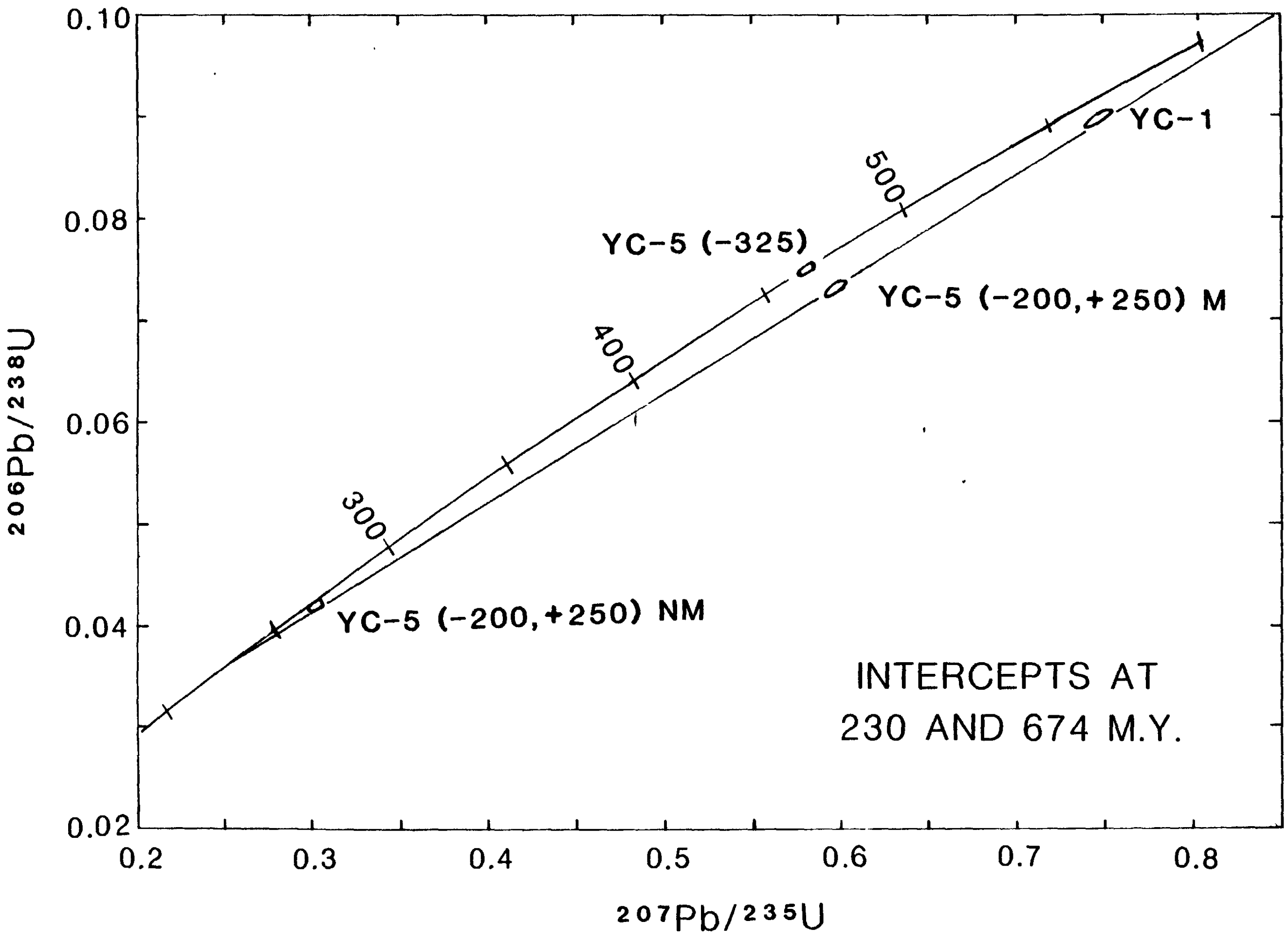

"HIGH SHOALS GNEISS"
K77-27
100
200
300
400
500
+100 NM
-325 M
0.10
0.08
0.06
0.04
0.02
0
0.2
0.4
0.6
0.8
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

Figure 43. Concordia diagram for zircons from the "Schist of Kings Creek" (YC-5) and from the metatonalite (YC-1). Sample numbers as in table 18.


0.10
0.08
0.06
0.04
0.02
206Pb/238U
0.2
0.3
0.4
0.5
0.6
0.7
0.8
207Pb/235U
300
400
500
YC-1
YC-5 (-325)
YC-5 (-200,+250) M
YC-5 (-200,+250) NM
INTERCEPTS AT
230 AND 674 M.Y.

cordant and yield opposing age information. The non-magnetic fraction gives U-Pb and Pb-Pb ages that are much younger than 470 m.y. whereas the Pb-Pb age of the magnetic fraction indicates an older age (Table 18, Fig. 43). The single analysis of zircon from the metatonalite is also discordant and indicates an even older age. A cord drawn through the three discordant fractions intersects concordia at 674 and 230 m.y.

Fullagar and Kish (1981), report a Rb/Sr mineral and whole-rock age of 299 ± 3 m.y. (1σ) for the Gastonia. The Cherryville quartz monzonite and a spodumene pegmatite district lie on the Inner Piedmont side of the Kings Mountain belt. They have Rb/Sr whole-rock ages of 340-350 m.y. (Kish, 1977, and written communication, 1982). Horton (1981a), believes that an outlier of the Cherryville lies partly within the Kings Mountain belt. The "High Shoals" therefore probably was emplaced during the waning stage of deformation and metamorphism which coincided with movement along the Kings Mountain shear zone.

There are a number of ways in which this data may be interpreted, but none which satisfactorily resolve the question of the age of the Kings Mountain belt metaigneous complex.

Lead isotopes in galena

Lead isotope compositions determined for galenas from the Castle's prospect vein, the Kings Creek barite deposit, and the Cameron mine each give the same model age - about 290 m.y. - although each reflects a different U/Pb value in source materials (Table 19). Although this age is too young (radiogenic) for the proposed ages of formation of the stratigraphic sequence in the Kings Mountain belt, it does fall within the range of K/Ar and Rb/Sr mineral ages (summarized by Fullagar and Kish, 1981), which represent the time at which the rocks cooled to a temperature corresponding to about lower greenschist facies temperatures, and thus are minimum ages.

A line drawn through the three galena data points and the Crowder's Mountain analysis reported by Kish and Feiss (1982), has a slope which corresponds to a secondary isochron age of 3.78 ± 0.30 b.y. ($2\ \sigma$) when 400 m.y. is used as the age of mineralization (Fig. 44). The slope age is similar to that of Piedmont massive sulfide deposits.

Although Castle's prospect (pyrite and galena in a quartz vein) and Cameron (siderite and galena in chlorite schist) are epigenetic vein deposits, the barite deposits may be volcanogenic in origin (Sharp and Hornig, 1981). Galena from the Kings Creek barite deposit, like that from

TABLE 19

Lead isotope compositions of galenas from Kings Mountain belt barite and vein deposits. Model ages and $^{238}U/^{204}Pb$ (μ) ratios were calculated using the parameters of Stacey and Kramers (1975). μ was calculated assuming an age of mineralization of 400 m.y.

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Model age (m.y.)	μ	$\delta^{34}S_{bar}$
Kings Creek barite mine						
PS-20801	($\delta^{18}O_{bar}$ = 4.66 °/oo)					15.89
PS-20802	18.044	15.527	37.618	288	9.69	
Crowder's Mountain barite mine						
--*	18.157	15.573	37.794	297	9.85	
Castle's prospect						
YE-25A	18.203	15.584	38.020	285	9.91	
Cameron mine						
PS-21101	18.322	15.630	38.324	289	10.1	

* Data from Kish and Feiss (1982).

Stone Hill, Alabama is relatively depleted both in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, giving it a decidedly uncontinental flavor despite the felsic volcanism associated with the deposit and the quartzites and marbles which constitute a large part of KMB stratigraphy (Horton and Butler, 1977; 1981).

The model presented in the preceeding section for the pattern of lead isotopes observed in Piedmont massive sulfide deposits can also be applied to KMB galenas: U/Pb-depleted source mixing with high U/Pb upper crustal material. The displacement of the line may represent a real time difference or it may reflect greater uranium enrichment relative to lead in the KMB source.

On a $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram (Fig. 44) KMB galenas occupy a field with the same relative position with respect to Piedmont massive sulfides as on a uranogenic lead diagram. On both, the KMB field is adjacent to and sub-parallel with the Piedmont massive sulfide field with little or no overlap.

Whether the galenas in the various KMB deposits formed during the same interval of time is not clear. Probably the barite lenses of the Carolina barite belt, including the Kings Creek and Crowder's Mountain deposits, were deposited at the same time since they apparently occur in a single stratigraphic horizon (Posey, 1981). The Castle's prospect vein occurs in the meta-igneous suite and may be related to either the igneous processes or subsequent metamorphism. The Cameron lead mine (Keith and Sterret, 1931), occurs close to or within the Kings Mountain shear zone and its relationship to stratigraphy is uncertain.

U-Th-Pb whole-rock systematics in metaigneous rocks

Four samples from the metaigneous sequence of the KMB were analyzed for lead isotope composition and for U, Th, and Pb concentrations (Table 20). Two of these were metatonalites, another was from Murphy and Butler's (1981) crystal-lapilli metatuff unit and the last from their "schist of Kings Creek".

The isotope data for the four form a line on a uranogenic lead diagram (Fig. 44) with a slope of 0.5665 ± 0.0140 (2σ). The line passes through the isotopic composition of galena from the Kings Creek barite deposit. If this point is included in the regression, the slope becomes 0.05831 ± 0.01116 (2σ). The co-linearity of the galena with whole-rock data probably indicates that the lead isotope ratios of the galena has not been significantly affected by metamorphism and may be representative of the original isotopic composition of igneous material in the area. The co-linearity of the whole-rock data suggests a genetic relationship between the metatonalite and the volcanic rocks, as well as lead in the barite deposits.

The suite of rock data and the Kings Creek galena have low $^{207}Pb/^{204}Pb$ ratios, which causes the line formed to fall significantly below an average growth curve (Fig. 44). Low $^{207}Pb/^{204}Pb$ ratios indicate a source of lead depleted in U/Pb relative to average orogene and upper continental crustal lead, such as the lower crust or mantle (Doe and Zartman, 1979). $^{238}U/^{204}Pb$ ratios of the suite are, with the exception of YC-1, significantly lower than the "average" value of about 9.7 (Table 20). The high ratio observed in YC-1 may be due to the proximity of the sample to the quartz vein which hosts the Southern Gold mine. Figure 45 illustrates the low $^{207}Pb/^{204}Pb$ ratio relative to other trends found in southern Appalachian metaigneous suites.

TABLE 20

Whole-rock lead isotope ratios and U, Th, and Pb concentrations from Kings Mountain belt (KMB) metaigneous rocks, and K-feldspar lead isotope compositions from the "High Shoals" gneiss (KMB) and Cherryville and spodumene pegmatites (Inner Piedmont). WR = whole-rock; KF-L and KF-R are K-feldspar leachate and residue analyses, respectively.

Sample no.	Type	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{208}\text{Pb}}{^{204}\text{Pb}}$	Pb	U	Th	$\frac{^{238}\text{U}}{^{204}\text{Pb}}$	$\frac{^{232}\text{Th}}{^{238}\text{U}}$	$\frac{^{232}\text{Th}}{^{204}\text{Pb}}$	Model age (m.y.)
					(----ppm-----)						
<u>Kings Mountain belt metaigneous rocks</u>											
Metatonalite											
YC-1	WR	19.896	15.636	39.313	4.63	1.55	4.74	21.9	3.16	69.3	
YC-2a	WR	18.880	15.576	39.069	5.82	.709	4.51	7.84	6.57	51.5	
Crystal-lapilli metatuff											
YC-3	WR	18.796	15.576	38.307	8.88	.791	2.98	5.67	4.89	22.1	
Schist of Kings Creek											
YC-5	WR	18.490	15.556	38.225	20.4	2.40	9.23	7.45	3.97	29.6	
"High Shoals" gneiss											
APL81-23	KF-L	18.398	15.621	38.199							
	KF-R	18.367	15.619	38.186							234
<u>Inner Piedmont intrusives</u>											
Cherryville pegmatite											
APL81-21	KF-L	18.254	15.651	38.179							
	KF-R	18.211	15.648	38.171							408

73p

TABLE 20 (CONT.)

Sample no.	Type	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb (ppm)	U (ppm)	Th (ppm)	$^{238}U/^{204}Pb$	$^{232}Th/^{238}U$	$^{232}Th/^{204}Pb$	Model age (m.y.)
Inner Piedmont intrusives (cont.)											
Spodumene pegmatite											
APL81-22	KF-L	18.358	15.649	38.197							
	KF-R	18.327	15.650	38.204							326

Figure 44. Lead isotope ratio diagrams of Kings Mountain belt galena and whole-rock data. The regression shown through the whole-rock points does not include the Kings Creek galena point. When that point is included in regression calculations, the slope is 0.0583 ± .0105 with a MSWD of 0.12 and a Pb-Pb isochron age of 541 ± 400 m.y.

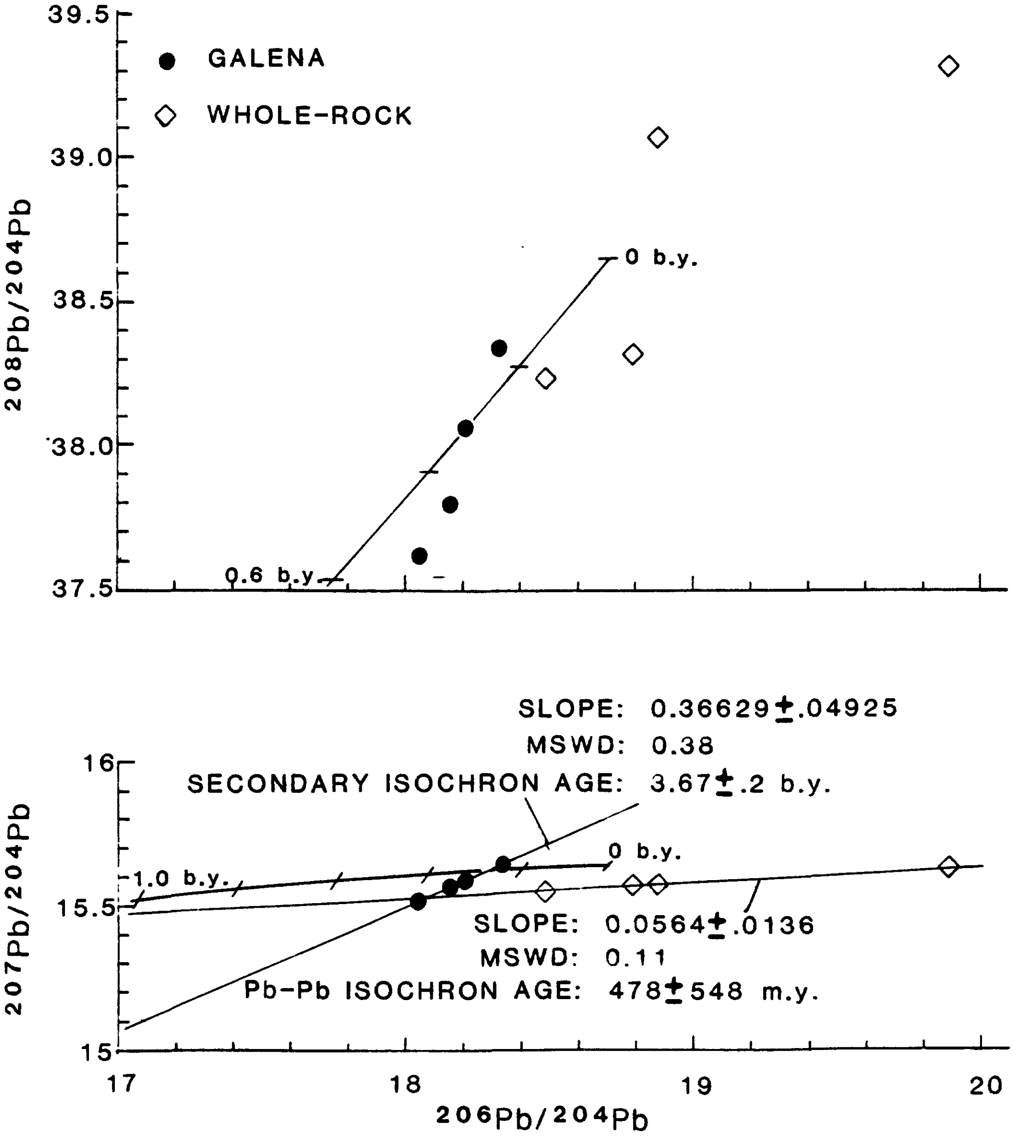
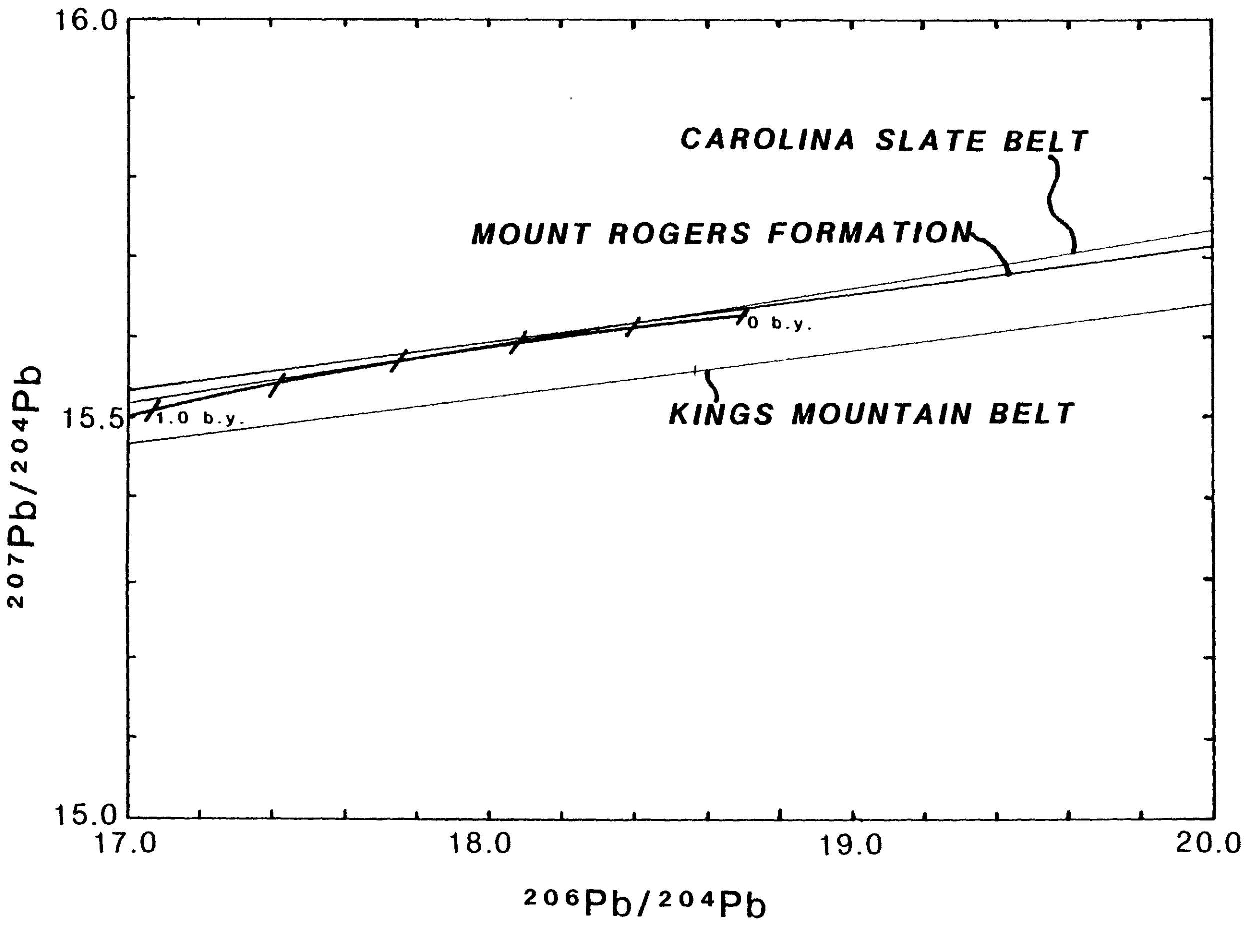

39.5
GALENA
WHOLE-ROCK
39.0
208Pb/204Pb
0 b.y.
38.5
38.0
37.5
0.6 b.y.
SLOPE: 0.36629±.04925
MSWD: 0.38
SECONDARY ISOCHRON AGE: 3.67±.2 b.y.
16
0 b.y.
1.0 b.y.
207Pb/204Pb
15.5
SLOPE: 0.0564±.0136
MSWD: 0.11
Pb-Pb ISOCHRON AGE: 478±548 m.y.
15
17
18
19
20
206Pb/204Pb

Figure 45. Pb-Pb isochron formed by Kings Mountain belt metaigneous rocks compared with regression through Mount Rogers Formation and Carolina slate belt whole-rock data, from figures 19 and 53, respectively.


16.0
15.5
15.0
17.0
18.0
19.0
20.0
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$
CAROLINA SLATE BELT
MOUNT ROGERS FORMATION
KINGS MOUNTAIN BELT
0 b.y.
1.0 b.y.

Lead in Kings Mountain belt and Inner Piedmont K-feldspar

Table 20 also presents lead isotope ratios found in several Kings Mountain belt and Inner Piedmont K-feldspars. The feldspars are from a pegmatitic phase of the Cherryville quartz monzonite and the Foote mine spodumene pegmatite, both on the Inner Piedmont side of the Kings Mountain shear zone, and from the "High Shoals" granitic gneiss which dominates the northern part of the Kings Mountain belt (Fig. 41). Lead in the leached fractions of the three feldspars show no great disparity. K-feldspar lead from the spodumene pegmatite is quite similar to that in the Cameron mine galena (Tables 19 and 20) and is also similar to that in "High Shoals" K-feldspar. The pegmatite is approximately the same age as the Cherryville quartz monzonite (340-350 m.y., Kish, 1977), but lead in Cherryville K-feldspar appears to be slightly less radiogenic than in the spodumene pegmatite K-feldspar.

Lead in K-feldspar from the "High Shoals" gneiss falls squarely within the fields defined by K-feldspar lead isotope ratios of the late orogenic granitic plutons on both $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagrams (Fig. 46). Zircons from the "High Shoals" have essentially concordant U/Pb ages of about 320 m.y. (see

Fig. 42), and add to the growing evidence of general lead isotopic uniformity in the late orogenic plutons throughout the Piedmont.

Figure 46. Lead isotope ratio diagrams with analyses of Inner Piedmont and Kings Mountain belt K-feldspars, with the fields defined by late orogenic (≃ 300 m.y.) granite K-feldspars for comparison. Lead isotope ratios of late orogenic granite K-feldspars are from Vitrac *et al.*, (1981), Kish and Feiss (1982) and this study.

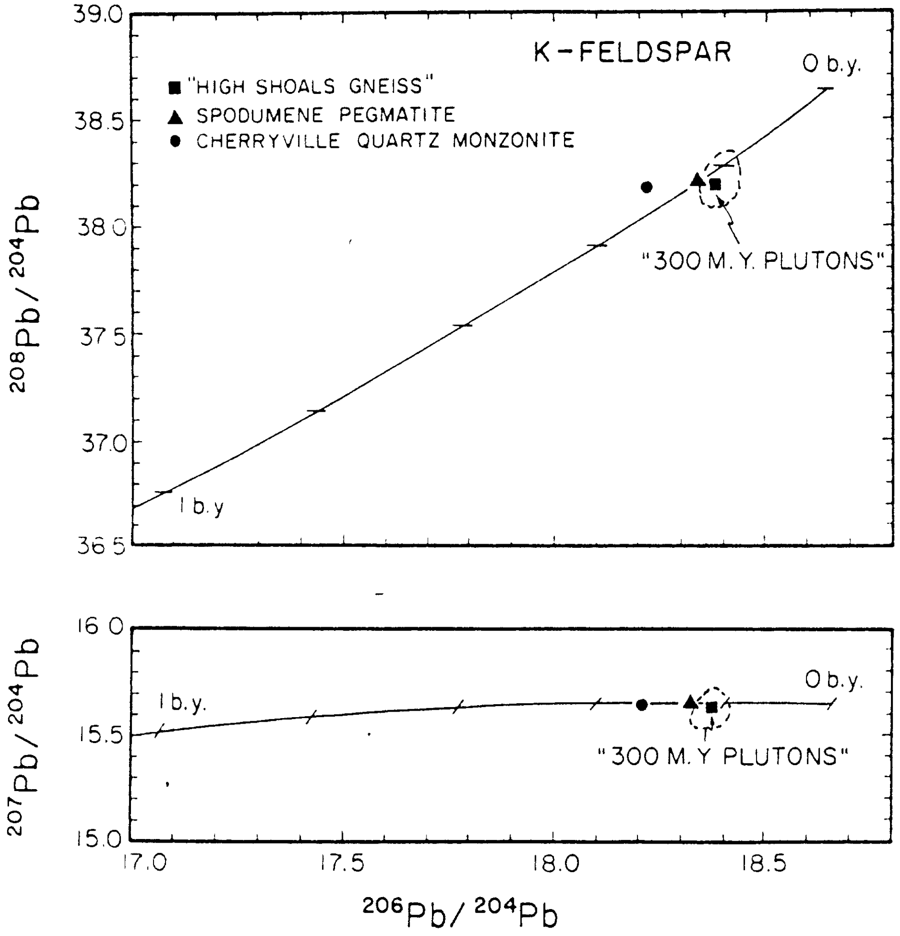
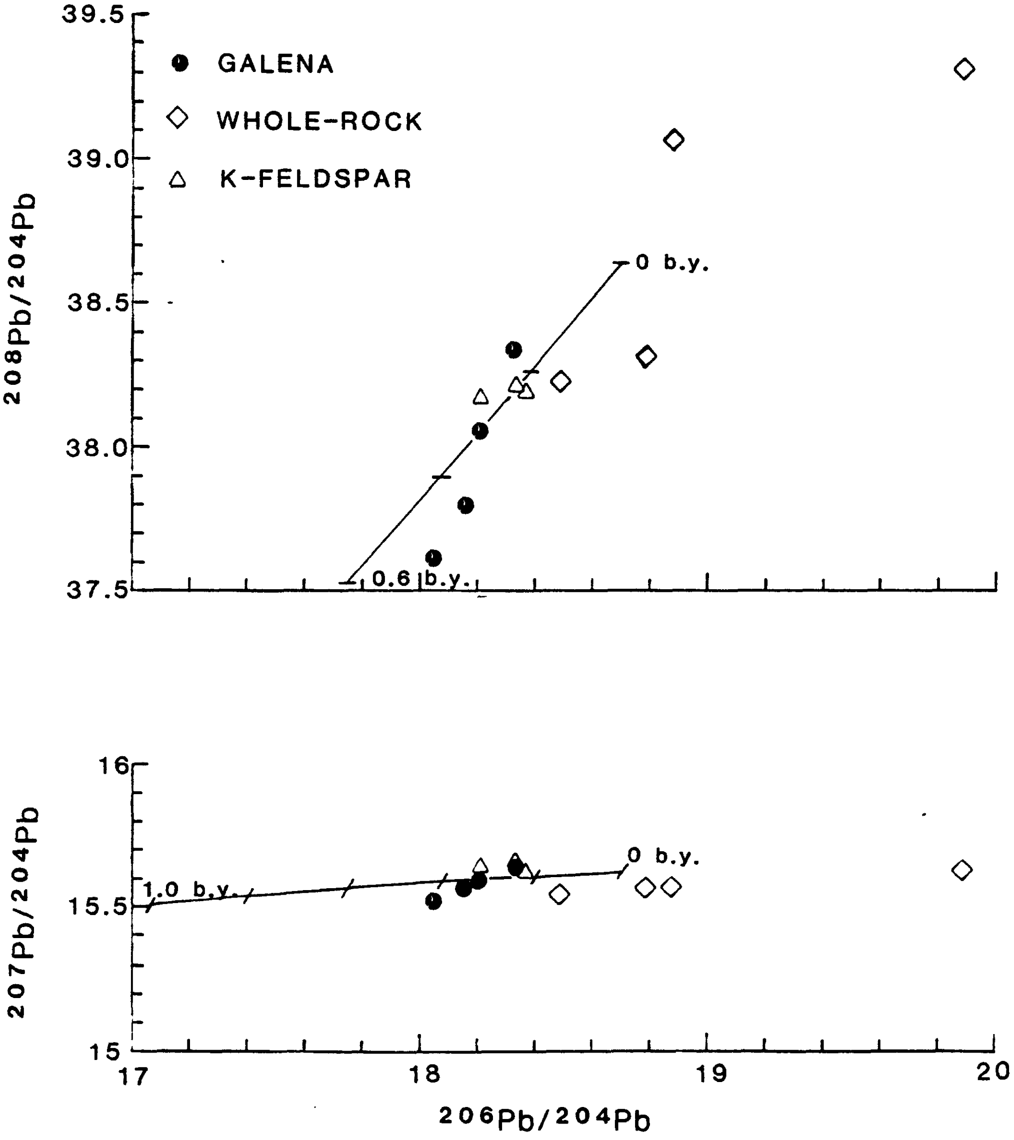

K-FELDSPAR
■ "HIGH SHOALS GNEISS"
▲ SPODUMENE PEGMATITE
● CHERRYVILLE QUARTZ MONZONITE
0 b.y.
1 b.y
"300 M.Y. PLUTONS"
39.0
38.5
38.0
37.5
37.0
36.5
208Pb/204Pb
16.0
15.5
15.0
207Pb/204Pb
1 b.y.
0 b.y.
"300 M.Y PLUTONS"
17.0
17.5
18.0
18.5
206Pb/204Pb

Figure 47. Kings Mountain belt composite lead isotope ratio diagrams illustrating galena, whole-rock and K-feldspar data.


39.5
39.0
38.5
38.0
37.5
208Pb/204Pb
GALENA
WHOLE-ROCK
K-FELDSPAR
0 b.y.
0.6 b.y.
16
15.5
15
207Pb/204Pb
1.0 b.y.
0 b.y.
17
18
19
20
206Pb/204Pb

Lead in the Kings Mountain belt and the Piedmont model

The similarity in the slopes of lines defined by galena lead isotope ratios from Piedmont massive sulfides and Kings Mountain belt deposits suggests that similar sources contributed lead to the rocks and ores of the two regions. The model proposed for the Piedmont isotopic pattern may be applied to the Kings Mountain belt. In that model the line formed by Kings Mountain belt galenas would represent a mixing line, with lead contributed by a source depleted in uranium relative to lead (low U/Pb ratio) mixing with lead from a relatively high U/Pb source. Low $^{207}Pb/^{204}Pb$ ratios in the Kings Creek barite deposit galena and in the metaigneous suite make these Kings Mountain belt rocks good candidates for material derived directly or with little contamination from the U/Pb depleted source region.

The consistently too-young model ages of galenas in the Kings Mountain belt and in Piedmont massive sulfides indicates that all source rocks have undergone an increase in U/Pb through time, either continuously or episodically. If the high U/Pb component was upper continental material the U/Pb increase of that end member is easily accounted for in the tendency of uranium to be concentrated in the upper crustal geologic environment (Doe and Zartman, 1979).

Doe and Zartman's (1979) plumbotectonics model defines two environments with low $^{207}Pb/^{204}Pb$ ratios: The mantle and lower continental crustal rocks. Several characteristics of the Kings Mountain belt data suggests that the depleted source area was not composed of lower crust material. (1) Where lower crustal rocks of much greater age contribute lead to a system the range of $^{207}Pb/^{204}Pb$ is generally much greater than that observed in Kings Mountain belt galenas (see e.g. Dickin, 1980). (2) Even if lower crust relatively close in age to Appalachian rocks was presumed to be involved, the effect of its lead contribution would be to increase the model ages of the Pb (i.e. the lead contributed would be less radiogenic) because of the enrichment of lead relative to uranium commonly observed in lower crustal rocks (Doe and Zartman, 1979). (3) U/Pb ratios in lower crustal rocks have not been observed to increase with time. Rather, the tendency is towards secular U/Pb decrease (Doe and Zartman, 1979). (4) The value of Th/U indicated by KMB and Piedmont massive sulfide galenas tends to be low rather than high as in most lower crustal materials.

Several other lines of evidence support the mantle as the ultimate source for the low $^{207}Pb/^{204}Pb$ component. Plutonic rocks of the Kings Mountain belt igneous suite range in composition from gabbroic to dioritic but tonalites and trondhjemites predominate. The metamorphosed volcanic rocks range from intermediate to felsic (Horton and Butler, 1977, 1981; Horton, 1981a). Such rocks are not believed to derive from the depleted and water-poor granulites typical of the lower crust. Further, Tatsumoto (1978) proposed that U/Pb in the mantle has been increasing with time, as must have been the case with the Kings Mountain belt source in order to produce model ages that are too young.

The pattern of ^{208}Pb/^{204}Pb ratios in Kings Mountain belt (and Piedmont massive sulfide) galenas also indicates an ultimate mantle source. The trend of ^{208}Pb/^{204}Pb is from low Th/U material to a higher Th/U source (Fig. 44). This could well be due to mixing between mantle and upper crustal lead. It would be difficult to derive this same pattern if a lower crustal source was involved. Thorium tends to be enriched relative to uranium in lower crustal rocks (Doe and Zartman, 1979), resulting in ^{208}Pb/^{204}Pb ratios that are radiogenic relative to their corresponding ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb ratios (see the lower crust growth curve in Figs. 6 and 7). No such excess enrichment in ^{208}Pb is seen in either galenas or rocks of the Kings Mountain belt or in the Piedmont massive sulfide deposits.

Lead isotope ratios in K-feldspars from adjacent Inner Piedmont igneous rocks and from the "High Shoals" gneiss cluster at the radiogenic end of the Kings Mountain belt galena trend. For this reason the Inner Piedmont rocks, at least, may be examples of rocks derived from or contributing to the relatively high U/Pb upper crust end member of the mixing model. Many granite/rhyolite rocks have a large upper crustal component of lead such as in the San Juans (Lipman et al., 1978) and the Yellowstone Plateau (Doe et al., 1982). The problem seems to be the age difference between the Inner Piedmont K-feldspars and the Kings Mountain belt metaigneous sequence. The similarity of lead isotope ratios of rocks of all ages in the southern Appalachian Piedmont, however, may be an argument in favor of this scenario.

Hatcher and Zietz (1980) recognized a major structural boundary in the Piedmont, the "central Piedmont suture", which they placed along the boundary between the Kings Mountain and Charlotte belts. Northwest of the boundary lies the eastern edge of the Paleozoic North American craton, underlain by granitic crust. To the southwest lies a terrain underlain by mafic or by mafic and granitic crust. As discussed above, lead isotope data from Kings Mountain belt metigneous rocks indicate a predominantly mafic source of lead in the rocks and presumably of the rocks themselves. In order for the lead to have survived intrusion relatively uncontaminated by continental material, any granitic crust present must have been thin. The more radiogenic lead in galenas from the vein and Crowders

Mountain deposits may be due to contributions from sedimentary material. Furthermore, Horton (1981a) and Milton (1980), have noted that the boundary between the Kings Mountain and Charlotte belts does not appear to involve any profound change in lithology or structural style. I concur, therefore, with Horton (1981a) and Horton and Butler (1981), that the position of the "central Piedmont suture" lies on the northwestern side of the Kings Mountain belt where the boundary with the Inner Piedmont is marked by the Kings Mountain shear zone and by profound lithological, structural and metamorphic discontinuity.

14. AREA AROUND THE HAILE AND BREWER MINES, SOUTH CAROLINA

The Haile and Brewer mines are located in the Carolina slate belt in a tectonic block bordered on the northeast by an extension of a Triassic border fault which apparently had an extended history (Butler and Howell, 1977), and on the southwest by a fault largely covered by Coastal Plain sedimentary rocks (Bell *et al.*, 1980; Bell, 1982). The southeastern fault is part of the Eastern Piedmont fault system of Hatcher *et al.* (1977). The structure of the tectonic block is dominated by a large northeast plunging anticline (Fig. 48). Regional geologic relations have been presented by Overstreet and Bell (1965a and b) and Bell *et al.* (1974). Preliminary reports on detailed geologic mapping have been made by Bell (1980) and Butler and Howell (1977).

Bell *et al.* (1980) divide the low-grade metamorphic rocks of the Carolina slate belt in the area into two units. The lower unit consists of schist, phyllites and quartzites derived from felsic volcanoclastic rocks. Primary textures are abundant in the greenschist facies rocks. The lower volcanoclastic unit is gradational into the upper unit which consists of thinly bedded and laminated meta-argillites and metasiltstones.

Bell *et al.* (1980) also describe six types of igneous rocks which have intruded the Haile-Brewer block, and which have ages ranging from late Precambrian-Cambrian to late Triassic and early Jurassic. These include a gneissic granitic pluton (technically in the Charlotte belt) called the Great Falls granite by Fullagar (1971), who reported its Rb/Sr whole-rock isochron age as 543 ± 155 m.y. (2σ); $\{(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_0 = 0.7041 \pm 0.0071)\}$; two large, late orogenic ($\simeq$ 300 m.y.) granitic plutons, the Liberty Hill and Pageland plutons: and a vast swarm of Mesozoic diabase dikes.

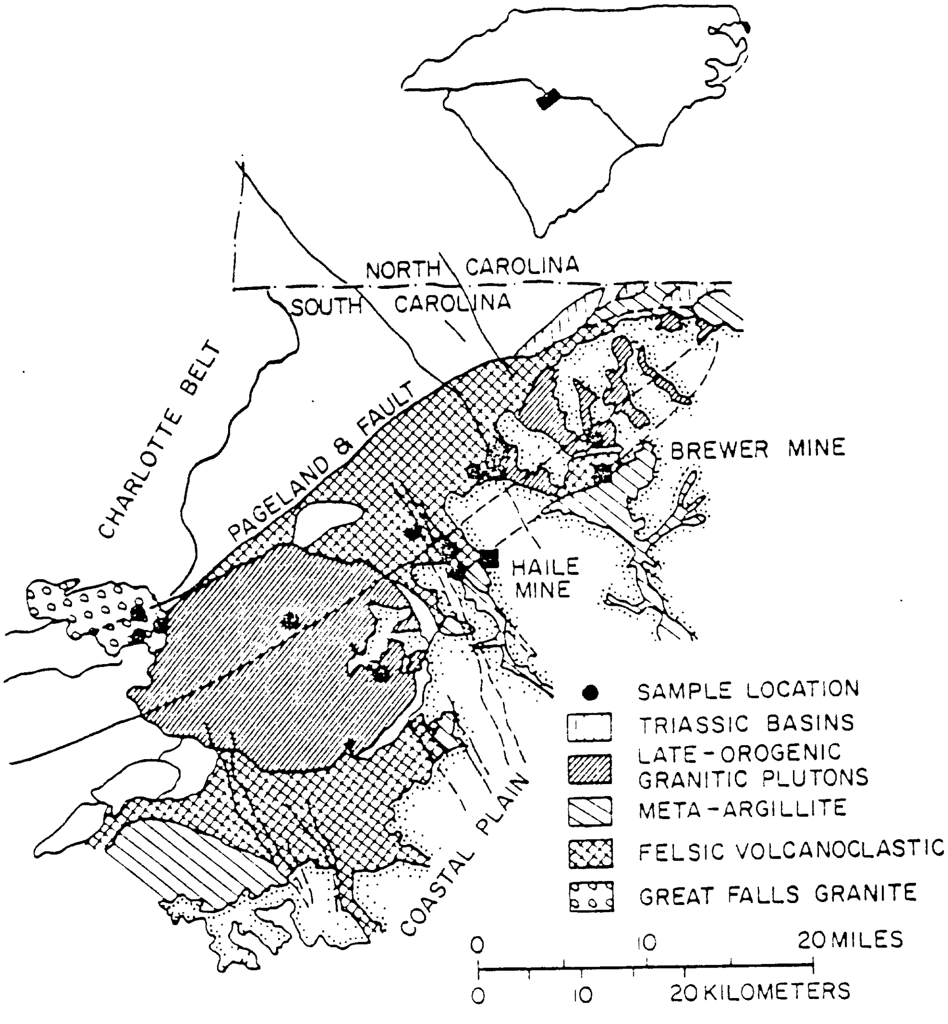
Slate belt metavolcanic rocks in the Haile-Brewer area have yielded muscovite K-Ar ages of 354 to 430 m.y. (Bell *et al.*, 1972). The K-Ar ages determinations were made on muscovites from alteration zones of the Brewer and nearby Blackman mines. The data rule out an association of mineralization with the younger igneous activity in the area, and these ages probably reflect the timing of regional metamorphism. Butler and Fullagar (1975) reported a poorly defined Rb-Sr whole-rock isochron from slate belt rocks northwest of the Haile-Brewer area which they interpret as indicating a minimum age of about 494 ± 29 (1σ) m.y. (as recalculated by Fullagar, 1981).

Spence *et al.* (1980, p. 70) described the (gold) mineralization at the Haile mine as "associated with siliceous, pyritic, and kaolinized felsic pyroclastic and tuffaceous rocks in an interbedded volcanic and volcanoclastic sequence of felsic to mafic tuffaceous rocks and argillaceous sediments". Mafic units are subordinate to felsic and the volcanic pile is cut by numerous metamorphosed mafic dikes. Gold occurs in highly siliceous rocks, in tuffaceous rocks, and in massive pyrite lenses. A zone of intense sericitic alteration underlies the ore zone. Spence et al. (1980) found relict textures in the altered material which indicate that it was originally a felsic ash flow. They proposed a hot springs origin for Haile ores and Worthington et al. (1980) extended the model to other lode gold deposits in the United States, including the nearby Brewer Mine. Both the Haile and Brewer deposits occur near the top of the lower, volcanoclastic sequence (Fig. 48).

The Brewer mine occurs along strike from Haile in densely silicified, locally brecciated, pyritized rock. Massive and disseminated topaz is common, very fine-grained massive pyrite occurs locally, as does relatively coarse-grained enargite, and gold is found in pyrite and is visible along joints. (Kinkel, 1970; Bell et al., 1980; Bell, 1982: Worthington et al., 1980).

While the Brewer ores contain some copper (as enar-

Figure 48. Geologic map of the Haile-Brewer area, South Carolina, showing sample locations. After Bell *et al.*, (1980). For clarity, only a few of the Mesozoic diabase dikes which are found in the area are shown.



AFTER BELL et al (1980)

gite), the only metal sulfide other than pyrite present at Haile in greater than trace amounts is molybdenite, which occurs locally as thin stringlets and disseminations. Schmidt (1978) described the Brewer mine area as being a possible porphyry copper-type deposit.

Results of sulfur isotope study

Twenty-four determinations of sulfur isotope ratios of Haile pyrite are presented in Table 21. The range of $\delta^{34}S$ values is -0.05 to + 4.22^{o}/oo and the mean is 2.0^{o}/oo. Pyrite in massive sulfide averages $\delta^{34}S = 1.0^{o}$/oo whereas disseminated pyrite is generally heavier, averaging 2.4^{o}/oo, Pyrite is ubiquitous in all rocks at the Haile mine. It occurs in large and small scale massive lenses, as very fine-grained scales and laminae, and disseminated as medium-sized and relatively coarse-grained (1-3 cm) zoned cubes. Data are insufficient to discern $\delta^{34}S$ variations between the various morphologies but values reported in Table 21 indicate that medium-sized cubes may have a wider range (1.15 to 3.59^{o}/oo, 5 samples) than fine-grained disseminated pyrite (1.41-2.90^{o}/oo, 8 samples). The heaviest sulfur was found in a coarse cube. Samples from the center and edge of this cube (sample 27-259, Table 21), vary in $\delta^{34}S$ ratio by 0.21^{o}/oo, which is probably not a significant difference.

A sample from breccia ore in the Hartman Pit, Brewer mine, has $\delta^{34}S_{py}$ = + 1.26 and enargite $\delta^{34}S$ = 0.04. These are within the range of values found at Haile. Equilibrium fractionation trends of sulfur isotopes between pyrite and enargite are not well known, but the observed $\delta^{34}S_{py} > \delta^{34}S$ enargite probably represents an approach to equilibrium fractionation.

$\delta^{34}S$ values from the Haile and Brewer mines are much lighter than those found in slate belt polymetallic massive sulfides and than in lower Paleozoic massive sulfide deposits worldwide (see Figs. 28 and 36). The relatively light sulfur indicates that little, if any, sulfur was derived from lower Paleozoic seawater sulfate. If the deposits were formed in a fully or partially restricted saline basin, sulfur would be enriched in the heavy isotope and $\delta^{34}S$ values would be higher than expected. The low values in the Haile and Brewer deposits suggests a strong magmatic sulfur component and may indicate that the ores formed in an environment dominated by fresh water. Alternatively, the low $\delta^{34}S$ values could indicate a lower temperature hydrothermal system than those responsible for polymetallic ores. If lower Paleozoic seawater sulfate was the source of sulfur, temperatures between 100 and 200° would produce the observed $\delta^{34}S$ ratios in sulfides.

There do not appear to be any regular directional variations in $\delta^{34}S$ ratios of Haile pyrite.

TABLE 21

Sulfur isotope compositions of pyrite from the Haile mine, South Carolina, and an analysis of pyrite and enargite from the nearby Brewer mine. Types of ore: M = massive pyrite; D = disseminated pyrite. Numbered prefix indicates diamond drill hole; core footage follows.

Sample no.	Type	$\delta^{34}S_{py}$	Description
HB-2	M	1.06	Massive pyrite in siliceous matrix (dump)
29-17	D	3.07	Medium-grained (m.g.) cubes along bedding and fractures in siliceous, bedded felsic tuff
29-67	D	2.42	Fine-grained (f.g.) py in siliceous felsic tuff
29-136	D	2.36	f.g. py in f.g. (lapilli?) tuff
27-59	sub-M	1.78	f.g. and m.g. py in felsic tuff
27-247	D	3.59	m.g. py in fragmental, f. to m.g., felsic tuff
27-259	D	4.22 4.01	Center of large zoned py cube Edge of cube
30-59	D	2.07	Large zoned py cube
2-68	D	2.90	f.g. py in thinly bedded felsic tuff
2-189	D	2.07	f.g. py and MoS_2 in vein cross-cutting foliation
2-199	D	1.89	m.g. py in alteration zone cross-cutting layering
2-203	D	2.27	Stringers of f.g. py in silicified lapilli tuff
2-331	D	1.20	m.g. py in lapilli tuff
2-368	D	1.41	f.g. py along bedding planes
2-445	D	2.58	f.g. py in f.g. felsic tuff
12-72	D	2.39	f.g. py in strongly foliated bedded tuff
12-116	D	1.15	m.g. py in white sericitized m.g. tuff
12-160	sub-M	0.05	Sub-massive py in sericitized tuff

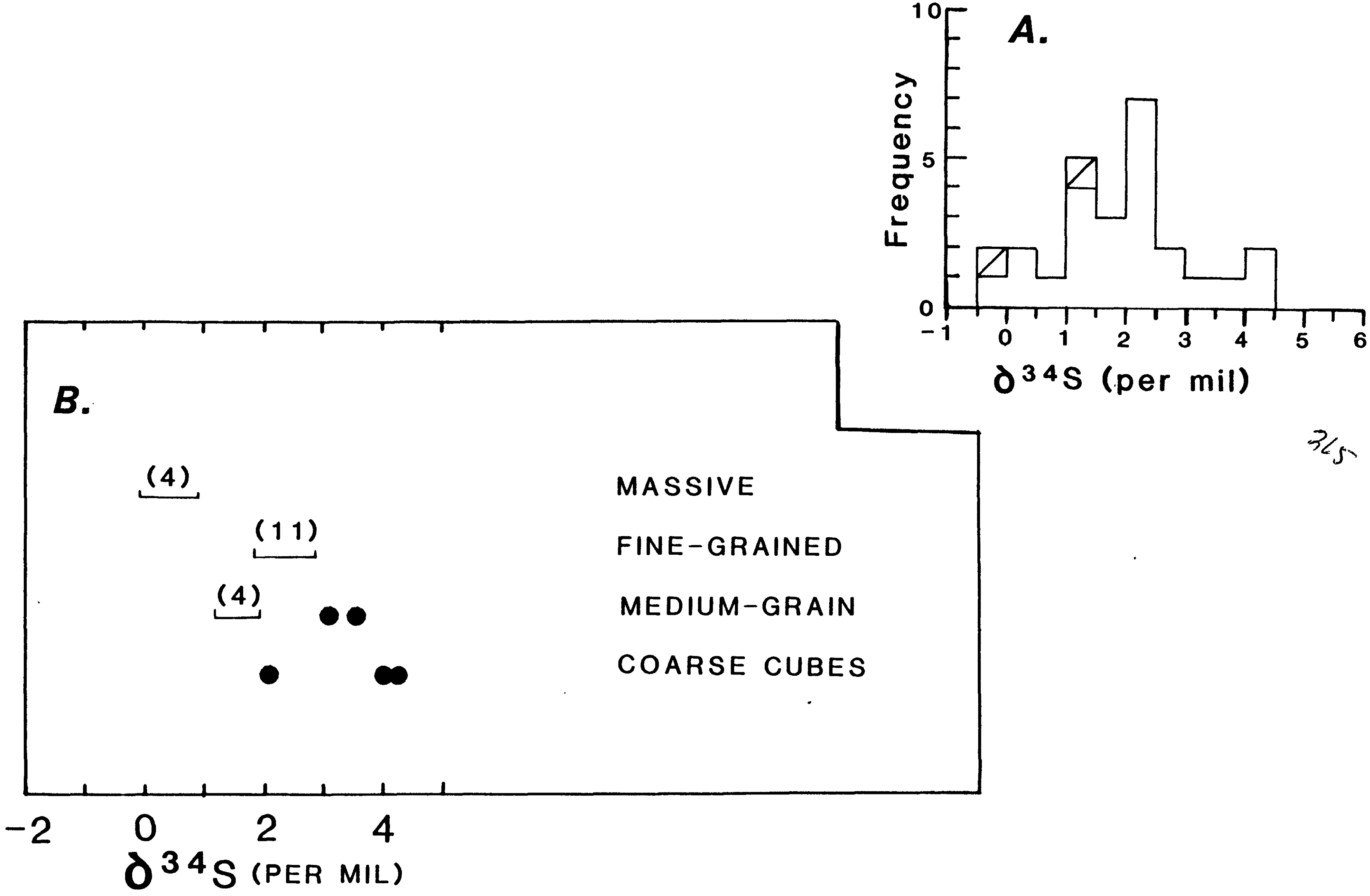
TABLE 21 (CONT.)

Sample no.	Type	$\delta^{34}S_{py}$	Description
12-166	M	2.01	Massive py
12-192	sub-M	1.74	Sub-massive py in sericitized tuff
7-322	M	0.91	Massive py
7-324	M	-0.05	Massive py
7-327	M	0.46	Massive py
Brewer mine			
HB-r	D	1.26 $\delta^{34}S_{en} = -0.04$	Py and relatively coarse enargite (en) in volcanic breccia (outcrop)

Figure 49. A. Frequency distribution of sulfur isotope ratios of Haile pyrite. The two patterned blocks show sulfur isotope ratios of Brewer mine pyrite and enargite (Table 20).

B. Ranges of Haile mine pyrite sulfur isotope ratios broken down by type of ore and pyrite size populations.

4.9


A.
Frequency
10
5
0
−1
0
1
2
3
4
5
6
δ34S (per mil)
B.
(4)
(11)
(4)
MASSIVE
FINE-GRAINED
MEDIUM-GRAIN
COARSE CUBES
−2
0
2
4
δ34S (PER MIL)

U-Th-Pb systematics in massive pyrite and host rocks

U-Th-Pb whole-rock analyses of felsic volcanic rocks of the Haile-Brewer block and of Haile massive pyrite (Table 22) reveal regular relationships between the concentrations of those elements. There is a linear relationship between uranium and thorium contents of the ore and rocks (Fig. 50a), whereas lead content has an apparent exponential relationship to both uranium and thorium contents. The relationships may be a reflection of fractionation trends within the sequence.

The isotope systematics also display regularities not usually observed in U-Th-Pb whole-rock data. Five of seven samples analyzed for U-Th-Pb form a line on a $^{206}Pb/^{204}Pb$ versus $^{238}U/^{204}Pb$ plot with an isochron age of 466 ± 40 m.y. (Fig. 51a). The diagrams on figure 51 are analogous to those for Rb-Sr and Sm-Nd isochron plots and the principles of their construction and use is the same. The y-axis intercept indicates the value of the y-axis parameter at the time of formation of the rocks ("initial" value). In figure 51a the intercept is $18.37 \pm 0.07 = (^{206}Pb/^{204}Pb)_0$. Of the two samples which do not fit on the line, one (HB-3) diverges in the direction of uranium loss (and/or lead gain) while the other (2-454) falls in the direction of uranium gain (and/or lead loss).

TABLE 22

Lead isotope composition and U, Th and Pb concentrations of Carolina slate belt rocks in the Haile-Brewer area, and of massive pyrite from the Haile mine. WR = whole-rock; WO-L and WO-R are HCl soluble and insoluble fractions, respectively, of massive pyrite.

Sample no.	Type	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Pb	U (------ppm------)	Th	$\frac{^{238}U}{^{204}Pb}$	$\frac{^{232}Th}{^{238}U}$	$\frac{^{232}Th}{^{204}Pb}$
Carolina slate belt metavolcanic rocks										
HB-3	WR	18.873	15.664	38.723	14.6	1.03	4.55	4.53	4.56	20.7
HB-4	WR	18.764	15.651	38.542	13.2	1.05	4.07	5.08	4.00	20.4
HB-7	WR	19.670	15.712	39.765	8.26	2.2	8.8	17.5	4.12	72.2
HB-8	WR	19.222	15.677	39.059	8.03	1.41	5.50	11.4	4.03	45.8
8-549.5	WR	19.051	15.669	38.958	11.1	1.51	6.69	8.78	4.58	40.2
2-454	WR	19.426	15.678	39.420	6.15	1.80	8.50	19.1	4.88	93.2
Massive pyrite from the Haile mine										
7-327	WR	18.432	15.623	38.181	28.6	0.613	2.21	1.36	3.72	5.05
12-166	WR	18.452	15.619	38.221						
12-166	WO-L	18.461	15.618	38.228						
12-166	WO-R	18.429	15.612	38.161						

Figure 50. A. U versus Th content of slate belt rocks and Haile massive pyrite.

B. Th versus Pb content, and

C. U versus Pb content of slate belt rocks and Haile massive pyrite.

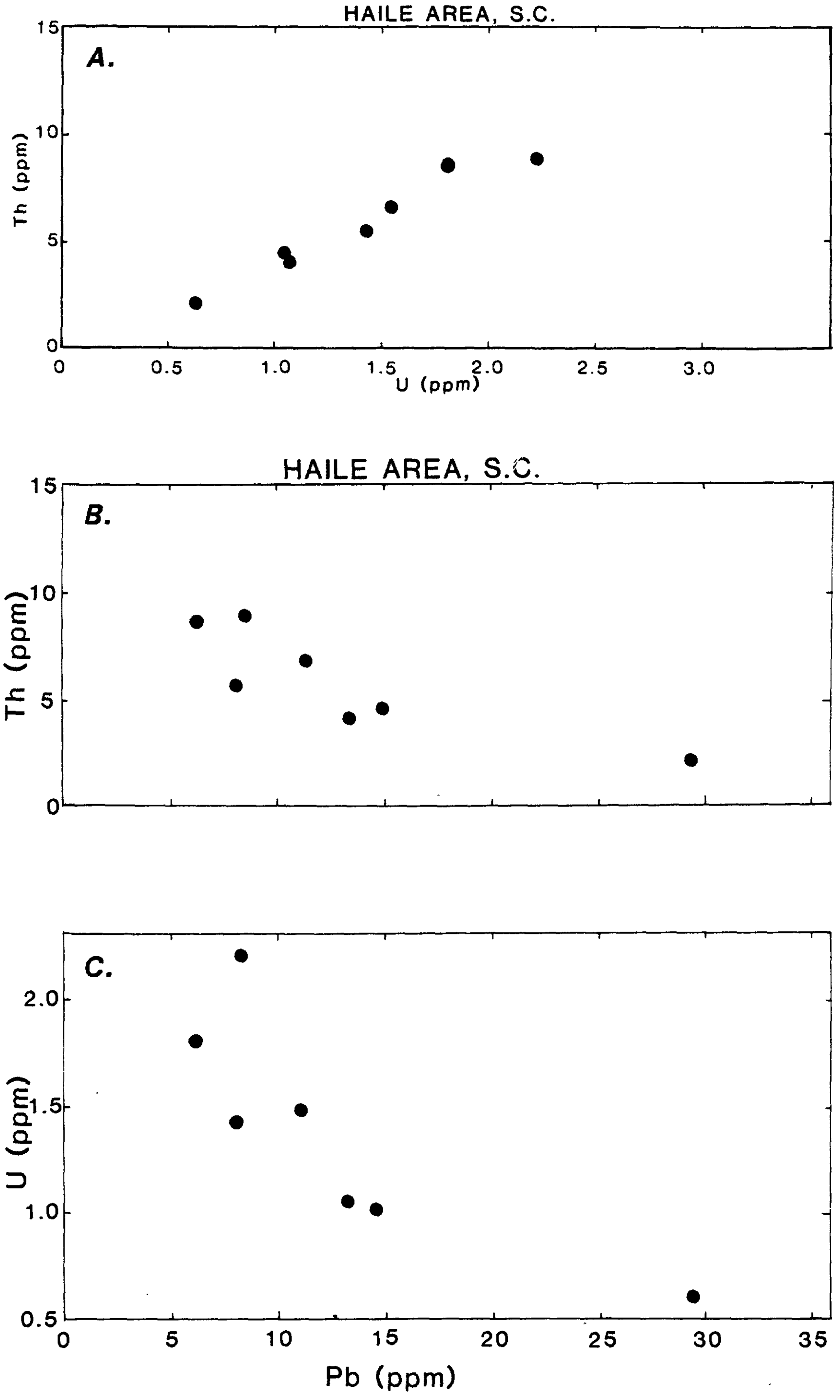
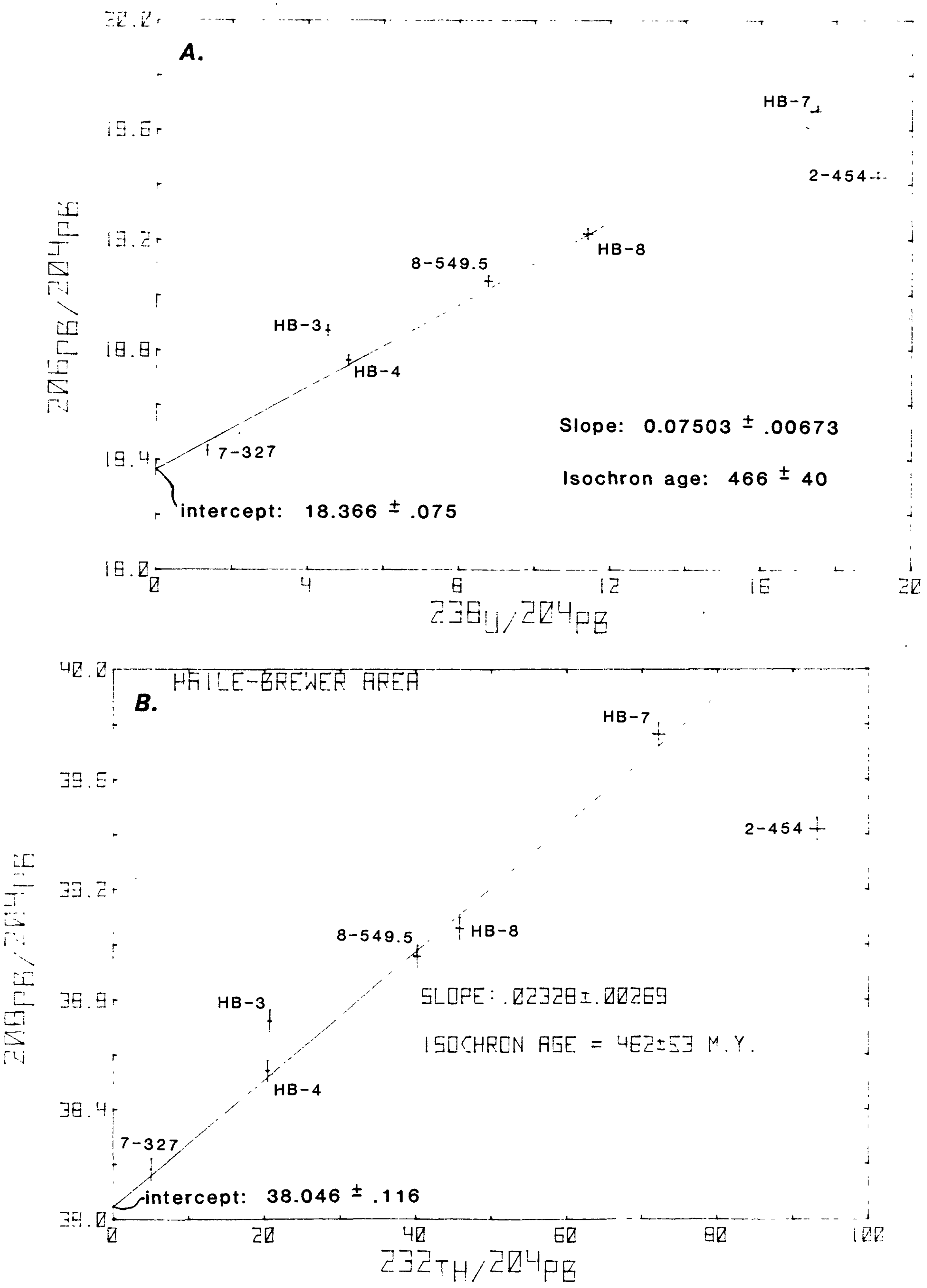

HAILE AREA, S.C.
A.
Th (ppm)
15
10
5
0
0
0.5
1.0
1.5
2.0
2.5
3.0
U (ppm)
HAILE AREA, S.C.
B.
Th (ppm)
15
10
5
0
C.
U (ppm)
2.0
1.5
1.0
0.5
0
5
10
15
20
25
30
35
Pb (ppm)

Figure 51. A. $^{206}Pb/^{204}Pb$ versus $^{238}U/^{204}Pb$ isochron plot showing regression through slate belt rocks and Haile massive pyrite.
HB-3 and 2-454 were not used in regression calculations. Points are represented by error crosses.
B. The same data on a $^{208}Pb/^{204}Pb$ versus $^{232}Th/^{204}Pb$ isochron diagram.


A.
20.0
19.6
19.2
18.8
18.4
18.0
0
4
8
12
16
20
206Pb/204Pb
238U/204Pb
HB-7
2-454
HB-8
8-549.5
HB-3
HB-4
7-327
intercept: 18.366 ± .075
Slope: 0.07503 ± .00673
Isochron age: 466 ± 40
B.
HAILE-BREWER AREA
40.0
39.6
39.2
38.8
38.4
38.0
0
20
40
60
80
100
208Pb/204Pb
232Th/204Pb
HB-7
2-454
HB-8
8-549.5
HB-3
HB-4
7-327
intercept: 38.046 ± .116
SLOPE: .02328±.00269
ISOCHRON AGE = 462±53 M.Y.

Isochronous relationships are not usually preserved in whole-rock U-Pb systems due in large part to the mobility of uranium. Rosholt et al., (1973), found that rocks in the Granite Mountains, Wyoming, had lost an average of 75% of their uranium. Most of the loss was apparently due to recent weathering and extended to a depth of at least 165 feet in drill core. An intensely weathered area such as the southern Piedmont might be expected to show the same effects. Disturbances other than weathering also might have effected uranium contents. After their deposition the slate belt volcanics in the Haile area were intruded by mafic dikes. Subsequent deformation and greenschist facies metamorphism was followed by intrusion of large granitic plutons. Finally, the Haile-Brewer block has one of the most extensive swarms of Mesozoic disabase dikes in the southern Piedmont. Under these circumstances, that five of seven samples fall as close to a line as they do seems incredible.

The age indicated by $^{206}Pb/^{238}U$ systematics (466 ± 40 m.y.) is significantly younger than isotopic and fossil ages reported from other parts of the southern Carolina slate belt which seem to be uniformly lower to middle Cambrian, (St. Jean, 1973; Carpenter et al., 1982; Wright and Seiders, 1980). Northwest of the Pageland fault, Butler and Fullagar (1975; as recalculated by Fullagar, 1981), reported a Rb-Sr whole-rock minimum age of 494 ± 29 (1σ)

m.y., which agrees within error with the U-Pb isochron age. There are no independent ages for slate belt rocks within the Haile-Brewer block. The similarity of the Haile-Brewer stratigraphic sequence with that of the Albermarle area, North Carolina indicates a degree of correlation. The lower volcanic sequence would then correspond to the late Precambrian-Cambrian Uwharrie Formation and the upper argillites to the Cambrian Tillery Formation. If this is the case then perhaps the 466 m.y. age represents the time at which Haile-Brewer rocks became a closed system with respect to uranium and lead. Intrusive, metamorphic, or weathering processes having disturbed U-Pb systematics in so regular a fashion is difficult to conceive.

Th-Pb systematics in the same rock samples, however, support the younger age implied by the U-Pb isochron. Figure 51b illustrates a $^{208}Pb/^{204}Pb$ versus $^{232}Th/^{204}Pb$ isochron with an age of 462 ± 53 m.y. $\{(^{208}Pb/^{204}Pb)_0 = 38.05 \pm 0.12)\}$. Unlike uranium, thorium is generally considered to be an immobile element and so is less likely to be disturbed by post-depositional processes. Several examples of Th-Pb isochrons which closely match independently determined ages have been published (e.g. Rosholt and Bartel, 1969; Farquharson and Richards, 1970; Rosholt et al., 1973; Manton, 1973). In figure 51b the two samples which fall off the line are the same as those that fall off the U-Pb isochron.

Both the U-Pb and Th-Pb regression lines have high mean squares of weighted deviates (MSWD). This high MSWD may be the result of a number of factors including small initial variability in lead isotope ratios and inhomogeneity in uranium, thorium, and lead concentrations or small post-depositional disturbances caused by any of the events listed above. The effect of initial variability may be particularly significant in this case since the samples may be from different layers and types of volcanic and volcanoclastic rock.

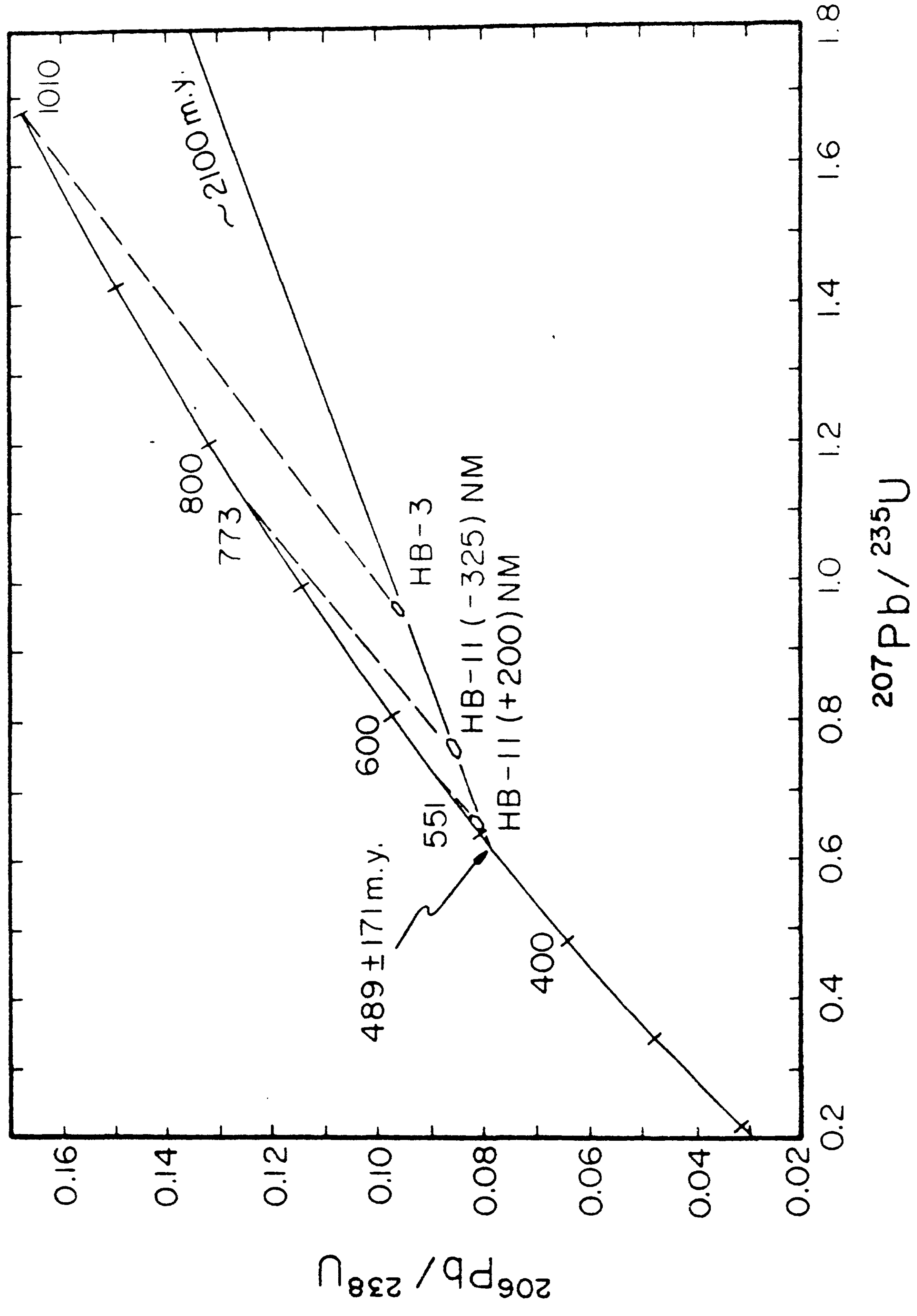
U-Pb zircon analysis of zircon from the Great Falls granite and a slate belt metavolcanoclastic unit (Table 23) lie along a poorly defined cord with a lower concordia intercept at 489 ± 171 m.y. (Fig. 52). The upper intercept of this line is not well resolved, but falls between 1800 m.y. and 2500 m.y. Without further evidence, however, the existence of an "old" source in the area must be regarded as tenuous. The validity of the plotting slate belt zircon (HB-3) with zircons from the Great Falls granite is questionable. All three fractions are discordant and have widely varying Pb-Pb ages. The 1.0 b.y. Pb-Pb age of the slate belt zircon may indicate the presence of Grenville-age rocks at depth and is supported by the ≃ 1.0 b.y. Pb-Pb isochron of Haile-Brewer area ores and rocks (Fig. 53). The source age indicated by the cord (Fig. 52) may be an

TABLE 23

Results of U-Pb analyses of zircons from the Great Falls granite and from a metavolcanic unit of the Haile-Brewer block in the Carolina slate belt. Size and magnetic fractions as in Table 18.

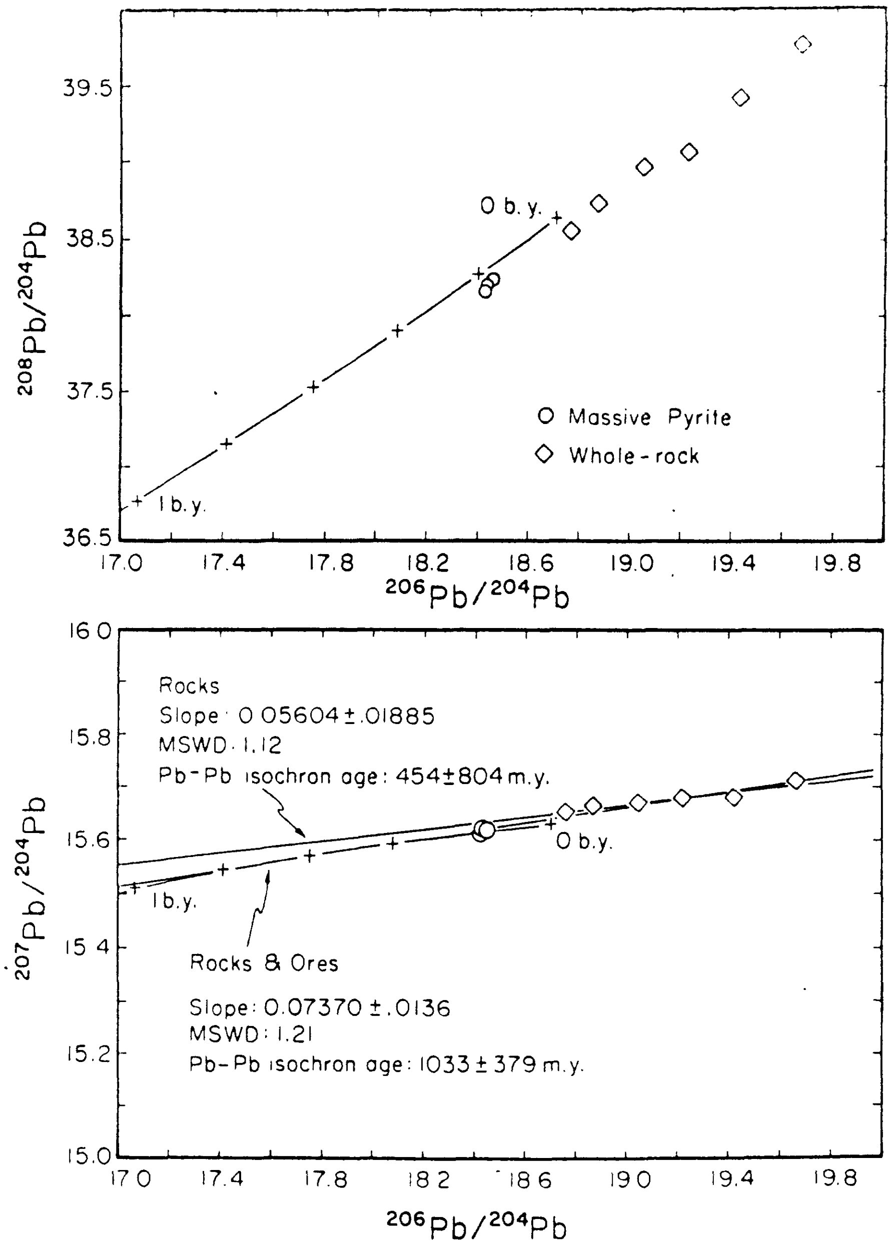
Sample no.	Pb	U	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$
	(---ppm---)		(----------atom percent----------).				(-------age (m.y.)-----)		
Great Falls granite									
HB-11									
(+200)NM	68.5	777	0.0293	79.54	5.085	15.34	502	511	551
(-325)NM	75.8	830	0.0176	80.51	5.485	13.98	527	576	773
Metavolcanoclastic rock									
HB-3	35.8	300	0.0402	69.72	5.653	24.58	589	684	1010

Figure 52. Concordia diagram for zircons from the Great Falls Granite (HB-11) and from a metavolcanoclastic unit of the Carolina slate belt (HB-3). The upper intercept of the cord is not well-defined, but seems to be restricted to between about 1800 m.y. and 2500 m.y.



1010
~2100 m.y.
800
773
600
551
400
489 ± 171 m.y.
HB-3
HB-11 (-325) NM
HB-11 (+200) NM
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
$^{207}Pb/^{235}U$
$^{206}Pb/^{238}U$

Figure 53. Lead isotope ratio diagrams of slate belt whole-rock and ore data from the Haile-Brewer area.


39.5
38.5
37.5
36.5
$^{208}Pb/^{204}Pb$
0 b.y.
1 b.y.
○ Massive Pyrite
◇ Whole-rock
17.0
17.4
17.8
18.2
18.6
19.0
19.4
19.8
$^{206}Pb/^{204}Pb$
16.0
15.8
15.6
15.4
15.2
15.0
$^{207}Pb/^{204}Pb$
Rocks
Slope: 0.05604±.01885
MSWD: 1.12
Pb-Pb isochron age: 454±804 m.y.
0 b.y.
1 b.y.
Rocks & Ores
Slope: 0.07370±.0136
MSWD: 1.21
Pb-Pb isochron age: 1033±379 m.y.
17.0
17.4
17.8
18.2
18.6
19.0
19.4
19.8
$^{206}Pb/^{204}Pb$

artifact of differential lead loss or it may reflect a real inheritance from some older material. The lower intercept of about 490 m.y. is consistent, however, with the Rb-Sr isochron age of Butler and Fullagar (1975) and is reasonably close to the ≃ 465 m.y. age suggested by whole-rock U-Pb and Th-Pb systematics. On the other hand, the Pb-Pb age (= 551 m.y.) of the largest (+ 200) Great Falls granite zircon fraction supports the Rb-Sr whole-rock isochron age of 543 m.y. reported by Fullagar (1971).

A regression on a ^{207}Pb/^{204}Pb versus ^{235}U/^{204}Pb plot of the data (not shown) also supports the older age, yielding an isochron age of 557 ± 97 $\{(^{207}\text{Pb}/^{204}\text{Pb})_o = 15.620 \pm 0.013\}$. The growth of ^{207}Pb from the decay of ^{235}U during this time, however, has been so small that all ^{207}Pb/^{204}Pb ratios are within error of each other and of the indicated initial ratios.

Pb-Pb plots of the same data (Fig. 53) also show linear relationships. On a ^{207}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb diagram, a line drawn through all whole-rock and ore data points (including three determination on sample 12-166, Table 22), has a slope corresponding to a Pb-Pb isochron age of about 1.0 b.y. There does not seem to be any way to reconcile this result with the U-Pb and Th-Pb isochron ages. If we assume, however, that the massive pyrite bodies had slightly different initial lead isotope ratios than the felsic volcanic rocks particularly a lower $^{207}Pb/^{204}Pb$ ratio and leave the ore data out of regression calculations, the whole-rock slope corresponds to a Pb-Pb isochron age of about 450 m.y. The Pb-Pb isochron ages have very large errors because of their shallow slopes which are approaching the slope of the growth curve. Assumption that the hydrothermal cell associated with mineralization carried some component of lead from rocks other than the felsic volcanics is reasonable. The presence of mafic units within the sequence could well have been a source having lower U/Pb ratios and contributing ^{207}Pb-depleted lead to the ores. This situation would create greater variability in initial lead ratios, but if these ratios were reasonably small for $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, then U-Pb and Th-Pb isochrons would still have significance. The concordancy of the whole-rock Pb-Pb isochron with the U-Pb and the Th-Pb isochrons supports this interpretation and also supports the younger age of Haile-Brewer block slate belt rocks.

The lead content of massive pyrite at Haile is enriched by only two to three times relative to country rock. It is depleted in uranium and thorium by about 0.5 to 0.25. If the isochron intercepts are accepted as initial isotope ratios, the effects of radiogenic growth in Haile massive pyrite is evident. The initial ratios are more radiogenic than lead in other Piedmont massive sulfide deposits discussed. This relation and the regularities of ore lead relative to country rock lead indicate that the former was largely derived from the latter.

The initial lead isotope ratios indicated for Haile-Brewer block slate belt rocks by the U-Pb and Th-Pb isochron plots are significantly more radiogenic than ratios found in slate belt polymetallic massive sulfide ores. Part of the difference may be attributable to normal growth of lead due to radioactive decay, if the age difference between the Haile-Brewer area and the part of the slate belt which hosts the polymetallic ores is real. Part of the isotopic difference, however, may be due to a difference in source rocks. U-Pb zircon analyses (Fig. 52) and the ore and rocks Pb-Pb isochron (Fig. 53) suggest the presence of older (at least Grenville age), continental crustal rocks in the Haile-Brewer block. No such evidence is known for the 550 m.y. old slate belt terrain. Lead isotope data from the Haile-Brewer area do not fit the mixing model developed for Piedmont massive sulfide and Kings Mountain belt isotope patterns. Again, the difference may be due to a dominant crustal component in the Haile-Brewer block.

Lead isotope systematics in other rocks of the Haile-Brewer block

The Haile-Brewer block contains an assortment of igneous rocks of diverse ages and types (Fig. 48). Several of these were sampled for comparison with the slate belt rocks and ores.

The Great Falls granite has a Rb-Sr whole-rock age of 543 ± 155 m.y. (Fullagar, 1971). It lies within the Charlotte belt and Bell (oral communication, 1982), believes that the Pageland fault, northwestern boundary of the Haile-Brewer block, passes through the Great Falls. Three whole-rock analyses of Great Falls granite have similar lead isotope ratios (Table 21, Fig. 54). They do not vary greatly from the Pb-Pb trends formed by slate belt volcanics. There has been some speculation that the Great Falls and like plutons are intrusive equivalents of slate belt volcanic rocks. The Rb-Sr age of the Great Falls is somewhat different, although within the range of errors, from the 460 m.y. old U-Pb, Th-Pb and Pb-Pb ages indicated for Haile-Brewer block volcanics. The latter ages require independent confirmation, however, for reasons discussed above.

Great Falls data fall to the uranium loss (lead gain) side of the U-Pb isochron in Figure 51A and to the thorium

TABLE 24

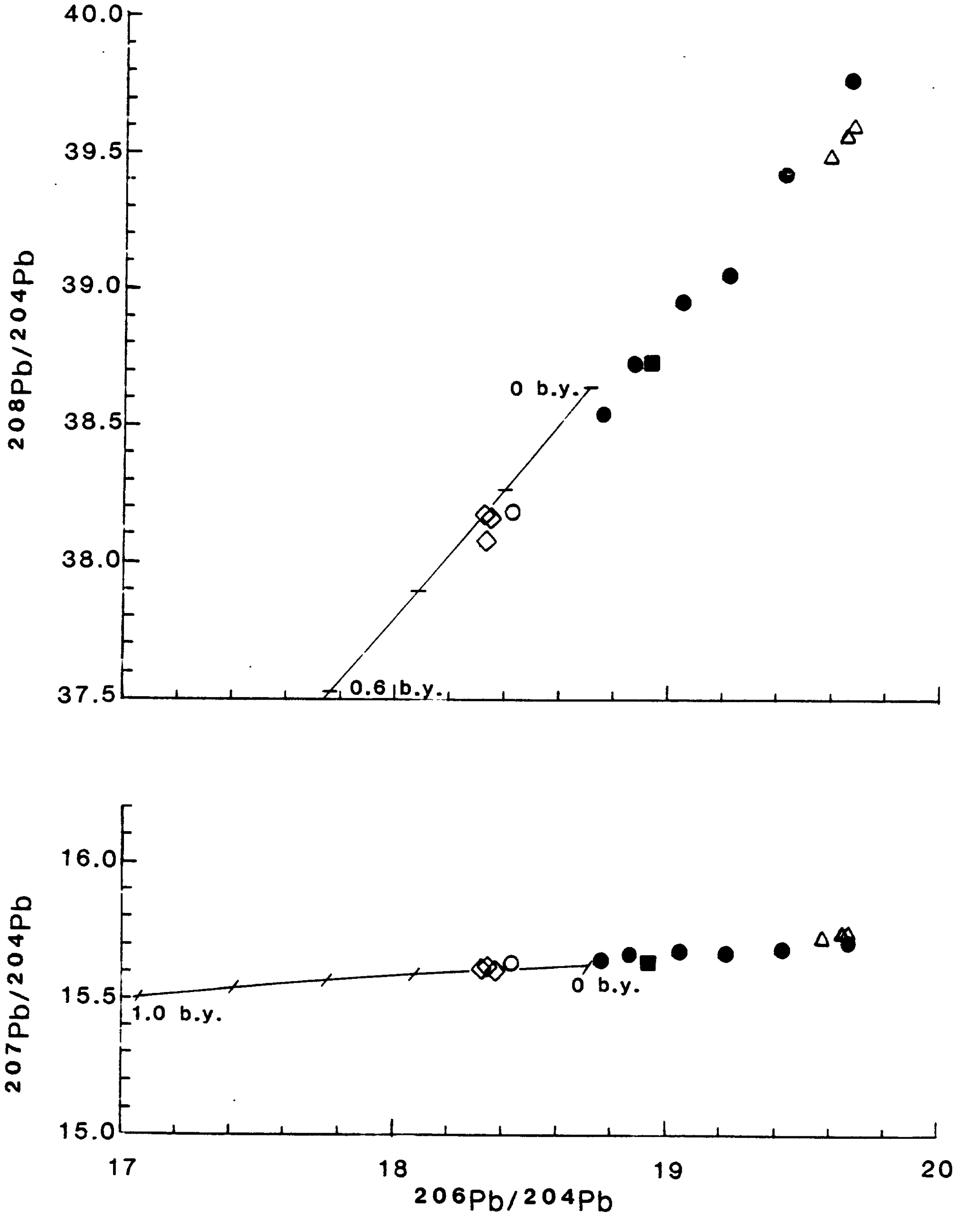
Whole-rock and K-feldspar lead isotope ratios and whole-rock U, Th and Pb concentrations for the Great Falls granite, the Pageland and Liberty Hill late orogenic plutons and the Mesozoic Flat Creek diabase dike, South Carolina. WR = whole-rock; KF = K-feldspar analysis.

Sample no.	Type	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb (----ppm-----)	U	Th	$^{238}U/^{204}Pb$	$^{232}Th/^{238}U$	$^{232}Th/^{204}Pb$	Model age (m.y.)
Great Falls granite {543 ± 155 (2σ)*}											
HB-9	WR	19.657	15.739	39.557	17.6	2.02	12.8	7.53	6.55	49.3	
HB-10	WR	19.665	15.732	39.591							
HB-11	WR	19.589	15.732	39.488	17.1	1.85	10.7	7.09	5.97	42.3	
Liberty Hill pluton {293 ± 15 (1σ)#}											
LG-101	KF	18.358	15.622	38.169							247
LG-103	KF	18.353	15.621	38.147							248
Pageland pluton {296 ± 5 (1σ)#}											
LG-201	KF	18.330	15.605	38.080							232
Flat Creek diabase dike {Triassic-Jurassic}											
DD-201	WR	18.939	15.634	38.728	3.44	.483	1.81	9.02	3.87	34.9	

* Rb-Sr whole-rock age (Fullagar, 1971)

\# Rb-Sr whole-rock age (Fullagar and Butler, 1979)

Figure 54. Lead isotope ratio diagrams showing data from various igneous rock types in the Haile-Brewer block. Massive pyrite analyses from the Haile mine are represented by one, averaged point (○). ● Carolina slate belt metavolcanic rocks; △ Great Falls granite; ◇ K-feldspars from the Liberty Hill and Pageland late orogenic granites; ■ Mesozoic Flat Creek diabase dike.


208Pb/204Pb
40.0
39.5
39.0
38.5
38.0
37.5
0 b.y.
0.6 b.y.
207Pb/204Pb
16.0
15.5
15.0
1.0 b.y.
0 b.y.
17
18
19
20
206Pb/204Pb

loss (lead gain) side of the Th-Pb isochron (Fig. 51b).

Two large late orogenic granitic plutons, the Liberty Hill and Pageland, intrude the Haile-Brewer block. These have Rb-Sr whole-rock ages of 293 ± 15 and 296 ± 5 (1σ) m.y. respectively (Fullagar, 1971; Fullagar and Butler, 1979). K-feldspar lead isotope ratios of these plutons are similar and fall in the restricted range of K-feldspar lead isotope ratios found in most Piedmont late orogenic granites (Vitrac et al., 1981; Kish and Feiss, 1982; this paper). Interestingly enough, the initial lead ratios indicated by the slate belt U-Pb and Th-Pb isochrons also fall within this range. This similarity may be largely coincidental since deriving both rock suites from the same source would require that the lead isotope ratios of such a source remained essentially unchanged for over 150 m.y. As with lead in the Great Falls granite, late orogenic pluton K-feldspar lead does not depart greatly from the trends of Haile-Brewer block slate belt lead on Pb-Pb diagrams (Fig. 54).

A sample from the Mesozoic Flat Creek diabase dike (Butler and Howell, 1977), also falls close to the regression lines (Fig. 54). Its $^{207}Pb/^{204}Pb$ ratio is only slightly lower than that in other area rock types with similar $^{206}Pb/^{204}Pb$ ratios, which is somewhat surprising for an olivine-normative mafic rock considered with a suite of silica-rich rocks. Pegram (1982) found that the Mesozoic dikes of North and South Carolina form trends that lie above (i.e. have higher ^{207}Pb/^{204}Pb ratios) the field of mid-ocean ridge basalts (MORB) on lead isotope ratio diagrams. He described the source of the dikes as isotopically distinct upper mantle material with only a small degree of contamination. Evidently this source must have had a higher U/Pb ratio than the source of more recent MORB.

The near fit of lead isotope data from the various igneous rock types of the Haile-Brewer block to single ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb regression lines could be used to support a model in which a single source, reactivated periodically, is responsible for the multiple periods of igneous activity. The major problem with such a model is the virtual identity of initial lead ratios in the late orogenic plutons (as indicated by K-feldspar lead) and the initial ratios inferred for the slate belt volcanics from U-Pb and Th-Pb isochronous relationships. The slate belt rocks are at least 150 m.y. older than the post-metamorphic plutons. The uranium content of the Liberty Hill Pluton ranges from 1.8 to 11.7 ppm and averages 3.4 ppm (Perry and Costain, 1977; Rohrer and Costain, 1977). Assuming that this is representative of uranium in its protolith, the ^{206}Pb/^{204}Pb ratio would have changed significantly in 150 m.y. Interestingly, Sinha and Mertz (1978), reported a Th-Pb isochron from the

Liberty Hill approximating an age of 300 m.y. whereas U-Pb systematics have been disturbed.

15. THE HAMME TUNGSTEN DISTRICT

The Hamme tungsten district, Vance County, North Carolina, has been the subject of a number of recent reports (Casadevall and Rye, 1980; Gair, 1977, 1981; Foose *et al*., 1980, 1981). The geology of the area around the district has been discussed by Espenshade (1947) and Parker (1963, 1968). The quartz-huebnerite veins at Hamme are associated with the emplacement of the Vance County pluton, an albite granodiorite intruding metavolcanics of the Carolina slate belt and tectonically bounded on the east by the Nutbush Creek fault zone (Fig. 55). The pluton intrudes the older, late Precambrian (600-750 m.y.) portion of the slate belt. Discordant U-Pb zircon analyses define a cord on a concordia diagram with an upper intercept at 571 ± 17 (2σ) m.y. (Table 25, Fig. 56), which probably represents the age of the rock. The lower intercept at about 130 m.y. probably has no age significance. The Pb-Pb ages of each of the three discordant fractions are consistent with the 571 m.y. intercept age.

The style of Hamme mineralization is quite different from that of other deposits considered in this report and is unique in the southern Appalachians. The tungsten-bearing quartz veins are concentrated on the western margin of the pluton near the contact with slate belt rocks.

Figure 55. Geologic map of the area around the Hamme tungsten district, North Carolina, showing sample locations. After Casadevall and Rye (1980).

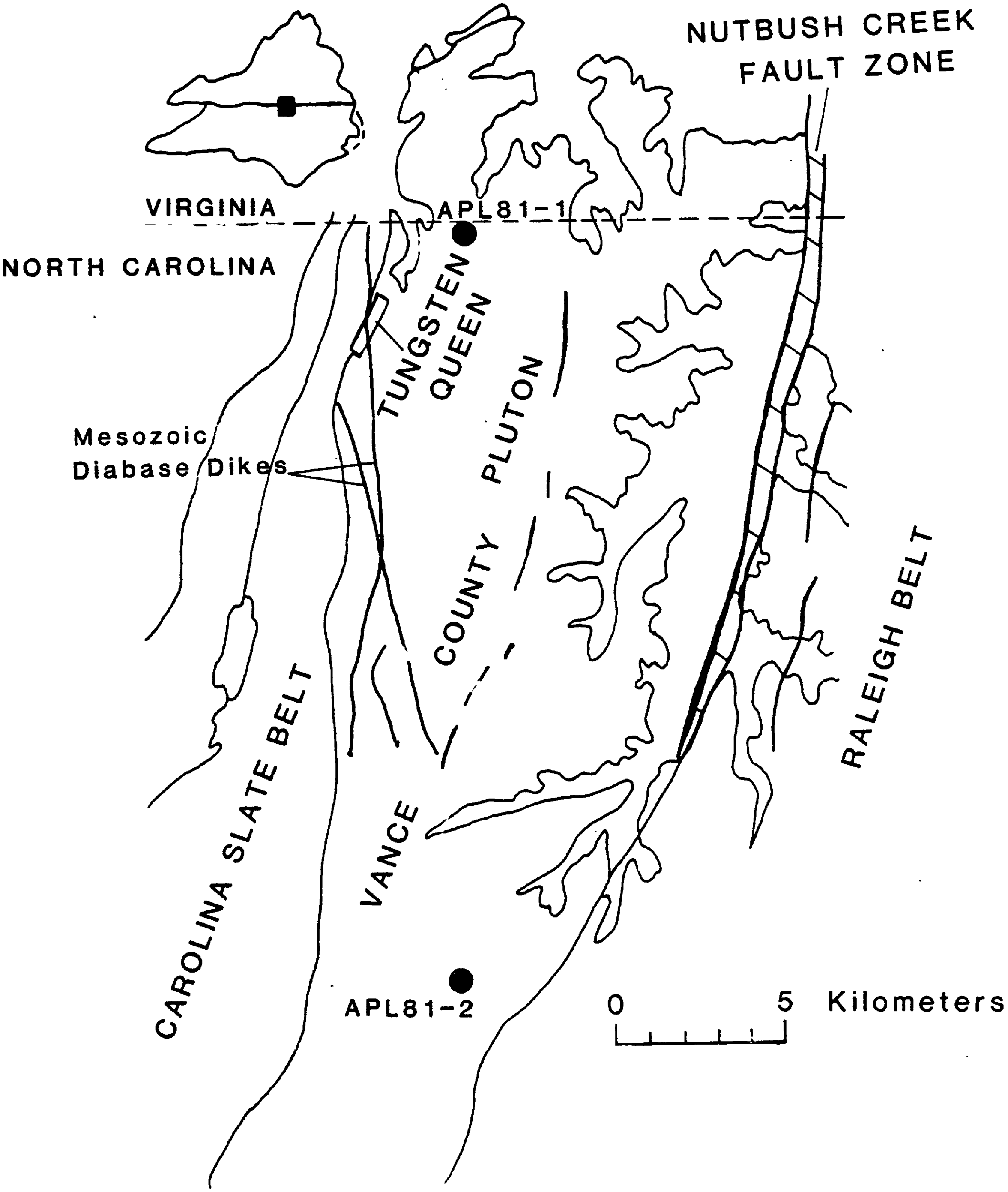

NUTBUSH CREEK
FAULT ZONE
VIRGINIA
APL81-1
NORTH CAROLINA
TUNGSTEN QUEEN
Mesozoic
Diabase Dikes
VANCE COUNTY PLUTON
RALEIGH BELT
CAROLINA SLATE BELT
APL81-2
0
5
Kilometers

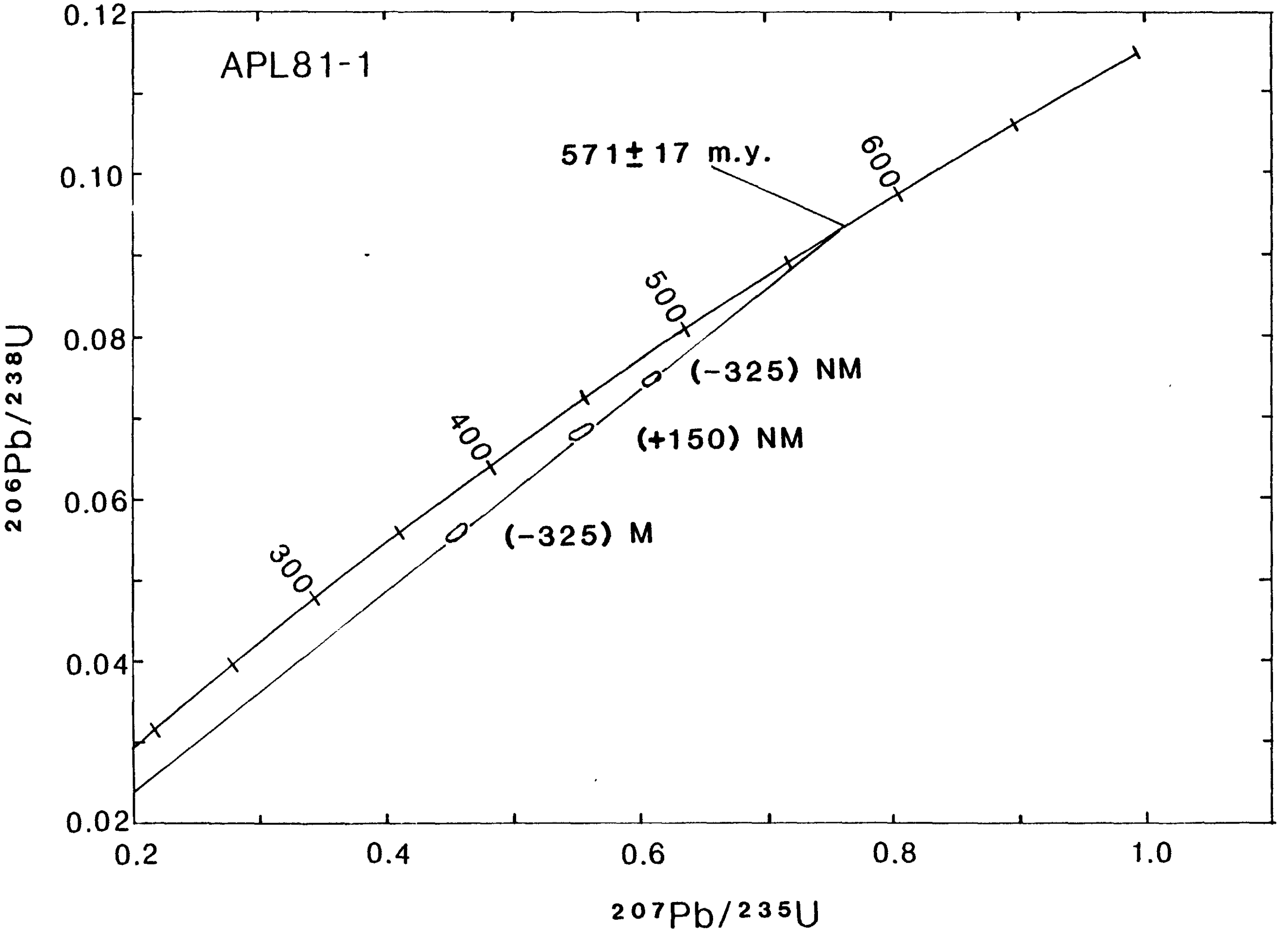
TABLE 25

Results of U-Pb analyses of zircons from the Vance County pluton, North Carolina. Size and magnetic fractions as in Table 18.

Sample no.	Pb	U	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$
	(---ppm--)		(-----------atom percent---------)				(------age (m.y.)------)		
Vance County pluton									
APL81-1									
(+150)NM	19.4	237	0.1185	73.88	6.089	19.91	424	448	572
(-325)NM	30.4	366	0.0274	77.54	5.006	17.43	463	483	582
(-325)M	38.8	598	0.0748	75.29	5.572	19.07	350	383	589

Lead isotope ratios of albite (APL81-2, Ab-R; Table 24) used as common lead correction.

Figure 56. Concordia diagram illustrating U-Pb zircon age data for the Vance County pluton.


APL81-1
571±17 m.y.
600
500
400
300
(-325) NM
(+150) NM
(-325) M
0.12
0.10
0.08
0.06
0.04
0.02
0.2
0.4
0.6
0.8
1.0
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

Glover and Sinha (1973) proposed that the Vance County pluton is comagmatic with the metavolcanics of the slate belt.

In a stable isotope study of the Tungsten Queen vein, Casadevall and Rye (1980), found that premetamorphic stable isotope systematics were largely preserved. These indicate that a predominantly meteoric water component, some input of sedimentary organic carbon, and a magmatic source of sulfur contributed to the mineralizing hydrothermal fluids. They favorably compare the origin of the Hamme vein with several well-known quartz-wolframite deposits.

Results of lead isotope studies

Five analyses of galena from the Tungsten Queen vein form a tight grouping of data (Table 26). The variation of the three lead isotope ratios is just slightly greater than analytical error (0.1%). Narrow ranges of isotopic values are common in deposits associated with igneous activity (e.g. Doe, 1978) and such an origin is indicated for the Hamme veins.

Table 26 lists results of whole-rock and albite lead isotope analyses of the Vance County pluton. A line fit through the data and the galena ratios has a slope which corresponds to a Pb-Pb age of 315 m.y. with a large error (Fig. 57). Model ages calculated for the galenas are also

TABLE 26

Galena (gn) lead isotope ratios from the Tungsten Queen vein, Hamme district, and whole-rock (WR) and albite (Ab) lead isotope compositions and WR U, Th and Pb concentrations from the Vance County albite granodiorite, North Carolina. Ab-L and Ab-R are albite leachate and residue, respectively.

Sample no.	Type	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb	U	Th	$^{238}U/^{204}Pb$	$^{232}Th/^{238}U$	$^{232}Th/^{204}Pb$
					(-----	ppm	------)			
Tungsten Queen vein										
PS-10701	gn	18.336	15.583	38.024						
TC-1736-3	gn	18.347	15.593	38.055						
*HW-104U	gn	18.337	15.600	38.071						
#HW-54U	gn	18.324	15.610	38.093						
#HW-215U	gn	18.347	15.607	38.082						
Vance County pluton										
HW-144U	WR	20.039	15.690	41.293	6.24	1.83	10.6	19.8	5.98	118.3
HW-181U	WR	18.800	15.618	38.647	15.4	1.67	6.36	6.94	3.93	27.3
HW-192U	WR	18.864	15.619	38.846	10.6	1.5	7.6	9.09	5.23	47.6
APL81-1	WR	18.865	15.621	38.765	12.2	1.27	5.49	6.68	4.47	29.8

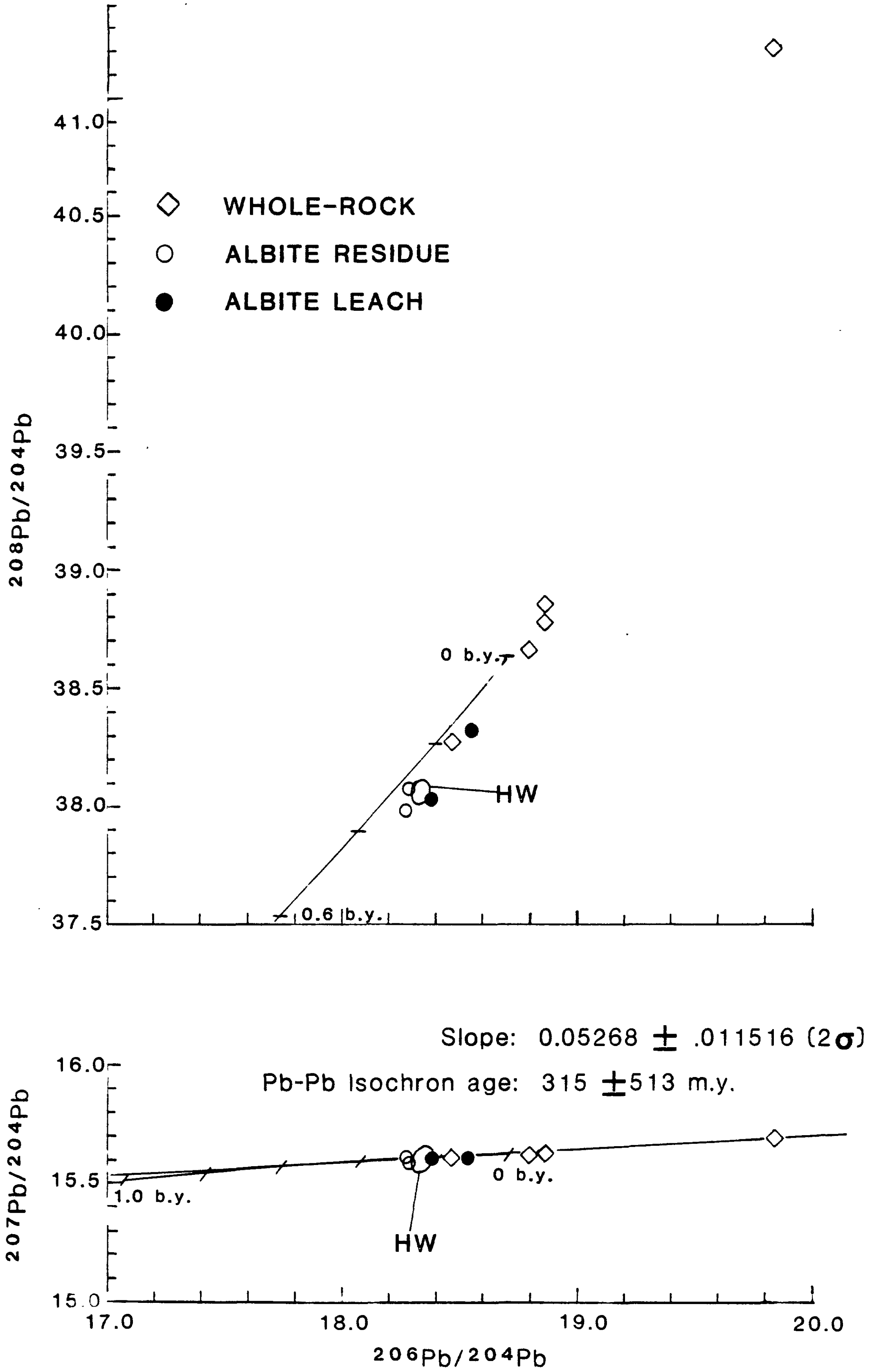
TABLE 26 (CONT.)

Sample no.	Type	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb	U	Th	$^{238}U/^{204}Pb$	$^{232}Th/^{238}U$	$^{232}Th/^{204}Pb$
					(-----	ppm	------)			
APL81-1	Ab-L	18.538	15.606	38.328						
APL81-L	Ab-R	18.292	15.595	38.076						
APL81-2	WR	18.465	15.610	38.266	8.42	0.270	2.24	2.03	8.57	17.4
APL81-2	Ab-L	18.364	15.613	38.036						
APL81-2	Ab-R	18.271	15.608	37.967						

* Doe and Zartman (1979).

\# Courtesy of B.R. Doe (U.S. Geological Survey, Reston); triple filament analyses by M.H. Delevaux (U.S. Geological Survey, Denver).

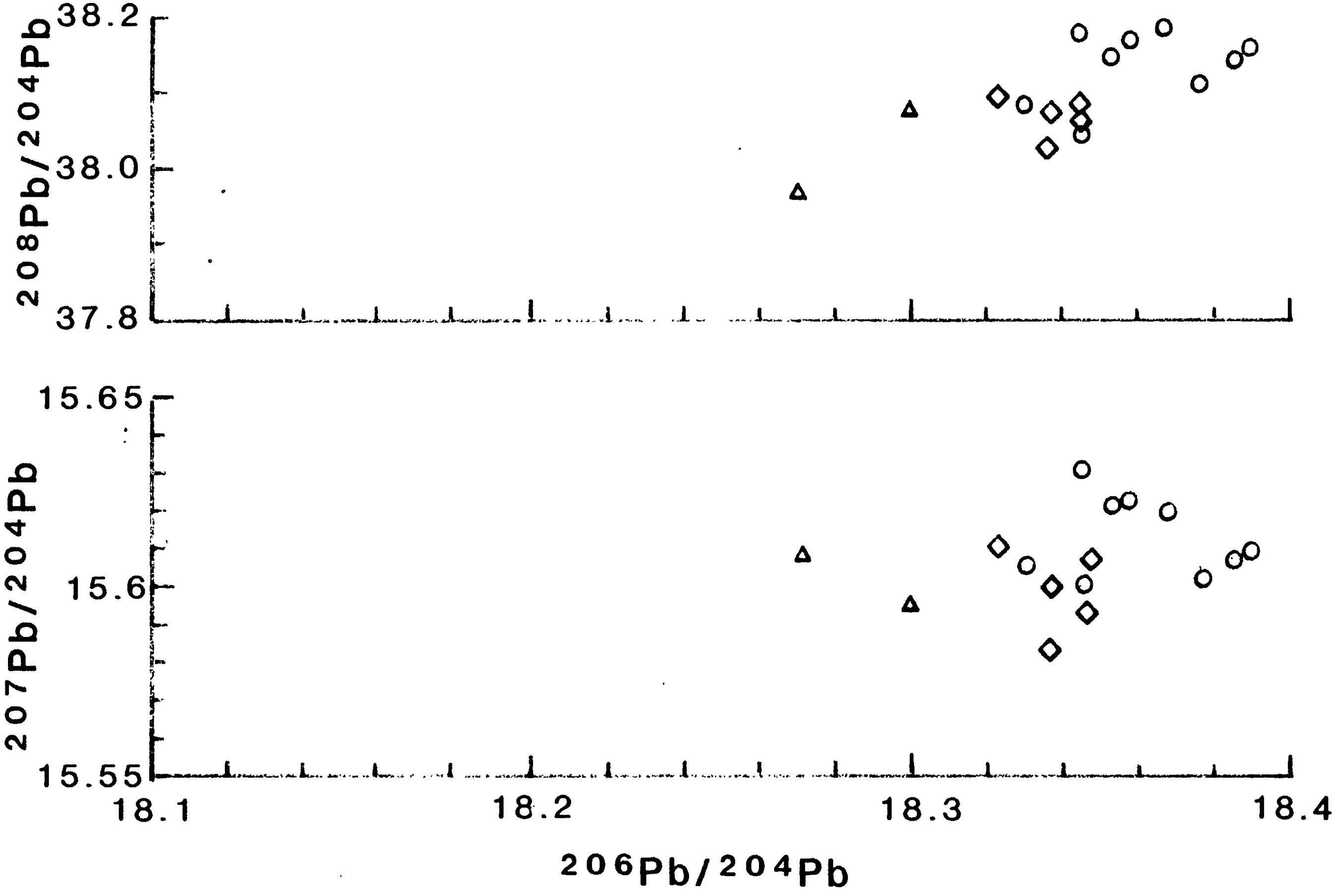
Figure 57. Lead isotope ratio diagrams illustrating results from Hamme tungsten vein galenas (HW) and from Vance County pluton whole-rock and albite determinations.



Slope: 0.05268 ± .011516 (2σ)

Pb-Pb Isochron age: 315 ±513 m.y.

Figure 58. Comparison of lead isotope ratios of Hamme galenas (◇), Vance County pluton albites (△), and late orogenic K-feldspars (○). Note the expansion of the ^{207}Pb/^{204}Pb scale necessary to resolve the data points.


208Pb/204Pb
38.2
38.0
37.8
207Pb/204Pb
15.65
15.6
15.55
18.1
18.2
18.3
18.4
206Pb/204Pb

too young (averaging 213 m.y.) for the 571 m.y. age indicated by U-Pb zircon analyses. The fields defined by Hamme galena lead ratios falls within the fields defined by K-feldspar lead isotope ratios from late orogenic (≃300 m.y.) granites (Fig. 58). Lead in albite from the Vance County pluton has ratios that are slightly less radiogenic than the galenas and the late orogenic plutons Kish and Feiss (1982) report a preliminary Rb-Sr whole-rock isochron age of about 300 m.y. for the Vance County pluton.

The Vance County granodiorite resembles other area plutons with ages of about 600 m.y. (Glover and Sinha, 1973) and geologically the zircon age of 571 m.y. is reasonable. Probably the Hamme galena lead isotope ratios have not been significantly altered by metamorphism since: 1) they have apparently retained their original lack of variation; 2) stable isotopes of sulfur, oxygen, carbon and hydrogen have retained their primary isotopic signatures; and 3) conditions of metamorphism within the quartz vein were apparently "dry" (Casadevall and Rye, 1980) which would discourage both mobilization of lead within the vein and introduction of lead from without. Why, then, are there so many auxiliary indications of a younger age for the pluton and its vein mineralization?

Zircons from the Vance County pluton are highly discordant (Fig. 56) and show that the system has been disturbed. The lower intercept of the cord defined by the zircons, at about 130 m.y., does not correlate with any geologic event in the area and so is probably meaningless. Disturbance of the U-Th-Pb systematics is also evident in the whole-rock data (Table 26). Figures 59 and 60 illustrate the effects of the disturbance. The 300 m.y. and 600 m.y. reference isochrons are shown for a range of possible initial lead ratios. The upper limit of this range is taken to be the average values for lead isotope ratios of Hamme galena and the lower is the ratios found in albite in sample APL81-2(R) (Table 26). Most data points fall in an irregular pattern between the two reference isochrons. In Figure 59, the samples fall to the uranium gain/lead loss side of the 600 m.y. isochrons. Similarly, on a $^{208}Pb/^{204}Pb$ versus $^{232}Th/^{204}Pb$ diagram (Fig. 60) the data lie on the thorium gain/lead loss side relative to the 600 m.y. isochrons. The general immobility of thorium indicates that loss of lead is the dominant feature of the U-Th-Pb system disturbance. The effects of the disturbance, which probably occurred during mid-Paleozoic metamorphism, make the present system not amenable to treatment by a simple, two-stage model. The regression through the data on a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot (Fig. 57), therefore represents a tertiary or higher order relationship and the Pb-Pb age is spurious.

Nevertheless, the galena (and albite lead isotope ratios, if representative of their original values) are radiogenic for their 570 m.y. age. They indicate that the lead in ore and rocks was derived from a source enriched in uranium and thorium relative to lead. Such a source would undergo significant changes in lead isotope ratios in 370 m.y. (570 to 300 m.y.) and so could not have served as the source of lead in late orogenic plutons. In this interpretation the coincidence of isotopic fields defined by Hamme galenas and late orogenic pluton K-feldspar is just that.

Galena and albite lead ratios are also similar to the initial ratios indicated for rocks and ores in the Haile-Brewer block, which may be as much as 150 m.y. younger than the Vance County pluton. Because there is no indication of a regional source with the extremely low U/Pb and Th/Pb ratios necessary to produce virtually no significant radiogenic lead through time, the coincidence of lead isotope ratios in rocks and ores of diverse ages must have some other, as yet unknown, significance. If each set of ratios represents initial values, then each subsequent event must have derived lead from a lower U/Pb and Th/Pb protolith. That is, Hamme tungsten vein galena drew lead from a higher U/Pb source than did rocks and ores of the Haile-Brewer block, which in turn had a more uranium enriched source of lead than most late orogenic plutons.

Hamme lead isotope ratios also indicate that sources of lead were different from those contributing to Piedmont massive sulfides. If Hamme galena lead isotopes are representative of their original values at 570 m.y., then they are substantially more radiogenic than the most radiogenic Piedmont massive sulfide deposit galena (Mineral, Virginia), which may reflect a greater upper continental crustal component contributing lead to the Hamme veins. The similarity of Hamme galena and feldspar lead to initial ratios indicated for Haile-Brewer area rocks and ore may suggest a similar source area.

Figure 59. $^{206}Pb/^{204}Pb$ versus $^{238}U/^{204}Pb$ plot of Vance County pluton whole-rock data, with 600 m.y. and 300 m.y. reference isochrons. "G" and "F" refer to possible initial isotope ratios. G = average of galena lead isotope ratios. F = ratios in APL81-2 (Ab-R).

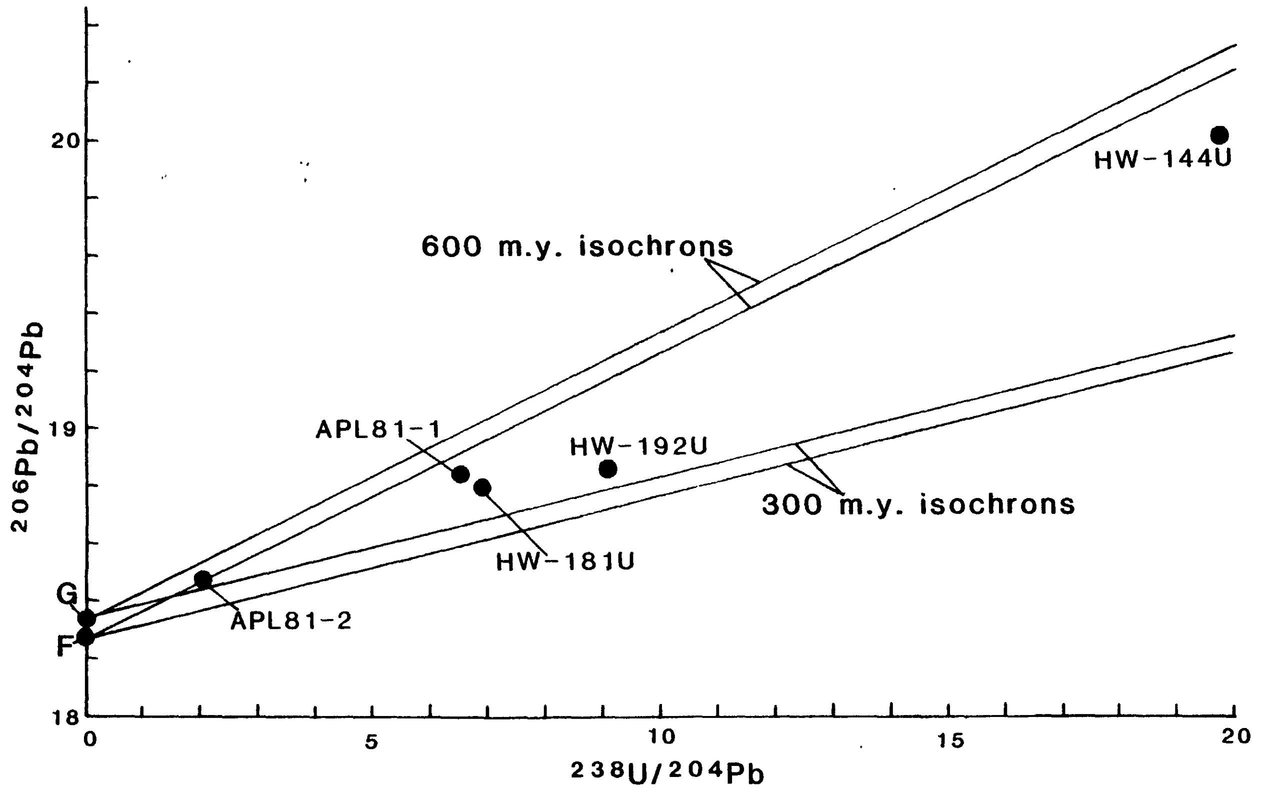
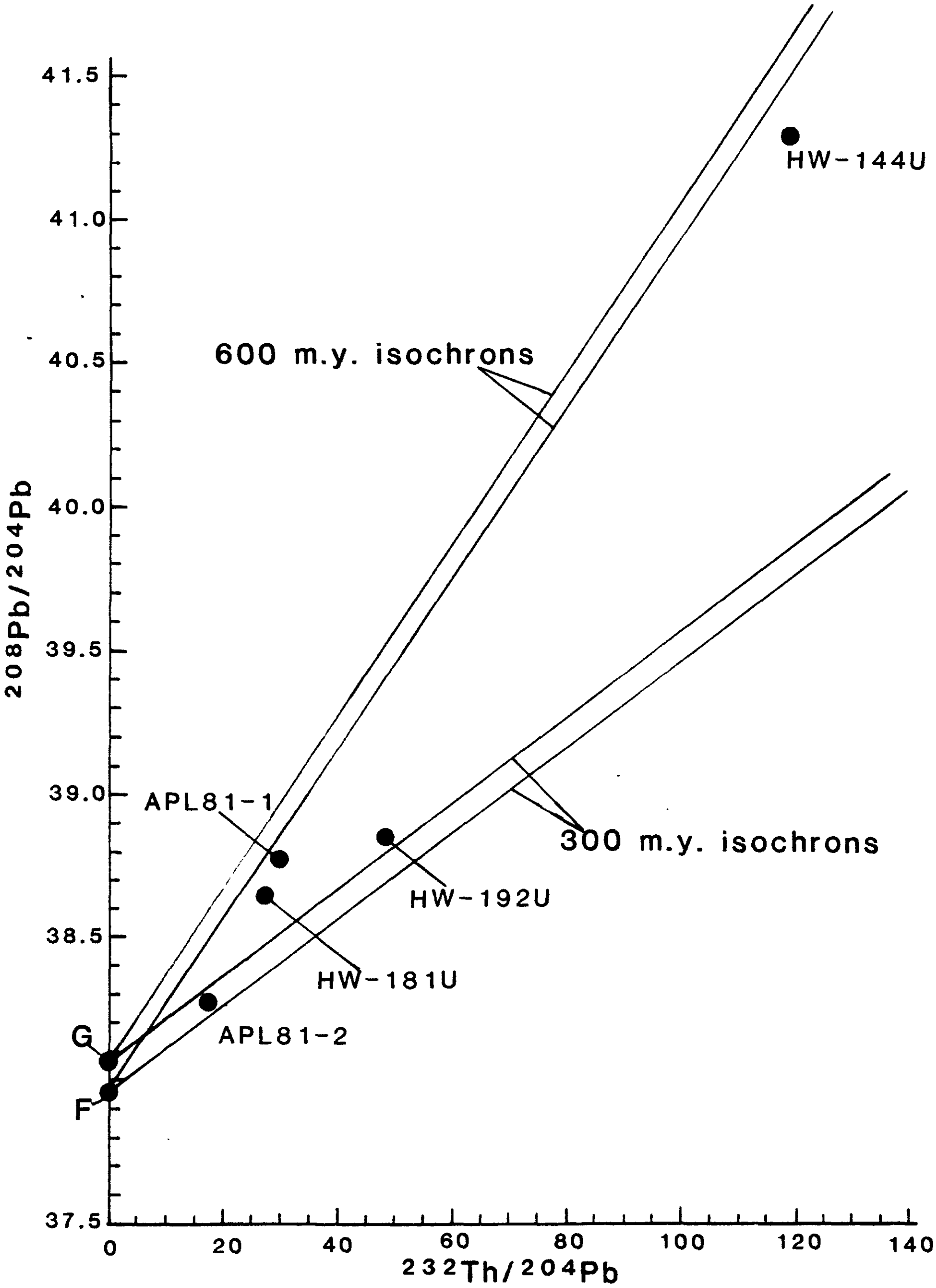

600 m.y. isochrons
300 m.y. isochrons
HW-144U
HW-192U
HW-181U
APL81-1
APL81-2
G
F
206Pb/204Pb
18
19
20
238U/204Pb
0
5
10
15
20

Figure 60. $^{208}Pb/^{204}Pb$ versus $^{232}Th/^{204}Pb$ plot of Vance County pluton whole-rock lead isotope ratios, with 600 m.y. and 300 m.y. reference isochrons. "G" and "F" as in figure 59.


41.5
41.0
40.5
40.0
39.5
39.0
38.5
37.5
208Pb/204Pb
0
20
40
60
80
100
120
140
232Th/204Pb
600 m.y. isochrons
300 m.y. isochrons
HW-144U
APL81-1
HW-192U
HW-181U
APL81-2
G
F

PART IV. COMPARISONS SPECULATIONS AND SUMMARY

16. LEAD ISOTOPE VARIATION IN THE CRYSTALLINE SOUTHERN APPALACHIANS

Lead in Sulfide Deposits

Lead in Piedmont province sulfide deposits has distinctly different lead isotope patterns than that in Blue Ridge deposits. Lead in Silver Hill-type massive sulfides of the Piedmont is somewhat radiogenic for the age of mineralization and forms steep regional slopes on lead isotope diagrams. Galena from Kings Mountain belt deposits forms a lead isotope trend which mimics the massive sulfide trend. Blue Ridge sulfide deposits generally contain lead that is much too radiogenic for their late Precambrian age, and the largest deposits (Ducktown, Gossan Lead) contain the most radiogenic lead. Blue Ridge galena lead isotope ratios lie along a relatively shallow slope on lead isotope plots. Figure 61 illustrates the fields defined by some southern Appalachian ores and rocks on $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagrams. For clarity, only data from Ducktown is used to represent Blue Ridge deposits.

The different lead isotope trends found in Piedmont and Blue Ridge galenas reflects differences in sources of lead. The steep regional slopes observed in Piedmont galena lead

Figure 61. Summary lead isotope ratio plots of southern Appalachian sulfide deposits. PMS - Piedmont massive sulfides; KMB - Kings Mountain belt; LOG - Late orogenic granites.

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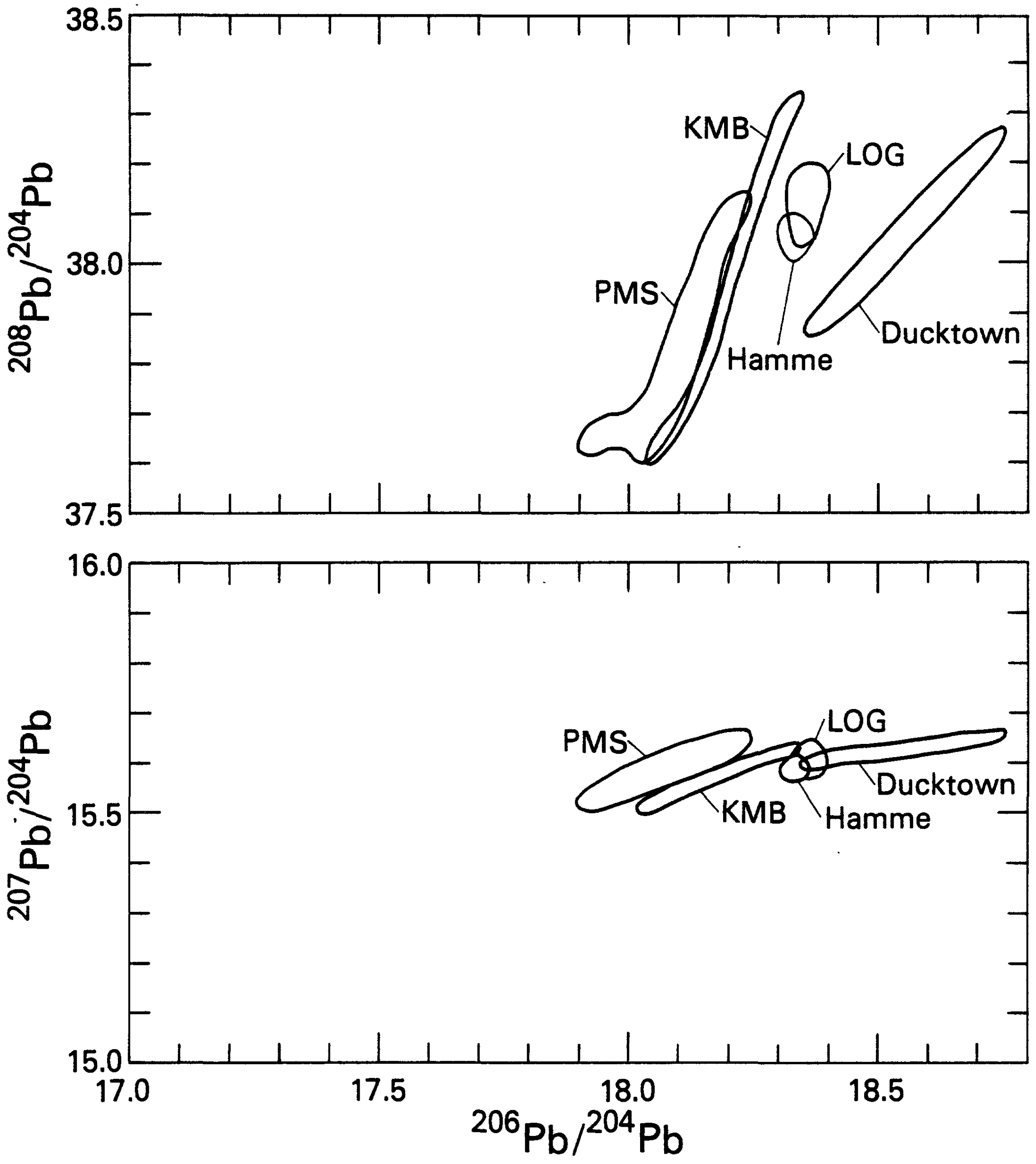

38.5
38.0
37.5
$^{208}Pb/^{204}Pb$
KMB
LOG
PMS
Hamme
Ducktown
16.0
15.5
15.0
$^{207}Pb/^{204}Pb$
LOG
PMS
Ducktown
KMB
Hamme
17.0
17.5
18.0
18.5
$^{206}Pb/^{204}Pb$

isotopes represents the mixing of low $^{207}Pb/^{204}Pb$ mantle-derived lead with higher $^{207}Pb/^{204}Pb$ upper continental crustal lead. Geographic patterns of lead isotopes suggests that upper continental material was of greater importance in the northeastern deposits and that the mantle-derived component increased to the southwest.

The shallow slope defined by lead isotopes in Blue Ridge deposits is the result of derivation of most of the lead from enclosing sedimentary sequences. The apparent correlation of sulfur and lead isotope ratios in Ducktown ores indicates that some other source probably contributed to the deposit, but the predominance of radiogenic lead suggests that the larger portion of lead was derived from a sedimentary source. The narrow range of $^{207}Pb/^{204}Pb$ relative to $^{206}Pb/^{204}Pb$ ratios in all Blue Ridge galenas measured indicates that no greatly older source contributed to lead mineralization. The range of Blue Ridge data may reflect a broad mixing line with the least radiogenic galena (Faber vein), deriving the bulk of its lead directly from Grenville-age basement rocks and the most radiogenic (Ducktown, Gossan Lead) deriving the greater part of their lead from uranium-rich clastic sediments of the Ocoee and Ashe sequences.

These sources of lead deduced from lead isotope patterns in Piedmont and Blue Ridge sulfide deposits are a reflection of the different tectonic environments in which mineralization occurred. The thick sedimentary sequences associated with late Precambrian rifting are evident in the highly radiogenic lead in Blue Ridge stratabound sulfides and in the range in isotopic values observed in Ducktown galenas. The restricted lead isotopic ranges found in Piedmont massive sulfides are typical of volcanic exhalative deposits in volcanic arc settings.

Lead in igneous feldspar

K-feldspar in late orogenic plutons (≈300 m.y.) display relatively narrow ranges of lead isotope ratios, as illustrated in Figure 62. The analysis of K-feldspar from the Castalia pluton, North Carolina (Vitrac _et_ _al_., 1981) is not included in these fields. Not only is its lead significantly more radiogenic than that in other late orogenic plutons but it has anomalously high initial $^{87}Sr/^{86}Sr$ relative to most of the others of this group (Fullagar and Butler, 1979).

Table 28 and Figure 62 collate all currently available feldspar lead isotope data from southern Appalachian igneous rocks. Other than the Castalia pluton, there is no difference in K-feldspar lead isotope ratios between the eastern and western trends of late orogenic plutons. Fullagar and Butler (1979), report that initial $^{87}Sr/^{86}Sr$

TABLE 28

Collation of available feldspar lead isotope data and corresponding strontium and oxygen isotope data from southern Appalachian igneous rocks, arranged by age groups. Lead isotope analyses of the Vance County pluton are of albite; all others are K-feldspar determinations.

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Model age (m.y.)	Age (m.y.)	Method	$\left(\frac{^{87}Sr}{^{86}Sr}\right)_o$	$\delta^{18}O$ (mean)	*Location	#Reference
Late orogenic granites (325 to 265 m.y.)										
Pageland, S.C.					296	Rb-Sr	.7038	6.0	E,CSB	1,9
1302	18.385	15.607	38.14	195						2
LG-201	18.330	15.605	38.080	232						3
Liberty Hill, S.C.					293	Rb-Sr	.7046	7.0	E,CSB	1,9
LG-101	18.358	15.622	38.169	247						3
LG-103	18.353	15.621	38.147	248						3
Lilesville, N.C.					326	Rb-Sr	.7047	-	E,CSB	1
1285	18.377	15.601	38.11	188						2
1285	18.389	15.609	38.158	196						4
Castalia, N.C.					313	Rb-Sr	.7141	-	E,CSB	1
1141	18.481	15.602	38.12	111						2
Sparta, Ga.					289	Rb-Sr	.7035	5.5	E,KB	1,9
GA4B	18.345	15.590	38.04	190						2
York, S.C.					322	Rb-Sr	.7044	8.2	W,CB	1,9
1372	18.344	15.631	38.18	276						2

3/D

TABLE 28 (CONT.)

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Model age (m.y.)	Age (m.y.)	Method	$\left(\frac{^{87}Sr}{^{86}Sr}\right)_o$	$\delta^{18}O$ (mean)	*Location	#Reference
Late orogenic granites (cont.)										
High Shoals, N.C.					320	U-Pb	-	-	W,KMB	3
APL81-23	18.367	15.619	38.186	234						3
420 to 340 m.y. intrusives										
Salisbury, N.C.					402	Rb-Sr	.7032	-	CB	5
553	18.319	15.593	37.961	216						4
Cherryville, N.C. (pegmatitic phase)					341	Rb-Sr	.7376	10.0	IP	6,9,11
APL81-21	18.211	15.648	38.171	408						3
Foote mine spodumene pegmatite, N.C.					340	Rb-Sr	.7326	-	IP	6,11
APL81-23	18.327	15.650	38.204	326						3
Whiteside, N.C.					≃400	Rb-Sr	≃.707	-	EBR	4,10
S	18.418	15.632	38.278	222						4
Spruce Pine pegmatite, McKinney mine, N.C.					≃390	Rb-Sr	≃.710	-	EBR	4,10
1268	18.403	15.638	38.242	246						4
620 to 500 m.y. plutons										
Roxboro granodiorite, N.C.					620- 575	U-Pb	-	-	CSB	7
K81-8	18.729	15.619	38.426	<0						3

TABLE 28 (CONT.)

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Model age (m.y.)	Age (m.y.)	Method	$\left(\frac{^{87}Sr}{^{86}Sr}\right)_o$	$\delta^{18}O$ (mean)	*Location	#Reference
620 to 500 m.y. intrusives (cont.)										
Vance County pluton, N.C.					571	U-Pb	-	-	CSB	3
APL81-1	18.292	15.595	38.076	240						3
APL81-2	18.271	15.608	37.967	283						3
Mount Rogers Formation rhyolites					690-640	Rb-Sr, U-Pb	-	-	WBR	8
MR-102	18.353	15.623	38.323	252						3
MR-103	18.511	15.624	38.507	136						3
MR-106	17.640	15.576	37.841	692						3
Grenville-age granitic pegmatite					≈1000		-	-	WBR	
GG-101	17.563	15.561	36.855	722						3

* Location codes

E	Eastern trend of plutons
W	Western trend of plutons
CSB	Carolina slate belt
ESB	Eastern slate belt
KB	Kiokee belt
CB	Charlotte belt
KMB	Kings Mountain belt
IP	Inner Piedmont
EBR	Eastern Blue Ridge
WBR	Western Blue Ridge

\# References

1. Fullagar and Butler, 1979
2. Vitrac *et al.*, 1981
3. This study
4. Kish and Feiss, 1982
5. Fullagar *et al.*, 1971
6. Kish, 1977
7. Glover and Sinha, 1973
8. Odom and Fullagar, 1971, 1982
9. Wenner, 1981
10. Kish *et al.*, 1976
11. Kish, written communication, 1982

Figure 62. Lead isotope ratios of feldspars from southern Appalachian igneous rocks compared with the fields defined by galena lead isotope ratios of southern Appalachian sulfide deposits. Abbreviations are the same as in figure 61. □ Grenville-age granitic pegmatite; ✕ Mount Rogers Formation; ◇ Vance County pluton; + Whiteside pluton and Spruce Pine pegmatite; ○ Salisbury and Roxboro plutons; △ Cherryville Quartz Monzonite, spodumene pegmatite and "High Shoals" Gneiss; ● Castalia pluton.

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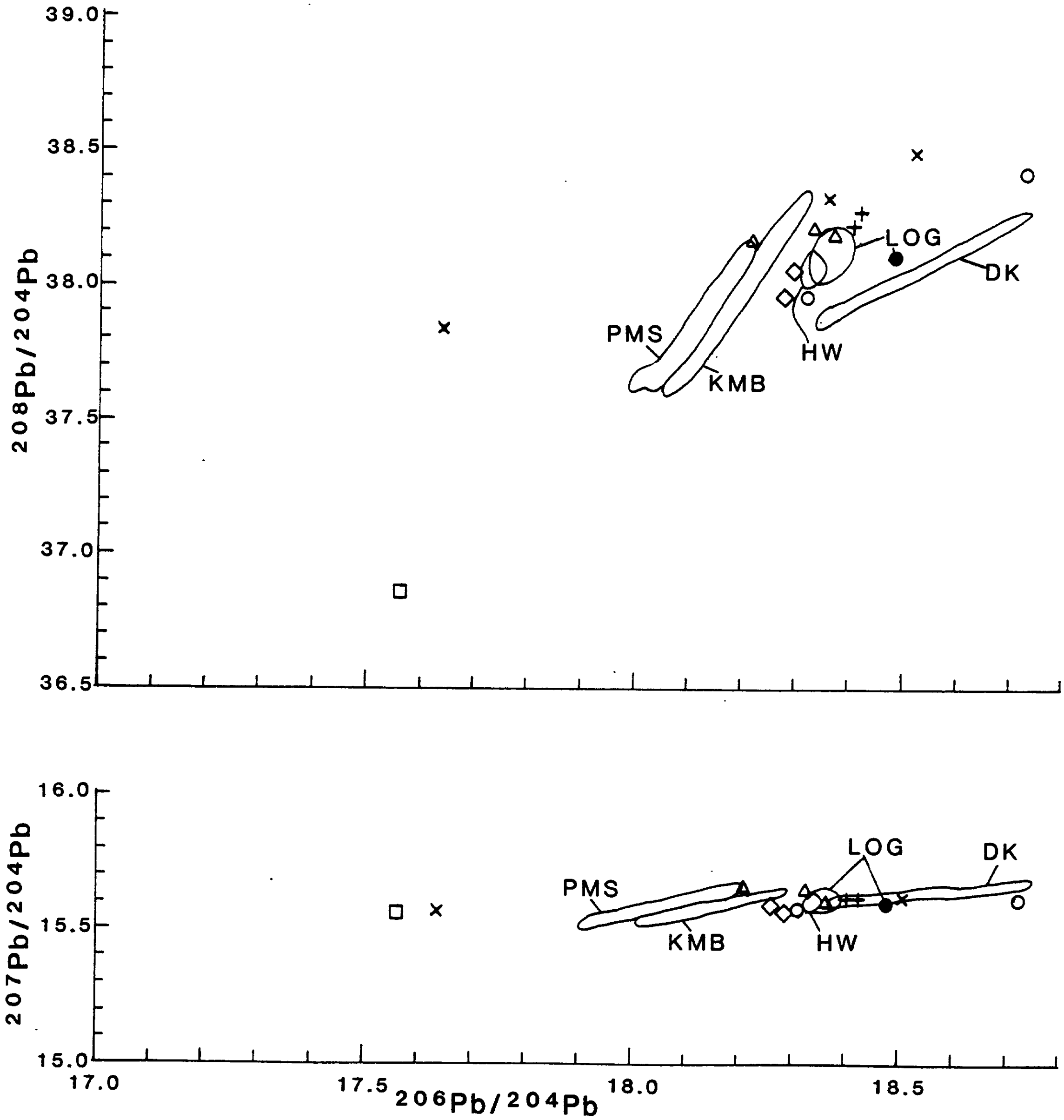

39.0
38.5
38.0
37.5
37.0
36.5
208Pb/204Pb
PMS
KMB
LOG
HW
DK
16.0
15.5
15.0
207Pb/204Pb
PMS
KMB
LOG
HW
DK
17.0
17.5
18.0
18.5
206Pb/204Pb

ratios are also similar in the two trends. In contrast, Wenner (1981) reports that oxygen isotopic composition of late orogenic granites is generally greater in western trend than eastern trend plutons. Similarly, Sando and Hart (1982), reported that initial neodymium isotope ratios are distinctly lower in Charlotte belt plutons than in those associated with the Carolina slate belt.

From the data presented in Table 28 and Figure 62, there are no great differences in feldspar lead isotope ratios in most of the various igneous age groups of the southern Appalachians. The exceptions are the Grenville-age pegmatite, which contains much less radiogenic lead than younger rocks, and K-feldspars from Mount Rogers Formation rhyolites, which have a wide range of $^{206}Pb/^{204}Pb$ ratios (17.64 to 18.51) and of $^{208}Pb/^{204}Pb$ ratios (37.84-38.51). K-feldspar from the 575 to 620 m.y. old Roxboro granodiorite (Glover and Sinha, 1973; Briggs et al., 1978) contains much more radiogenic lead than other southern Appalachian plutons, probably reflecting the low lead content (qualitative observation) of the feldspar.

If these exceptions are excluded, the total ranges of lead isotope ratios of feldspars from igneous rocks ranging in age from 620 to 290 m.y. are: $^{206}Pb/^{204}Pb$ = 18.21 to 18.48 (1.5%); $^{207}Pb/^{204}Pb$ = 15.59 to 15.65 (0.4%); and 37.96 - 38.28 (0.8%). If we also exclude the Castalia K-feldspar analysis the range of $^{207}Pb/^{204}Pb$ ratios remains the same, but the $^{206}Pb/^{204}Pb$ range is reduced to 18.21-18.39 (1.0%) and the $^{208}Pb/^{204}Pb$ range becomes 37.96-38.20 (0.6%). These ranges include the 571 ± 17 m.y. Vance County pluton, a ≃350 m.y. pluton and pegmatite from the Inner Piedmont belt, and two Paleozoic plutons of the eastern Blue Ridge, as well as 300 m.y.-old plutons.

The data presented in Table 28 is far from a complete accounting of feldspar lead isotopes in southern Appalachian plutons, but is all that is currently available. If we assume that the feldspar lead is representative of the isotope ratios prevailing at the time of emplacement, however, these preliminary results indicate a remarkable uniformity of isotope compositions in plutons of diverse ages and tectonic settings. The similarity is most remarkable for the Inner Piedmont and Blue Ridge plutons. These areas are known to be underlain by Grenville-age basement rocks (Hatcher and Zietz, 1980). The Cherryville Quartz Monzonite has a much higher initial $^{87}Sr/^{86}Sr$ value than plutons southeast of the Inner Piedmont and also has significantly higher oxygen isotope compositions (Kish, 1977; Wenner, 1981). Feldspar lead isotope composition from the Cherryville, however are only slightly different than in most other Paleozoic plutons. Perhaps of significance, the Cherryville contains the least radiogenic $^{207}Pb/^{204}Pb$ lead of the "main group" despite its ≃350 m.y. age. The nearby spodumene pegmatites have a similar age and also have a high initial $^{87}Sr/^{86}Sr$ ratio (Kish, 1977). K-feldspar from the Foote mine pegmatite, however, has lead isotope ratios that are similar to those in late orogenic plutons. K-feldspars in the Whiteside pluton and a Spruce Pine district pegmatite in the Blue Ridge of North Carolina, also contain lead similar in isotopic composition to the late orogenic granites (Kish and Feiss, 1982). Lead in K-feldspar from the ≃400 m.y. Salisbury pluton and in albite from the ≃600 m.y. Vance County pluton is only slightly less radiogenic than the late orogenic group.

If these few examples are representative of other plutons of their age and tectonic affilitations, then the relatively narrow range of lead isotope ratios is perplexing. Repeated withdrawal of lead from a single regional source requires that the source have an unusually low U/Pb ratio in order to produce little lead isotopic variation in 300 m.y. of Appalachian igneous activity. Wenner (1981) has shown that late orogenic plutons in the Charlotte and Carolina slate belts have significantly lower oxygen isotope compositions than those of the Inner Piedmont, and that these generally correlate with I-type granite characteristics in the Charlotte and slate belts and S-type characteristics in the Inner Piedmont. Presumably the Blue Ridge Paleozoic intrusives would show greater similarity to Inner Piedmont plutons. Wenner's data are not consistent with a single source.

The Cherryville Quartz Monzonite and spodumene pegmatites of the Inner Piedmont generally have initial $^{87}Sr/^{86}Sr$ ratios (Kish, 1977) significantly higher than Charlotte and Carolina slate belt plutons. Inner Piedmont granitic gneisses, generally have intermediate initial $^{87}Sr/^{86}Sr$ ratios (e.g. Harper and Fullagar, 1981).

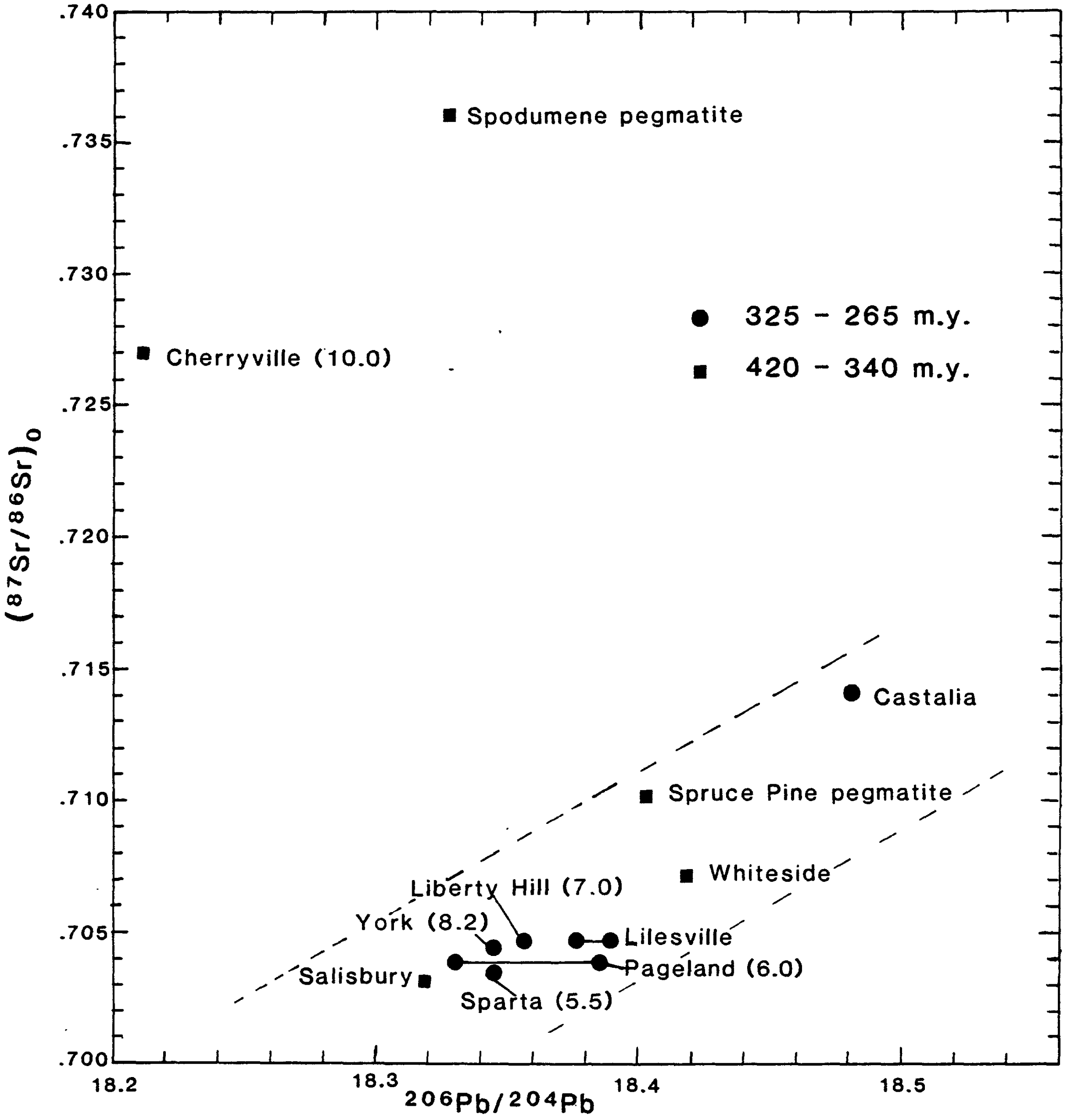
A single regional source of lead to explain the relative constancy of lead isotopic ratios must have had low U/Pb ratios, but its $^{207}Pb/^{204}Pb$ ratio need not have been particularly low. One possible source fitting these criteria is cratonized Grenville-age crust. Such a high grade terrain would be expected to have low U/Pb values but need not have the low $^{207}Pb/^{204}Pb$ ratios typical of similar but much older rocks. Geophysical data (Hatcher and Zietz, 1980) as well as oxygen isotope and petrographic criteria, however, rule out the ubiquitous presence of such crustal rocks beneath the Piedmont required for this source model. Further, although a few very high grade areas of Grenville age rocks occur locally, granulitic basement is relatively scarce in outcrop.

A mixing model covering 300 m.y. of igneous activity in distinct tectonic settings also seems inviable. Presumably the components available for mixing would be different in a 600 m.y. volcanic arc and in a 300 m.y. post-collision terrain, and would have distinct isotopic characteristics. Wenner (1981) found two distinct patterns of correlation between oxygen and initial strontium isotope ratios in late orogenic plutons which can be interpreted as simple mixing trends. The Charlotte and Carolina slate belt trend suggests a mafic igneous protolith mixed with small amounts of sedimentary material. The Inner Piedmont trend indicates a more sialic igneous source also mixed with some sedimentary material. The broad positive correlations between initial strontium and lead isotope ratios (Figure 63) supports a general mixing model.

If it is assumed that the mafic protolith of the Charlotte and slate belt plutons is the same as or derived from the same source as the least radiogenic galenas in Piedmont massive sulfides, the effective $^{238}U/^{204}Pb$ ratio of the protolith must have been greater than 10.7 for the period between 550 and 300 m.y. to produce the observed lead isotope ratios in the late orogenic plutons. This value is somewhat high for mafic igneous material, perhaps reflecting the sedimentary component observed in oxygen isotope values (Wenner, 1981). Such a model does not explain, however, why feldspar lead isotope compositions are similar in plutonic rocks of varying age in the eastern Blue Ridge, Inner Piedmont, and the Piedmont southeast of the Inner Piedmont.

That galena in Hamme tungsten veins (≃ 600 m.y.), initial ratios in Haile-Brewer block felsic volcanic rocks (≃ 465? m.y.), and late orogenic K-feldspars (≃ 300 m.y.) have similar lead isotope ratios has been noted previously. A possible explanation for this coincidence is that each succeeding igneous event drew a greater proportion of its lead from a U/Pb and Th/Pb-depleted source. In such an interpretation the similarity of lead isotope ratios is fortuitous, and reflects the different mix of source materials available at various locations through time.

Figure 63. $(^{87}Sr/^{86}Sr)_o$ versus $^{206}Pb/^{204}Pb$ plot for some southern Appalachian igneous rocks. Sources of data are listed in table 28. Numbers after names are average oxygen isotope ratios from Wenner (1981). Dashed lines are to emphasize the broad, positive correlation between initial strontium and lead isotope compositions. The lines connect multiple K-feldspar lead analysis from same pluton.


.740
.735
.730
.725
.720
.715
.710
.705
.700
$(^{87}Sr/^{86}Sr)_0$
18.2
18.3
18.4
18.5
$^{206}Pb/^{204}Pb$
● 325 - 265 m.y.
■ 420 - 340 m.y.
Spodumene pegmatite
Cherryville (10.0)
Castalia
Spruce Pine pegmatite
Whiteside
Liberty Hill (7.0)
York (8.2)
Lilesville
Pageland (6.0)
Salisbury
Sparta (5.5)

17. A MODEL FOR THE PATTERNS OF LEAD ISOTOPES IN SOUTHERN APPALACHIAN ROCKS AND ORES

Although more data are clearly required to construct a definitive "plumbotectonic: model for the southern Appalachians, a preliminary attempt may be made using currently available information.

The lead isotope data of southern Appalachian rocks and ores appears to form patterns which may be related to distinct crustal blocks. These blocks may be characterized by the nature of the basement over which the rocks developed. The data indicates three broad crustal regimes which will be referred to as regions underlain by basements I, II and III.

Basement I

The Blue Ridge and Inner Piedmont, on the western side of the southern Appalachian orogen, appear to have been predominantly underlain by continental crust of Grenville age: Basement I (Fig. 64). Basement I corresponds to the eastern edge of North America during late Precambrian to Cambrian time. It probably was thinner under the Inner Piedmont than under the Blue Ridge, and may have been locally discontinuous, due to late Precambrian rifting, in East-

Figure 64. "Crustal block" map of the southern Appalachians illustrating areas characterized by Type I, II, or III lead isotope ratios.

Diagonal lines - Basement I type lead.

Crosshatch - Basement II type lead.

Light stipple - Basement III (mixed) type lead.

Heavy stipple - Mesozoic basins.

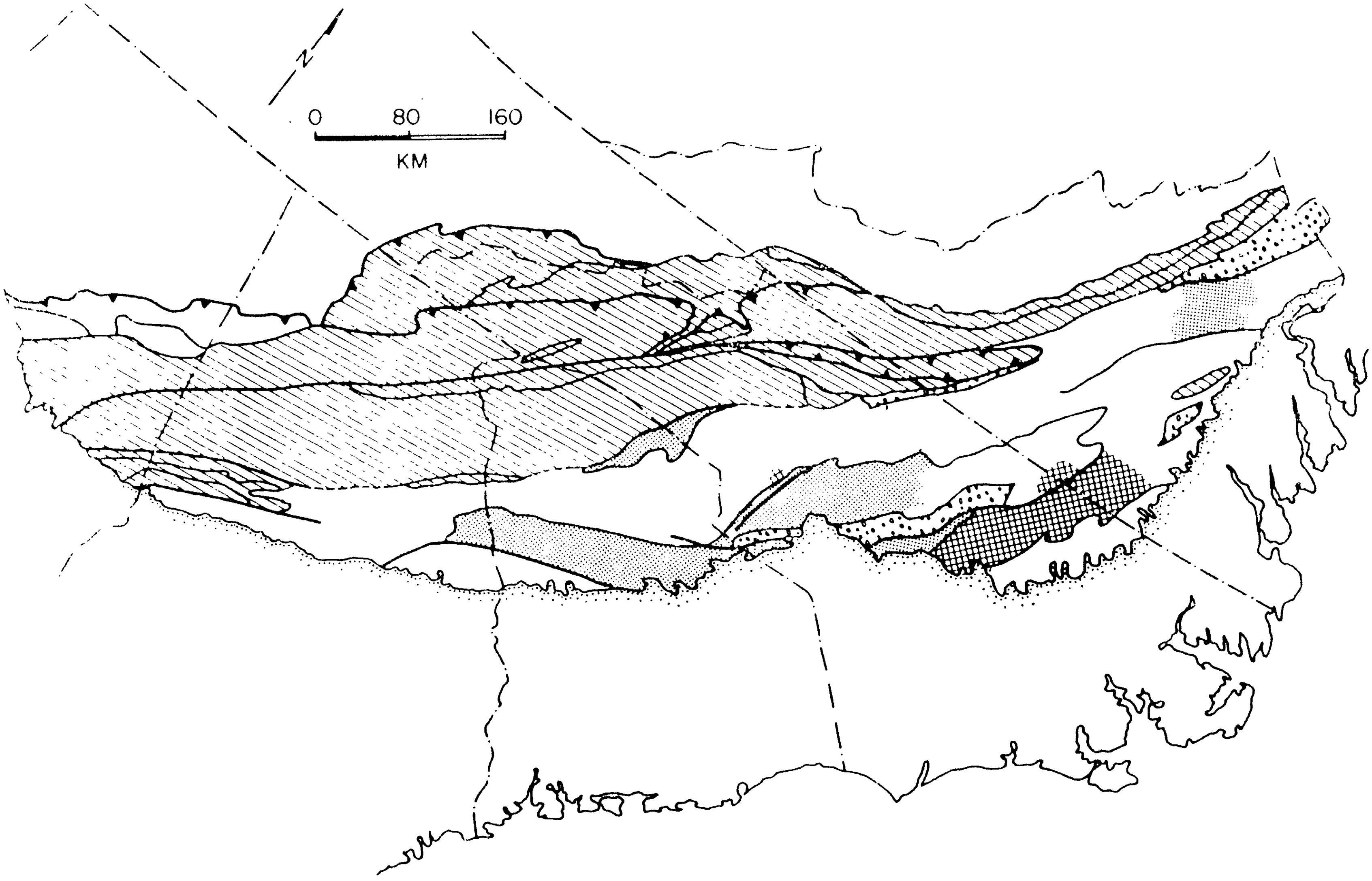
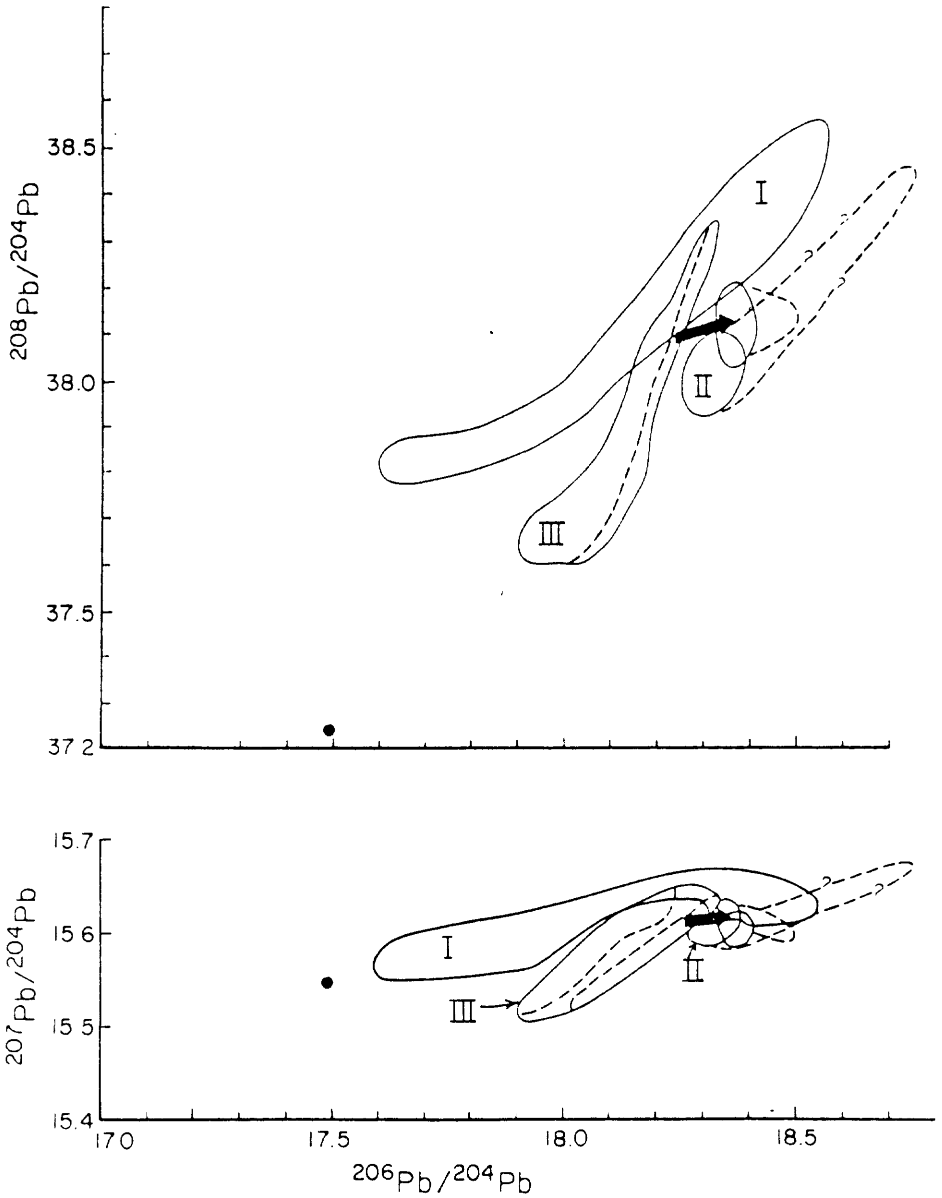

N
0
80
160
KM

Figure 65. Lead isotope ratio diagrams illustrating fields defined by lead of basement type I, II, and III and in late orogenic plutons. Dashed field with "?" extends the field of basement II to include the radiogenic Roxboro pluton feldspar. Heavy arrows indicate a possible lead isotope growth path from mixed basement III- type lead that could result in lead isotopes of late orogenic pluton K-feldspars. The field of late orogenic plutons also has a dashed extension to include the anomalous Castalia pluton. Filled dot (●) represents the lead isotope ratios of the Grenville-age granitic pegmatite.


208Pb/204Pb
38.5
38.0
37.5
37.2
I
II
III
207Pb/204Pb
15.7
15.6
15.5
15.4
I
II
III
17.0
17.5
18.0
18.5
206Pb/204Pb

ern Blue Ridge where mafic igneous rocks are relatively common.

Lead isotope ratios of igneous rocks and K-feldspars and of vein sulfide galenas in Basement I terrain lead is characterized by relatively high $^{208}Pb/^{204}Pb$ ratios, indicating a source with relatively high Th/U and Th/Pb ratios (Fig. 65), and by a general decrease in $^{208}Pb/^{204}Pb$ from west to east. Mount Rogers formation rhyolites have higher $^{208}Pb/^{204}Pb$ ratios (relative to corresponding uranogenic lead ratios) than do the Paleozoic plutons of the eastern Blue Ridge (Figs. 21 and 62), and the Paleozoic plutons appear to have slightly higher relative $^{208}Pb/^{204}Pb$ than the Cherryville Quartz Monzonite (CQM) and the Foote Mine pegmatite (FMP) which lie at the present eastern edge of the Inner Piedmont. The CQM and FMP have substantially less radiogenic $^{206}Pb/^{204}Pb$ ratios (Fig. 62) and higher initial $^{87}Sr/^{86}Sr$ ratios (Fig. 63) than the older Paleozoic plutons of the eastern Blue Ridge. This may be due to the presence of fragments of mafic crust interspersed in the basement of the eastern Blue Ridge (Hatcher and Zietz, 1980). A component of mafic material mixed with lower continental crust may have reduced the $^{208}Pb/^{204}Pb$

Stratabound massive sulfide deposits of the Blue Ridge are not included in the Basement I field on figure 65. Lead in these deposits has substantially lower $^{208}Pb/^{204}Pb$ ratios, indicating a lower Th/U ratio in source material than is found in rocks and vein galenas of Basement I terrain. The difference may be due to the derivation of the greater portion of the lead in stratabound ores from sedimentary rocks (derived largely from high level Basement I terrain), which would have had significantly lower Th/U ratios than lower crustal Basement I terrain, the proposed source of Blue Ridge rock and vein galena lead.

Basement II

Basement II (Fig. 64), is found along the eastern boundary of the exposed Appalachian orogen. It is less well known geologically and geochemically as well as isotopically than most of the region but recently evidence has been accumulating that this belt was the locus of extensive Alleghanian deformation and metamorphism (Farrar *et al.*, 1981; Snoke *et al.*, 1980).

Glover *et al.*, (1978), reported a Grenville age for the State Farm gneiss in the eastern Piedmont of Virginia. The Pb-Pb age of a single zircon fraction of a Haile-Brewer block (which, I propose, belongs in this eastern zone) metavolcanoclastic unit indicates an inheritance from Grenville-age rocks (Table 23, Fig. 52). There is a tenuous indication of an even older basement terrain in the Haile-Brewer block

(Fig. 52). Gravity and aeromagnetic patterns (Hatcher and Zietz, 1980), indicate that the eastern Piedmont is underlain by granitic crust. Basement II terrain, then, is at least partially underlain by Grenville-age rocks.

Lead isotope ratios (Fig. 65) from rocks and ores interpreted as belonging to Basement II terrains, however, have substantially lower relative ^{208}Pb/^{204}Pb ratios than Basement I terrains. Basement II-derived rocks also appear to have lower ^{207}Pb/^{204}Pb ratios.

Included in the Basement II fields (Fig. 65) are data from the 570 m.y. old Vance County and Roxboro plutons, the average lead isotope ratios of galena from the Hamme tungsten deposit, the initial ratios of slate belt rocks and ores from the Haile-Brewer block, and a K-feldspar determination from the ≃ 400 m.y. Salisbury pluton. Of these, the Salisbury presents the most difficult case for the inclusion in the Basement II group. Its initial ^{87}Sr/^{86}Sr ratio (Fullagar et al., 1971) is among the lowest in the southern Appalachians (Fig. 63), casting doubt on a continental crustal protolith, and geographically it lies solidly within the Basement III terrain (Fig. 64). Basement III is described below as a mixed mafic-granitic crustal terrain, but seems to have greater affinity for Basement I than II. The Salisbury may then represent a "mixed" source not properly included with Basement II, but also apparently out of place in either Basements I or III.

Of the representatives of Basement II type lead isotope ratios, albite from the oldest unit, Vance County pluton, is the least radiogenic. K-feldspar from the contemporaneous Roxboro granodiorite appears to contain a component of radiogenic lead (Table 28, Fig. 62). On the basis of lead isotopes alone, galena from the Hamme veins appear to be younger, but the radiogenic lead in the galenas may be the result of an added component of "extra-plutonic" lead. Meteoric characteristics of oxygen isotopes and the sedimentary organic nature of carbon isotope systematics (Casadevall and Rye, 1980), of the Hamme veins support the contribution of some material by the country rock. This may well have included a component of radiogenic lead.

The 400 m.y. old Salisbury pluton has K-feldspar lead isotope ratios that are slightly more radiogenic than those of the Vance County pluton. If the source of these two bodies was similar, normal lead isotopic growth is indicated, although in a somewhat low U/Pb ratio environment.

Haile mine massive pyrite and nearby metavolcanoclastic units have initial lead isotope ratios of $^{206}Pb/^{204}Pb = 18.366 \pm .075$, $^{207}Pb/^{204}Pb = 15.620 \pm 0.013$, and $^{208}Pb/^{204}Pb = 38.046 \pm 0.116$, as indicated by isochron intercepts (see Chapter 14). These ratios are more radiogenic than the Vance County pluton and Salisbury feldspars.

All of the lead isotope ratios from rocks included in Basement II have model ages that are too young for their ages of formation. The lower $^{208}Pb/^{204}Pb$ of Basement II lead relative to Basement I lead indicates a lower Th/U ratio in the former. The generally lower $^{207}Pb/^{204}Pb$ ratios also indicates a long-term history of somewhat lower U/Pb ratios in Basement II. The initial $^{87}Sr/^{86}Sr$ ratio of the Salisbury pluton is relatively low (Table 17; Fullagar *et al.*, 1971) as is that of the Great Falls granite in the Haile-Brewer block (0.7041 ± 0.071; Fullagar, 1971). The combination of radiogenic lead and low initial $^{87}Sr/^{86}Sr$ ratios may indicate a lower crustal source for these two areas and for Basement II-derived rocks in general.

Basement III

The area designated as underlain by Basement III lies between the Basement I and Basement II terrains. Basement III is envisioned as a region underlain by mafic crust containing fragments of granitic crust (cf. Hatcher and Zietz, 1980). Basement III consists of the southern part of the Carolina slate belt (excluding the Haile-Brewer block) and the Charlotte and Kings Mountain belt (Fig. 64).

As previously discussed, lead isotope ratios of galenas from Piedmont massive sulfide deposits and Kings Mountain belt ores support a model in which lead from upper continental crustal material is mixed with mantle or mantle-derived material to form apparent secondary isochrons with steep slopes. From relationships observed on Figure 65, it seems evident that material from Basement I terrain supplied the upper continental end-member of the mix. If Vance County pluton feldspar is representative of the least radiogenic Basement II-derived material, then there could be little or no Basement II contribution to the Basement III mix.*

Lead isotope ratios of galenas from the Mineral district, Virginia, fall within the fields defined by Basement I-derived lead. The lower ends of the Basement II fields (Fig. 65) have quite distinct combinations of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios. Lead isotope ratios in Kings Mountain belt meta-igneous rocks lie along a regression line which intersects the least radiogenic lead in Kings Mountain belt galenas (Fig. 44) and lie close to the least radiogenic Stone Hill, Alabama, galena. The Kings Mountain belt rocks may be representative of material derived directly or with little contamination from the U/Pb- and Th/U-depleted, mafic crustal component of the Basement III terrain.

* This is the primary reason why the affiliation of the Salisbury pluton with Basement II is doubtful (see previous section).

Model lead isotope evolution of Basement III end members

The lead isotope data from Piedmont massive sulfide deposits (PMS) and from Kings Mountain belt (KMB) galenas may be mathematically manipulated to yield effective lead isotope growth curves for the two end members of Basement III lead. For this purpose the Stone Hill deposit will be assumed to have formed at about the same time as other PMS: ≈550 m.y. ago.

Because the U/Pb and Th/Pb ratios of both end members must have increased through time in order to yield model ages that are too young in all deposits, the simple growth equation

$$\left(\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{t_2} = \left(\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}}\right)_{t_1} + \left(\frac{^{238}\mathrm{U}}{^{204}\mathrm{Pb}}\right)_{p} \left[e^{\lambda_8 t_1} - e^{\lambda_8 t_2}\right]$$

and the analogous equations for ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb, do not suffice. Nor is it possible, with the data at hand, to evaluate an episodic model of U/Pb and Th/Pb increase. Although a model of continuous (or "linear") growth ignores possible complexities, it will suffice to describe current knowledge of the Basement III systems.

Cumming and Richards (1975) developed an equation for lead evolution in a system with continuous increase of ^{238}U/^{204}Pb and ^{232}Th/^{204}Pb:

$$\left(\frac{{}^{206}Pb}{{}^{204}Pb}\right)_{t_2} = \left(\frac{{}^{206}Pb}{{}^{204}Pb}\right)_{t_1} + \left(\frac{{}^{238}U}{{}^{204}Pb}\right)_{p} \left\{ e^{\lambda_8 t_1}\left[1 - R\left(t_1 - \frac{1}{\lambda_8}\right)\right] - e^{\lambda_8 t_2}\left[1 - R\left(t_2 - \frac{1}{\lambda_8}\right)\right] \right\}$$

with similar equations for ${}^{207}Pb/{}^{204}Pb$ and ${}^{208}Pb/{}^{204}Pb$, where R is a rate factor with dimensions of inverse time. In the following discussion 3.7 b.y. will be used as the time at which the Appalachian systems began separate evolution, following the model of Stacey and Kramers (1975) and the age indicated by the apparent secondary isochron.

The lead isotope ratios of the least radiogenic galena from Stone Hill (MO-3; Table 16) are assumed to represent an upper limit of the ratios of the depleted source (mantle) at 550 m.y. As calculated from these ratios, μ at 550 m.y. had a value of 9.86. If, however, Stone Hill lead contains some component of basement I-type material, this value of μ is too high. In addition, the KMB data suggest a lower value of μ. $\mu = 9.7$ will therefore be used as an upper limit of the value in the southern Appalachian depleted source at 550 m.y.

Using Tatsumoto's (1978) value of $\mu = 7.5$ for the mantle after bulk differentiation at 3.7 b.y. and the value 9.7 at 550 m.y. a rate factor, R, can be calculated and substituted into Cumming and Richards' (1975) equation.

The values obtained by this method for the modern lead isotope ratios of the depleted source are reasonable (Table 27A). They are somewhat less radiogenic than the average modern lead ratios of Cumming and Richards (1975) and Stacey and Kramers (1975), and than the average modern "orogenic" values of Zartman and Doe (1981). They are considerably more radiogenic than either the mantle or lower crust values of Zartman and Doe (1981). Doe and Zartman's (1979) and Zartman and Doe's (1981) lower crustal lead is characterized, however, by high ^{208}Pb/^{204}Pb ratios relative to corresponding uranogenic lead ratios. Such is not the case with southern Appalachian Basement III.

There appears to be a mathematical error in Cumming and Richards' (1975) equation. It does not yield reasonable results, with such large rate factors as are indicated for the southern Appalachian example, when times older than about 1.0 b.y. are used for t_2.

The upper crustal component of lead in Basement III is represented by the average lead isotope ratios of nine galenas from Mineral district massive ore: ^{206}Pb/^{204}Pb = 18.219; ^{207}Pb/^{204}Pb = 15.644; ^{208}Pb/^{204}Pb = 38.151. At 550 m.y., these are calculated to indicate $\mu = 10.3$ and ^{232}Th/^{204}Pb(ω) = 39.9. The rate factors used assume that at 3.7 b.y. $\mu = 8.5$ and $\omega = 33.0$ (Table 27B).

TABLE 27

Assumed and calculated parameters defining possible mantle (long-term low U/Pb ratio) and upper crustal (high U/Pb) growth curves . The present day ratios may represent current values for average upper crust and mantle derived materials in the southern Appalachians. A) mantle or mantle-derived growth curve values. B) upper crustal growth curve values.

$\times 10^9$yr	μ	ω	$\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}}$	$\frac{^{207}\mathrm{Pb}}{^{204}\mathrm{Pb}}$	$\frac{^{208}\mathrm{Pb}}{^{204}\mathrm{Pb}}$	$\frac{\mathrm{Th}}{\mathrm{U}}$	Remarks
A)							
3.7	7.5	29.2	11.152	12.998	31.23	3.89	1.
1.0	9.39	35.9	17.570	15.458	*	*	2.
0.55	9.7	37.0	17.919	15.525	37.644	3.81	3.
0.0	10.1	38.4	18.643	15.577	37.978	3.80	2.
B)							
3.7	8.5	33.0	11.152	12.998	31.23	3.88	1.
0.55	10.3	39.9	18.219	15.644	38.151	3.88	4.
0.0	10.6	41.1	19.013	15.699	38.579	3.88	2.

1. Data from Stacey and Kramers (1975), Tatsumoto (1978), and Zartman and Doe (1981).
2. Calculated using model of Cumming and Richards (1975). * can not be meaningfully calculated using this example and Cumming and Richards' equation.
3. Least radiogenic galena lead isotope ratios from Stone Hill, Alabama.
4. Average of nine galena lead isotope ratios from Mineral district, Virginia, massive ore.

The modern lead isotope ratios calculated for the upper crustal and mantle components of Basement III define a line with a slope of 0.3297, which corresponds to a Pb-Pb isochron age of about 3.6 b.y., matching the apparent ages calculated for the PMS and KMB regressions.

It is also an interesting exercise to calculate the lead isotope "age" of the KMB galenas from the less radiogenic, and presumable older, lead isotope ratios of PMS galena. Using the least radiogenic Stone Hill galena and μ = 9.7, the apparent "age" of the Kings Creek barite galena is calculated to be 473 m.y. Similarly, galena from the Cameron mine has lead isotope ratios yielding an "age" of 490 m.y. when calculated from the average Mineral district $^{206}Pb/^{204}Pb$ value. These results are difficult to evaluate in light of the opaqueness of the U-Pb zircon data, but it is interesting to note that the two calculated "ages" are reasonably similar to each other, and also resemble some of the ages indicated by KMB zircon analyses (Table 18).

Late orogenic granites

The major period of deformation and metamorphism in the southern Appalachians was associated with the Ordovician Taconic orogeny. Most late orogenic (≃300 m.y.) plutons are undeformed and unmetamorphosed. The exceptions are found in the eastern Piedmont (Basement II terrain ?) in south-central South Carolina (Snoke et al., 1980) and in eastern Virginia (Farrar et al., 1981). The "High Shoals" gneiss in the Kings Mountain belt has also been found to belong to the late orogenic group (Table 18; Fig. 42), an indication that Alleghanian deformation may be more extensive than previously believed. Late orogenic plutons are found from the Kings Mountain belt in the west to the subsurface of the Coastal Plain, where they are most common.

Lead isotope ratios of K-feldspars from six of the late orogenic plutons form a tight grouping on ratio diagrams (Figs. 62 and 65). A seventh, the Castalia pluton, North Carolina, has a more radiogenic $^{206}Pb/^{204}Pb$ ratio than the others (Kish and Feiss, 1982; Vitrac et al., 1981; summarized in Table 28).

The lead isotope fields defined by late orogenic pluton K-feldspars (Fig. 65) may indicate a component of lead from each of the older basement terrains. The fields coincide in part with both of the Basement I and Basement II terrain fields. A component from the "mixed" terrain (Basement III) may be present, but more radiogenic due to normal growth of lead through radioactive decay (perhaps, for example, along the paths of the arrows, Fig. 65).

18. COMPARISON WITH ISOTOPE SYSTEMATICS IN OTHER APPALACHIAN-CALEDONIAN SULFIDE DEPOSITS

Sediment-Hosted Deposits

Few high precision lead isotope analyses and not sulfur data have been published from the Appalachian Zn (±Pb) Mississippi Valley-type deposits. Those few are plotted in figure 66, along with fields defined by data from Blue Ridge and Piedmont sulfide deposits. Also shown on the figure are reported analyses from carbonate-hosted Carboniferous Pb-Zn deposits, Ireland (Boast _et al_., 1981) and from the sandstone-hosted Laisvall Pb-Zn deposit, Sweden (Rickard _et al_., 1981). Three new lead and sulfur isotope analyses from two lower Silurian sandstone-hosted Appalachian Valley and Ridge Pb-Zn deposits are reproted in table 29 and figure 66.

Appalachian Zn-Pb deposits contain much more radiogenic lead than the sulfide deposits of the crystalline southern Appalachians, although they are generally less radiogenic than Mississippi Valley deposits. Foley _et al_. (1981) have recently discussed Austinville-Ivanhoe, Virginia, lead ratios relative to those of Mississippi Valley ores.

The Laisvall Pb-Zn deposit of late Precambrian to lower

Paleozoic age is extremely radiogenic compared to other Appalachian-Caledonian deposits of similar age. Galena impregnations in the lower Silurian Tuscarora sandstone have lead isotope ratios similar to late orogenic plutons of the Piedmont, but have sulfur that is enriched in the heavier isotope and which is isotopically similar to sulfur in both the Shawangunk, New York, and Laisvall deposits (Table 25; Rickard _et_ _al_., 1979, 1981). Rickard _et_ _al_. (1979, 1981) report that galena sulfur isotopic ratios at Laisvall range from 22.0 to 28.0 $^0/_{00}$. They suggest that these heavy $\delta^{34}S$ values may be the result of the degradation of hydrocarbons in the presence of sulfate. The three $\delta^{34}S$ values from Tuscarora and Shawangunk sulfides fall within the range of $\delta^{34}S$ of Laisvall. There is no evidence of sulfate or hydrocarbons in either Appalachian deposit, but extensive evaporites are present in the upper Silurian of the Appalachian basin and the lower Silurian clastic sequence contains some of the most productive oil and gas horizons in the Appalachians (see Colton, 1970, for a summary of Appalachian basin stratigraphy).

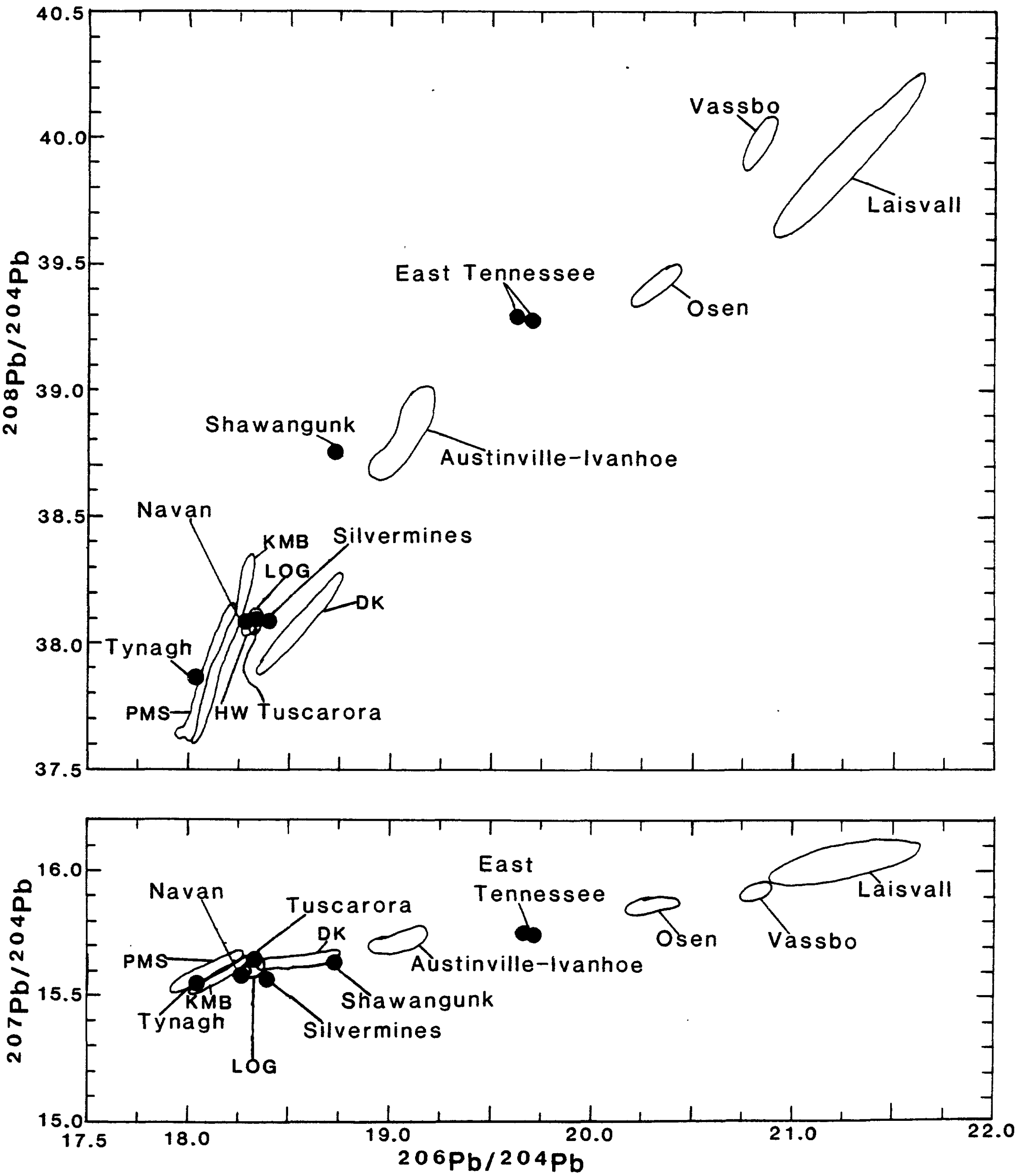
The occurrence of galena in the Tuscarora sandstone is similar in many respects to the sandstone lead-type deposits recently described by Bjørlykke and Sangster (1981). They proposed a model for the genesis of sandstone lead deposits in which lead is derived from the decomposition of feldspar in the basement or basement-derived arkose and is transport-

TABLE 29

Galena lead and sulfur isotopic composition of mineralization in the lower Silurian Tuscarora and Shawangunk sandstones.

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	$\delta^{34}S_{sp}$	$\delta^{34}S_{gn}$
Tuscarora Sandstone, Walker Mountain, Virginia					
VR-01001	18.367	15.619	38.182		23.19
Shawangunk mine, Wurtsboro, New York					
NY-201	18.713	15.632	38.743		
NY-202	18.708	15.630	38.740	24.87	22.23

Figure 66. Lead isotope ratios of sediment hosted Appalachian and Caledonide deposits compared with Piedmont and Blue Ridge sulfide deposits. For clarity, only Ducktown is used to represent Blue Ridge data. Abbreviations: PMS - Piedmont massive sulfides; KMB - Kings Mountain galenas; DK - Ducktown; HW - Hamme tungsten district galenas; LOG - Late orogenic pluton K-feldspar. Data sources: East Tennessee - B.R. Doe; Laisvall - Rickard *et al.*, (1981); Osen, Vassbo - Bjørlykke and Thorpe (1982); Austinville-Ivanhoe - Foley *et al.*, (1981); Navan; Tynagh, Silvermines - Boast *et al.*, (1981).


40.5
40.0
39.5
39.0
38.5
38.0
37.5
208Pb/204Pb
Vassbo
Laisvall
East Tennessee
Osen
Shawangunk
Austinville-Ivanhoe
Navan
KMB
Silvermines
LOG
DK
Tynagh
PMS
HW
Tuscarora
16.0
15.5
15.0
207Pb/204Pb
East
Tennessee
Laisvall
Navan
Tuscarora
DK
Osen
Vassbo
PMS
Austinville-Ivanhoe
KMB
Tynagh
Shawangunk
Silvermines
LOG
17.5
18.0
19.0
20.0
21.0
22.0
206Pb/204Pb

ed by groundwater. Deposition occurs in porous basal quartz sandstone in semiarid to arid climates. The Tuscarora sandstone unconformably overlies the Ordovician clastic sequence. An arid climate in the late Silurian is indicated by extensive evaporite beds and may have had its beginnings as early as the early Silurian.

The unradiogenic character of the Tuscarora galena lead relative to Shawangunk and Laisvall may be due to a substantial non-basement component in the underlying Ordovician clastics, which were derived from the uplift associated with the Taconic orogeny. Late Precambrian to Ordovician igneous material was probably present, along with Grenville-age basement material, in the elevated source terrain. If sandstone lead deposits are an early diagenetic feature, as suggested by Bjørlykke and Sangster (1981), the time between deposition of the Ordovician clastics and the removal and redeposition of lead was relatively short. The unradiogenic character of Tuscarora galena may be the result of this short residence time which allowed only a small amount of in situ radiogenic growth and enrichment, combined with lead from basement and younger igneous material.

Bjørlykke and Sangster (1981) note that the lithologic setting of the Shawangunk deposits is similar to that of sandstone lead deposits. The Shawangunk mine, however, occurs in fracture-fill veins (Sims and Hotz, 1951; Gray, 1961) in the lower Silurian quartz pebble conglomerate.

Whether these are remobilized equivalents of sandstone lead-type deposits is not known. Mineralogically, Shawangunk ores differ from sandstone lead deposits in that sphalerite predominates over galena. Rickard et al. (1981) found a wide range of lead istope ratios in Laisvall galenas. Two galenas from the Shawangunk mine, however, have lead isotope compositions that are virtually identical. The radiogenic character of the lead can be explained by derivation from a clastic sedimentary source, but whether the process was similar to that which produces sandstone lead deposits is unknown.

The sphalerite-galena pair from the Shawangunk mine analyzed for sulfur isotopic composition seems to be approaching isotopic equilibrium and indicates a temperature of deposition of about 250°C. This is too high for the groundwater systems envisioned by Bjørlykke and Sangster (1981) as responsible for sandstone lead deposits and seems to indicate a hydrothermal system. A more thorough sulfur isotope study is needed, however, to confirm this reconnaissance result.

Lead isotope ratios reported (Boast et al., 1981) from three Carboniferous carbonate-hosted Pb-Zn deposits in central Ireland are also shown in Figure 66. Ratios of Silvermines and of most Navan galenas are similar to those found in K-feldspars in Appalachian late orogenic plutons, also of Carboniferous age. Vitrac et al. (1981) reported that

Hercynian granitic plutons from around the North Atlantic basin have a relatively narrow range of K-feldspar lead isotope ratios. Lead in Silvermines and Navan may have been largley derived from similar Hercynian igneous activity. The fault-related Tynagh deposit, however, contains nonradiogenic lead and has $^{207}Pb/^{204}Pb$ nearly as low as that in the southern Appalachian Stone Hill massive sulfide and Kings Creek barite deposits.

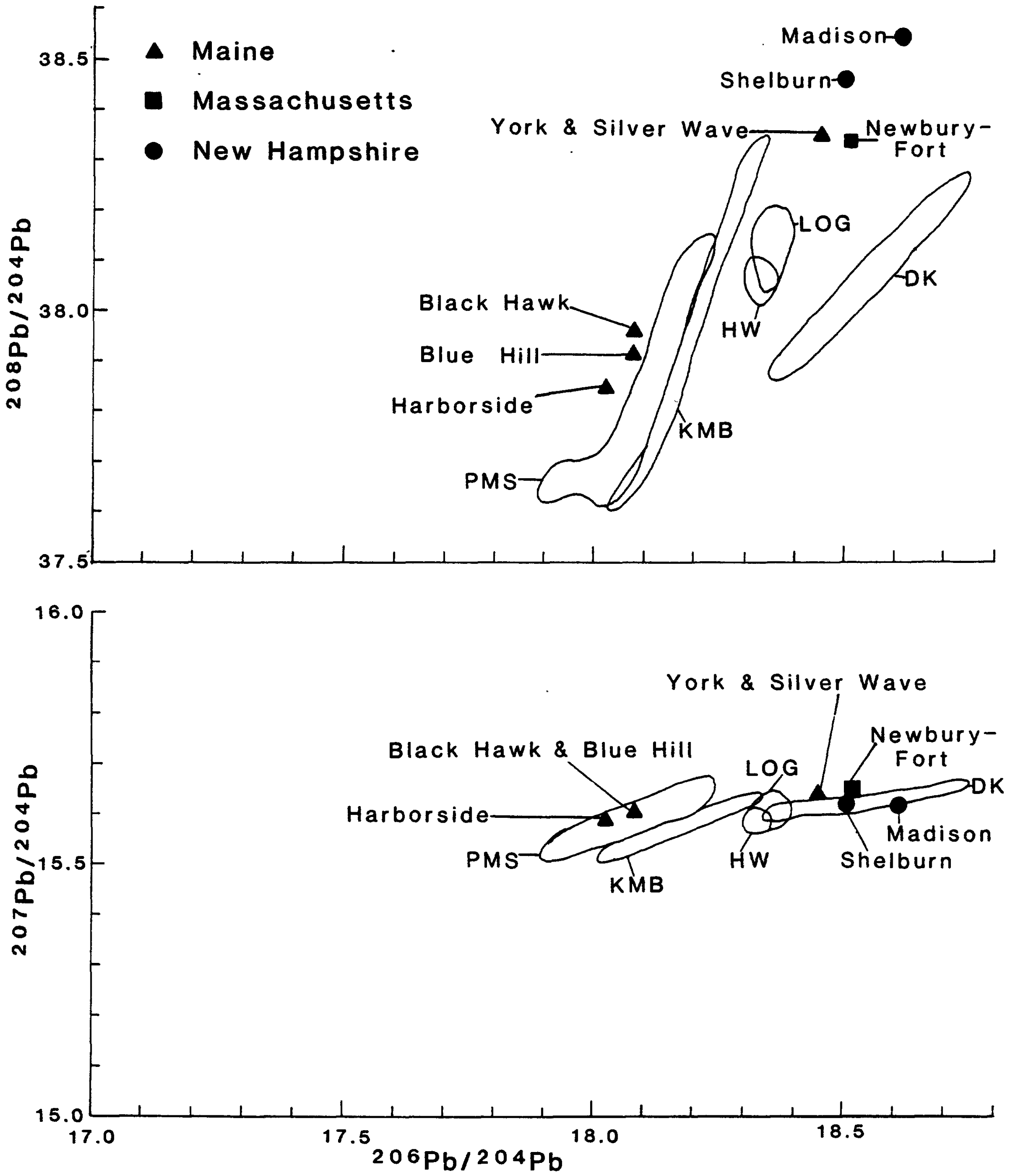
New England

Doe and Zartman (1979) reported a number of high-precision lead isotope ratios from New England sulfide deposits. These fall into two groups of ratios (Fig. 67). Epigenetic deposits from Maine, New Hampshire, and Massachusetts have radiogenic lead isotope compositions and particularly have high $^{208}Pb/^{204}Pb$ ratios, indicating a source enriched in thorium. Replacement(?) and conformable sulfides in eastern Maine of late to middle Paleozoic(?) age contain lead that has lower $^{206}Pb/^{204}Pb$ than southern Appalachian Piedmont massive sulfides, indicating lower U/Pb ratios in the sources of the Maine ores.

Caledonides

Table 30 presents some new data from some Caledonian

Figure 67. Lead isotope ratios of New England sulfide deposit galenas compared with those of southern Appalachian deposits. Abbreviations are the same as for figure 66. New England data from Doe and Zartman (1979).


▲ Maine
■ Massachusetts
● New Hampshire
208Pb/204Pb
38.5
38.0
37.5
Madison
Shelburn
York & Silver Wave
Newbury-Fort
LOG
DK
HW
Black Hawk
Blue Hill
Harborside
KMB
PMS
207Pb/204Pb
16.0
15.5
15.0
York & Silver Wave
Newbury-Fort
Black Hawk & Blue Hill
LOG
DK
Harborside
Madison
PMS
HW
Shelburn
KMB
17.0
17.5
18.0
18.5
206Pb/204Pb

sulfide deposits in Scotland and Ireland. The Aberfeldy district, Perthshire, consists of stratabound Ba-Zn(±Pb) deposit in schists of the late Precambrian-lower Paleozoic Easdale Group of the Dalradian Supergroup (Coats *et al.*, 1980). Lead isotope ratios of three galenas from the district (Table 30) are much less radiogenic than any Appalachian ratios. Swainbank *et al.* (1981) also reported galena lead isotope ratios from Aberfeldy and also found unradiogenic values that are particularly low in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$. Swainbank *et al.* (1981) attributed the low lead ratios to derivation from Lewisian lower crustal rocks. They reported a secondary isochron, when 570 m.y. is used for the age of mineralization, of 2560 m.y. Aberfeldy lead isotope ratios reported by Swainbank *et al.* (1981) and in this paper form two discrete groups. The representatives of these groups presented in Table 30 are geographically distinct. L-79 is from the Foss deposit on the eastern side of the district whereas L-80 and L-90 are from the Farragon Hill area in the central part of the district. Whether a geographic separation is supported by Swainbank *et al.*'s (1981) data is not clear.

Tyndrum is a Zn-Pb deposit associated with fracture-filling quartz veins in the Tyndrum-Glen Fyne fault in a quartzite unit overlying the unit enclosing the Aberfeldy deposits. Macroscopically, Tyndrum ores closely resemble the mineralization in the Shawangunk deposit (New York).

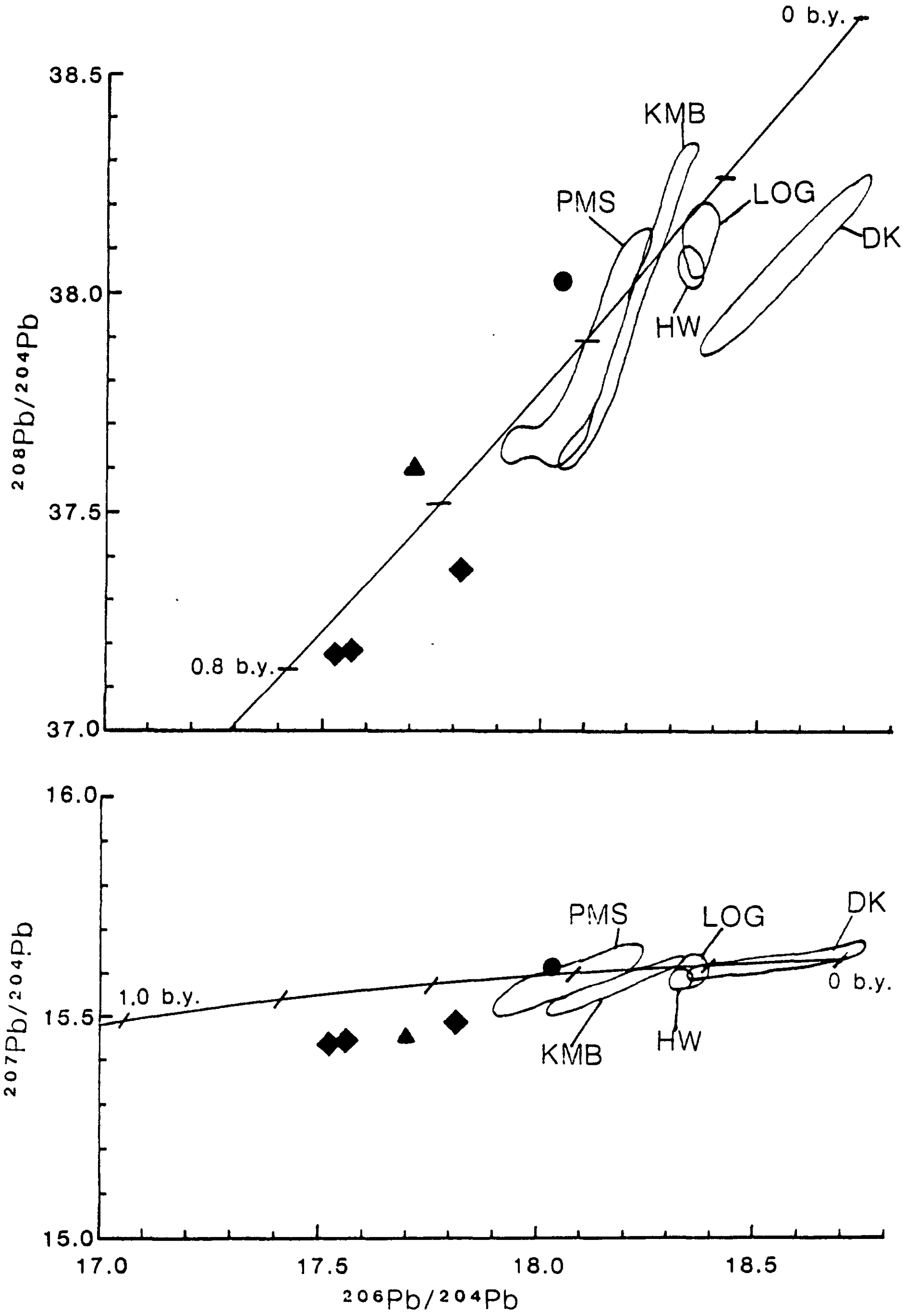
TABLE 30

New galena lead isotope compositions from Caledonian ore deposits, Scotland and Ireland. Model ages were calculated using the parameters of Stacey and Kramers (1975).

Sample no.	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Model age (m.y.)
Aberfeldy district, Perthshire, Scotland				
L-79	17.813	15.488	37.369	386
L-80	17.525	15.438	37.174	509
L-90	17.561	15.445	37.182	495
Tyndrum, Perthshire, Scotland				
L-78	17.704	15.452	37.602	396
Avoca mines, County Wicklow, Ireland				
L-77	18.038	15.612	38.026	465

Figure 68. Lead isotope ratio diagrams showing ratios from some sulfide deposits of the Scottish and Irish Caledonides, compared with the fields defined by some southern Appalachian deposits. ● Avoca, County Wicklow, Ireland; ◆ Aberfeldy district, and ▲ Tyndrum, Perthshire, Scotland. Abbreviations as in figure 66.

360


0 b.y.
38.5
38.0
37.5
37.0
KMB
PMS
LOG
DK
HW
0.8 b.y.
$^{208}Pb/^{204}Pb$
16.0
15.5
15.0
PMS
LOG
DK
1.0 b.y.
0 b.y.
KMB
HW
$^{207}Pb/^{204}Pb$
17.0
17.5
18.0
18.5
$^{206}Pb/^{204}Pb$

Lead in a Tyndrum galena is also unradiogenic and has a higher ^{208}Pb/^{204}Pb ratio than Aberfeldy but a similar ^{207}Pb/^{204}Pb ratio. The ^{206}Pb/^{204}Pb ratio is intermediate between the Aberfeldy ratios reprted here (Table 30; Fig. 68).

The most radiogenic Aberfeldy galena (L-79) and the Tyndrum sample have^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb ratios that fall on the 3.7 b.y. pseudoisochron defined by southern Appalachian Piedmont massive sulfide deposits. This can only be interpreted as coincidental if Lewisian basement served as the source of lead in the Dalradian deposits.

Avoca Mines, County Wicklow, Ireland, is a volcanic exhalative deposit in upper Ordovician continental margin felsic volcanics (Sheppard, 1980). A single galena lead isotope determination has a ^{206}Pb/^{204}Pb ratio that is less radiogenic than most southern Appalachian Piedmont galenas (Table 30, Fig. 68). The ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb ratios are relatively high, however, reflecting a greater upper continental crustal contribution to lead in the Avoca deposit. This contribution is consistent with a continental margin volcanic arc setting of the ores and their host sequence.

19. SUMMARY

Lead and sulfur isotope compositions from Ducktown massive sulfide bodies seem to indicate that these elements were derived from two distinct sources. Most of the lead was apparently drawn from the thick pile of clastic sediment of the Ocoee Supergroup. A large component of the sulfur may have originated as seawater sulfate. If the average $\delta^{34}S$ value of about $+4\,^0/_{00}$ represents seawater-derived sulfur, the corresponding $\delta^{34}S$ of seawater sulfate, using "Sangster's rule" would have been about $21\,^0/_{00}$.

Several factors indicate that a second source contributed in some way to Ducktown mineralization and that it was characterized by relatively unradiogenic lead and a $\delta^{34}S$ value of about zero per mil. The positive slope of the correlation between lead and sulfur isotope ratios, if real, does not seem to be derivable from either metamorphic processes or from processes operating in a purely sedimentary environment. Rift basin normal faulting or fracture zones are postulated to have penetrated a deep-seated source area, probably mafic in composition. Samall amounts of igneous material used the fault as a passageway, resulting in the amphibolite bodies bound in the Ducktown district and along strike. Cu- and Zn-rich hydrothermal fluids also used the permeable zone as a conduit. Heat generated by the magmatic fluids set up a hydrothermal circulating cell, perhaps dominated by seawater, in surrounding sediments which leached radiogenic lead and sulfides from the sedimentary sequence. The skewing of the sulfur isotope frequency distribution towards zero, and the absence of any values of $\delta^{34}S$ less than zero suggests the mixing of an igneous source having $\delta^{34}S \simeq 0^0/_{00}$ with sulfur dominated by positive $\delta^{34}S$ values, perhaps seawater.

Mineralization may have occurred in two or three pulses. Lead isotope ratios of galenas and massive sulfide fall in three discrete groups that are not separable by type of ore, host rock, or by ore body. The pulses may represent repeated openings of the proposed fracture zone.

Such a fault or fracture conduit system has not been recognized at Ducktown and would be difficult to document because of the lack of marker horizons and of subsequent multiple deformation and metamorphism. Geologic evidence in favor of fault control consists of the localization of minor stratabound sulfide occurrences in a linear belt along strike with Ducktown, the restricted occurrence of amphibolite, the only known igneous rocks in the Great Smoky Group, to this same linear belt, and the regional tectonic setting inferred for the western Blue Ridge.

Detailed comparison of characteristics of Ducktown massive sulfides with those of major sediment-hosted stratiform

Cu and Pb-Zn deposits, as outlined by Gustafson and Williams (1981), reveals major differences. This suggests that Ducktown, although in an overwhelmingly sedimentary environment, should not be classified with the sediment-hosted deposits described by Gustafson and Williams (1981).

Sulfide mineralogy at Ducktown is similar to that found in volcanic-associated stratabound Cu-Zn deposits. The virtual absence of recognizable volcanic rock is the chief difficulty with comparisons between Ducktown and the volcanogenic group. The model proposed here may be a way around this difficulty.

Lead in other stratabound sulfide deposits of the Blue Ridge has a wide range of isotopic compositions. Galena from the Great Gossan Lead is similar to Ducktown group II lead isotopic composition, but with lower $^{207}Pb/^{204}Pb$ ratios, which may reflect greater contribution of lead by mafic material, which is abundant in the Gossan Lead section. Galenas from the Gossan Lead deposits do not appear to have the range of lead isotopic compositions found at Ducktown, nor do they exhibit any "grouping". Sulfur isotope compositions from other Blue Ridge massive sulfides fall within the range of Ducktown data.

Two galena lead isotope analyses from mineralized quartz veins of the eastern Blue Ridge, reported by Kish and Feiss (1982), indicate derivation of most of their lead from

Grenville-age basement rocks.

U-Th-Pb whole rock analyses of rhyolites from the Mount Rogers Formation, which is at least partially correlative with the Ocoee, result in a reasonable Pb-Pb slope age of about 640 m.y. Isotopic similarity between the least radiogenic Mount Rogers K-feldspar and a Grenville-age pegmatitic K-feldspar supports the conclusion that the rhyolites are largely derived from relaitively Th-rich basement rocks.

Lead in the least radiogenic Mount Rogers K-feldspar has lead isotope ratios much lower than any galena from Blue Ridge stratabound sulfide deposits. More radiogenic K-feldspars and whole rock lead analyses reveal substatially higher $^{208}Pb/^{204}Pb$ ratios, a result of their Th-enriched protoliths. The same is observed in K-feldspars in Blue Ridge Paleozoic plutons. Lead isotope ratios indicate that Ducktown and other massive sulfides could not have derived their lead from sources similar to Mount Rogers rhyolites or to the Paleozoic plutons.

Piedmont province volcanogenic massive sulfide deposits contain lead with uniform lead isotope ratios, a common feature of similar deposits worldwide. In the Mineral district, Virginia, massive sulfide lenses contain galena with uniform lead isotope compositions but galena in sericitic quartzite underlying the Julia ore body has a relatively wide range including more radiogenic lead ratios, suggesting that these have been remobilized. Mineral lead isotope ratios are similar to those in Bathurst district, New Brunswick, galenas. They lie slightly above the "orogene" curve, suggesting ensialic arc volcanism (Doe and Zartman, 1979). Model ages that are too young are the result of a U/Pb-rich source(s).

The average $\delta^{34}S$ value of about $+9^0/_{00}$ of sulfide minerals from the Mineral district indicates a value of about $+26^0/_{00}$ for contemporaneous seawater sulfate, which is believed to approximate the value of Cambrian seawater (Claypool _et_ _al_., 1981). Average $\delta^{34}S$ ratios appear to be lower in the Julia and Cofer lenses than in the Arminius, Sulphur, and perhaps the Allah Cooper bodies. The difference may be due to variable chemical conditions or to a lateral zoning effect. The Sulphur and Arminius ore bodies are mineralogically and geographically distinct from the Cofer and Allah Cooper lenses. The position of Julia is spatially uncertain, but more similar mineralogically to Cofer.

Isotopic equilibrium temperature calculations do not show consistent relationships. The average temperature of about 420°C may approximate original temperatures; it is too low for amphibolite grade metamorphism. The metamorphism is probably responsible, however, for the inconsistency of the temperature pair data. Trends of $\delta^{34}S$ changes in individual ore bodies are tenuous.

Lead isotope ratios in veins of the Virginia gold-pyrite belt are radiogenic and highly variable. The cross-cutting nature of the mineralized belt and the radiogenic isotope compositions indicate post-Chopawamsic vein formation, perhaps during metamorphism.

Stratabound polymetallic sulfide deposits of the Carolina slate belt are associated with volcanic sequences of similar age (≃550 m.y.). The Mineral district is also thought to be in rocks that are about 550 m.y. old (Pavlides, 1981). Lead isotope ratios in all the deposits become decreasingly radiogenic from northeast to southwest, which suggests a decreasing upper continental crustal lead component in the ores to the southwest. Mineral and slate belt deposits and the deposits of the Northern Alabama Piedmont, which have an uncertain relationship with the rest of the Appalachians, form a trend of lead isotope ratios with a slope corresponding to a secondary isochron age of about 3.7 b.y. The line is interpreted as a mixing line between a low U/Pb source and upper crustal lead. Galena and whole-rock data from the Kings Mountain belt reinforce this interpretation and indicate that the mantle is ultimately the U/Pb depleted source. An average trend formed by K-feldspar lead isotope ratios from Hercynian plutons around the North Atlantic has a slope corresponding to an age of about 3.8 b.y. (Vitrac *et al.*, 1981), which suggests a similar mix of source materials.

The young model ages of all Piedmont massive sulfides, however, are the result of enrichment of uranium (and thorium) relative to lead in all source materials through time. Tatsumoto (1978) presented evidence that U/Pb and Th/Pb ratios in the mantle have been increasing since at least 1.5 b.y. ago. Lower crustal rocks, another possible source of lead with low $^{207}Pb/^{204}Pb$ ratios, generally have undergone U/Pb decrease through time. Lead from the mantle or from mantle-derived material, mixing with U/Pb-enriched upper crustal lead, with the latter component decreasing to the southwest, seems to best fit the data at hand.

The tectonic position of the Northern Alabama Piedmont is probably analogous to that of portions of the Blue Ridge, but age relations and geologic correlations are uncertain. The relationship of the Stone Hill deposit to Mineral district and Carolina slate belt massive sulfides, therefore, is ambiguous and the lead isotope data has not helped to resolve it. The similarity between lead isotope ratios in Stone Hill and in the Pyriton deposit is problematical. If Stone Hill is presumed to be late Precambrian(?) and Pyriton is either Devonian or Cambro-Ordovician, the similarity may be coincidental. Given the uncertainties involved, however, the similarity should not be ignored when considering the nature of the Hollins Line Fault and the stratigraphic relationship of the Talladega Group and the Ashland Supergroup.

Whole-rock U-Pb and Th-Pb isochrons from Carolina slate belt rocks in the vicinity of the Haile and Brewer mines, South Carolina, indicate an age of about 465 m.y., generally younger than ages determined from other parts of the slate belt. The regularity of U, Th, and Pb concentrations in felsic volcanic rocks and in massive pyritic ores as well as isotope patterns indicate that lead in rocks and ore had similar sources. The pyrite lenses, however, also contain a component of lead with a low $^{207}Pb/^{204}Pb$ ratio, which may have come from more mafic rocks in the volcanic pile.

Initial lead isotope ratios derived from U-Pb and Th-Pb isochron plots indicate that lead in Haile ores was radiogenic at the time of deposition relative to slate belt Pb-Zn-Cu deposits. Intital ratios for the slate belt volcanic rocks and massive pyrite are similar to lead isotope ratios found in K-feldspars from late orogenic plutons. There was a minimum of 150 m.y. between deposition of slate belt rocks and intrusion of the late orogenic granites, which is sufficient time for significant radiogenic growth of lead. The similarity of lead isotope ratios in two events widely separated in time suggests a source with low U/Pb for the later plutons relative to the source of slate belt felsic volcanics.

An average $\delta^{34}S$ value of $+2.0^{0}/_{00}$ for Haile pyrite is significantly lower than values indicated by a reconnaissance survey of sulfur isotope compositions in other slate belt stratabound sulfide deposits. The relatively light sulfur indicates that considerably lower temperatures of mineralization prevailed at Haile or, alternatively, that little sulfur was derived from lower Paleozoic seawater sulfate which would suggest a strong magmatic sulfur component.

Discordant zircons from the Vance County pluton in North Carolina indicate an age of 571 ± 17 m.y., which is presumably also the age of the associated Hamme tungsten veins. Whole-rock U-Th-Pb systematics of the pluton were disturbed at some time after emplacement, probably during regional metamorphism. Loss of lead seems to have been the major effect of the disturbance on the U-Th-Pb system.

Galena, which is a primary vein mineral in the Hamme veins, has uniform lead isotopic ratios that are similar to ratios of late orogenic granite K-feldspars and to initial ratios of slate belt rocks in the Haile-Brewer block. Because these igneous event occurred over a period of at least 300 m.y., a decrease in U/Pb and Th/Pb ratios of source materials through time is indicated.

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APPENDIX A: SAMPLE LOCATIONS AND DESCRIPTIONS

The samples described in this section are arranged by the table number in the main text in which the results of analyses appear. Those who provided samples for this study are cited after sample descriptions, Core samples described as "Tennessee Copper" are kept at the Tennessee Chemical Company's Ducktown facility. Depth in core is given in feet (e.g. 62'), as this is the measure used during core logging. The letters "d.d.h." stand for "diamond drill hole". For cases in which a sample is represented in more than one table, the description is given only at the first occurrence. Subsequently, the table number under which the sample is described is given.

TABLE 2: Ducktown galenas

The Ducktown district is located in Polk County, Tennessee, near the mutual border of Tennessee, Georgia and North Carolina at Lat. $35^{o}2'$N, Long. $84^{o}22.5'$W. The Payne prospect is in Fannin County, Georgia, southwest of Ducktown.

DK-1	Calloway ore body. Large mass of gn + po ± cpy in a quartz vein at level 18, sublevel 3, at 4.50N.

DK-19	Calloway, d.d.h. 982, 62'. Sp and blebs of gn in Cu-Zn ore.
DK-29	Calloway, d.d.h. 1080, 63-64' (level 24, sublevel 2). Massive ore containing po, py, with minor cpy, sp, gn, and mg in tremolite gangue.
DK-31	Calloway, d.d.h. 1065, 6' (level 26, cross section 5.5). Po, cpy, sp and act, calc ± gn + sp in siliceous mineralized zone.
DK-47	Mary-Polk County ore body, d.d.h. 1223, 47' (4th level, Polk County body, cross section 125N). Scattered blebs of gn and sp in trem-act schist.
DK-48	Mary-Polk Co., d.d.h. 1222, 46', (level 10, cross section 435N). Quartzite containing garnet, blebby gn, and silicates.
DK-52	Boyd ore body, d.d.h. 688, 48' (level 10, cross section 1260S). Sp + gn in ser-bio-qtz schist.
DK-74	Cherokee ore body, d.d.h. 1185, 188' (level 14, cross section 24.30N). Qtz containing po, sp, cpy, and scattered blebs of gn.
DK-83	Cherokee, d.d.h. 1213, 126' (surface, cross section 31N). Quartzite containing po, sp, and scattered gn.
DK-36	Payne prospect, d.d.h. 8, 969'. Po, sp, and gn disseminated in fine-grained qtz-bio schist.

TABLE 3: Ducktown "Whole-ore"

DK-16	Calloway, d.d.h. 973, 65' (level 24, sublevel 2,

cross section 3S). Massive pyrite ore.

DK-82 Cherokee, d.d.h. 1198, 173' (level 14, cross section N26). Massive pyrrhotite.

DK-89 Cherokee d.d.h. 1229, 161' (surface, cross section 29N). Massive pyrite.

TABLE 4: Sulfur Isotope compositions of Ducktown Sulfides.

These samples are described under Table 2.

TABLE 6: Lead and Sulfur isotope Compositions from other Blue Ridge sulfide deposits. All samples in this list were contributed by R.H. Carpenter, Carpenter Exploration Co., Athens, Georgia, except as noted.

Fontana district, Adams mine, Swain County, North Carolina.
Lat. 35°18.8'N, Long. 83°46.1'W.
BS-10101 Cpy-rich ore with minor sp and gn.

Gossan Lead, Carroll and Grayson Counties, Virginia
Gossan Howard pit: Lat. 36°42.5'N, Long. 80°55.9'W.
715 Massive po-mg ore with minor gn.
JRC-474 Contributed by J.R. Craig, Virginia Polytechnical Institute (VPI).
Freeport Sulfur: d.d.h. 117, 1253.5'
JRC-846 Contributed by J.R. Craig, VPI.

Swift mine, Paulding County, Georgia. Lat. $33^{\circ}49.5'$N, Long. $85^{\circ}02'$W.

BS-30101 Py cubes up to 5mm disseminated in chlorite schist. Note that py was the mineral analyzed for lead isotopic composition.

Little Bob mine, Paulding County, Georgia. Lat. $33^{\circ}53'$N, Long. $85^{\circ}02'$W.

BS-30201 Py + sp massive sulfide. No separable or visible galena, but an HCl leach of a 150mg split yielded enough Pb to indicate the probable presence of microscopic galena.

Ore Knob, Ashe County, North Carolina. Lat. $36^{\circ}23.9'$N, Long. $81^{\circ}19.9'$W.

BS-10301 420' level. Massive sulfide.

BS-10302 700' level. Massive sulfide.

Culhowee mine, Jackson County, North Carolina. Lat. $35^{\circ}8'$N, Long. $83^{\circ}5.3'$W.

BS-10201 Sulfides (mainly py) disseminated in qtz-bio schist.

TABLE 7: Mount Rogers Formation, Grenville-age pegmatite, and mafic dike.

MR-101 Whitetop Mountain, Virginia. $36^{\circ}39.3'$N, $81^{\circ}36.4'$W

Ryholitic tuff breccia. "Rhyolite B" of Rankin (1967).

MR-102 Whitetop Mountain, Virginia. 36°38.1'N, 81°36.3'W K-feldspar phenocrysts in fine-grained ground mass. "Rhyolite B" of Rankin (1967).

MR-103 Whitetop Mountain, Virginia. 36°38.1'N, 81°36.3'W K-feldspar phenocrysts in "Rhyolite B" of Rankin (1967)

MR-104 Whitetop Mtn., Virginia. 36°38.1'N, 81°36.3'W. Coarser grained tuff (?) in "Rhyolite B" of Rankin (1967).

MR-106 Whitetop Mtn., Virginia. 36°37.6'N, 81°35.2'W. "Rhyolite C" of Rankin (1967).

GG-101 36°27.9'N, 81°44.6'W. Quartz and K-feldspar pegmatite in a sequence of amphibolite and granitic gneiss.

GG-103 36°27.9'N, 81°44.6'W. Greenstone dike cutting granitic gneiss at same location as GG-101.

TABLE 8: Mineral district, Louisa County, Virginia: galena lead isotope ratios. Approximately 38°2.5'N, 77°53'W. The prefixes "U58A", "101J", "27S" and "CV80-86" indicate the diamond drill hoe number. Numbers following indicate footage.

Arminius ore body

U58A-620 1800 level. Coarse-grained massive sp, py, minor gn. J.R. Craig, VPI.

Cofer ore body

PS-02001 Massive, coarse-grained py, sp, gn. R.H. Carpenter, Athens, Ga.

PS-02002 Massive py, sp, minor gn. J.E. Gair, U.S. Geological Survey, Reston, Virginia.

PS-02003 Massive gn, sp; subordinate py. J.R. Craig, VPI.

Allah Cooper ore body (38°4.5'N, 77°51.6'W)

PS-03001 Massive, coarse-grained gn, sp, with interstitial cpy. R.H. Carpenter, Athens, Ga.

Sulphur ore body

27S-542 Massive py, sp, minor gn.

Julia ore body

101J-860 Massive ore with py, sp; minor gn, cpy.

CV80-86-1611 Blebs of gn + sp in sericitic quartzite.

CV80-86-1729 Coarse gn cubes in sericitic quartzite.

CV80-86-1961 Large gn cub (1.5 cm) in open space lined with well-terminated quartz crystals in sericitic quartzite.

TABLE 9: Samples are briefly described in the table.

TABLE 10: Virginia gold-pyrite belt. These samples are from the collection of the U.S. National Museum of

Natural History (USMNH).

Mineral Ridge, Fairfax County, Virginia (exact location unknown).

USMNH 10832 Py, gn, gold and tetradymite in mineralized quartz vein. There is a photomicrograph of a polished section of this sample in Craig and Vaughan (1981, p. 222).

Whitehall mine, Spotsylvania County, Virginia. 38°14.3'N, 77°44.2'W.

USMNH 79032 Py + gold with galena and an unidentified bismuth mineral.

TABLE 11: Cid district, Davidson County, North Carolina.

Silver Hill. 35°42.4'N.80°6.9'W

PS-10101 Fine-grained sp-gn layers separated by thin py-silica rich bands. Dump.

PS-10102 Fine-grained bands of sp-gn and py-silica with soft sediment deformation structures. Dump.

PS-10107 Disseminated gn, sp, cpy in siliceous metatuff. Dump.

Silver Valley. 35°43.6'N, 80°6.9'W.

PS-10301 Very thin seams of sulfides (mostly gn, sp) in light gray chert. R.H. Carpenter, Athens, Ga.

PS-10302 Massive gn-rich ore with minor sp. From the collection of the North Carolina Dept. Mineral Resources (NCDMR).

TABLE 12: Gold Hill district, Rowan and Cabarrus Counties, North Carolina.

Union Copper mine. 35°30.25'N, 80°21.4'W

PS-10204 Intimately mixed sp, gn in strongly sheared chlorite schist. Dump.

PS-10207 Gn, sp, and cpy in quartz vein. Dump.

PS-10211 Large gn crystals in quartz v3in in argillite. Dump.

Silver Shaft. 35°29.9'N, 80°21.4'W.

PS-10601 Sp-gn-sericite schist. NCDMR.

TABLE 13: Linconton-McCormick district, Wilkes and Lincoln Counties, Georgia, and McCormick County, South Carolina.

Dorn mine. 33°55'N, 82°17.5'W.

PS-20101 Massive gn, cpy, and yellow sp ore. R.H. Carpenter, Athens, Ga.

Magruder mine. 33°46.6'N, 82°33.8' W.

PS-30101 Disseminated and thinly layered py, sp, and gn in reworked volcanic sediments. R.H. Carpenter, Athens, Ga.

TABLE 14: These samples are described in Kish and Feiss (1982).

TABLE 15: Carolina slate belt massive sulfide sulfur isotope compositions. Many of these samples and locations have been described under Tables 11, 12, and 13. Only those not previously listed are included here.

Silver Hill mine. 35°43.6'N, 80°6.9'W.

DK-65 Tennessee Copper d.d.h. 5, 740'. Massive, fine-grained sp + gn ore.

DK-63 Tennessee Copper d.d.h. 5, 747'. Massive pyritic ore

PS-10103 Massive pyritic ore. Dump.

PS-10105 Disseminated pyrite in siliceous meta-argillite Dump.

Union Copper. 35°30.25'N, 80°21.4'W.

PS-10205 Disseminated sulfides in siliceous matrix. Dump.

Dorn mine. 33°55'N, 82°17.5'W.

PS-20102 Bedded py + sp in fine-grained schist. Dump.

Jennings mine, Lincolnton-McCormick district, South Carolina 33°52.9'N, 82°17.6'W.

TC4-204-211 Tennessee Copper d.d.h. 4, 204-211'. Layers and clasts of pyrite in tuff. H. Bell, U.S. Geological

Survey, Reston, Va.

PS-21204 Massive barite from "barite hill" southeast of Jennings mine. H. Bell.

TABLE 16: Northern Alabama Piedmont

Pyriton deposit, National Pyrite and Copper Co. mine, Clay County, Alabama. 33°21.6'N, 85°45.3'W.

BS-40101 Banded pyrite in Hillabee greenstone. Dump.

Stone Hill copper mine, Cleburne and Randolph Counties, Alabama. 33°22.5'N, 85°26.2'W (Sect. 35, T-17S, R-11E)

MO-3 Sp- and gn-rich massive ore, assayed 14%Pb. D. Whittington, Florida State University.

MO-9 Same as MO-3; assayed 3% Pb.

DK-60 Tennessee Copper d.d.h. 13, 139-143'. Amphibolite.

DK-61 Tennessee Copper d.d.h. 12, 733.5-734'. Massive ore with high Zn content.

TABLE 18: High Shoals Gneiss zircon

K77-27 About 0.5 km south of village of High Shoals, North Carolina, on County Road 1812. Collected and zircons separated by S.A. Kish.

TABLE 19: Kings Mountain belt galenas

Kings Creek barite mine. 35°04'N, 81°26'W.

PS-20801 Massive barite from open pit.

PS-20802 Mill separates of galena disseminated in massive barite. J.R. Butler, University of North Carolina, Chapel Hill (UNC).

Cameron mine. $35^{\circ}2.4'$N, $81^{\circ}40.25'$W.

PS-21101 Gn in a matrix of siderite and chlorite. W.E. Sharp, University of South Carolina.

Castle's prospect. $35^{\circ}2.7'$N, $81^{\circ}23.9'$W.

YE-25A Large py and gn crystals in quartz veins. J.R. Butler, UNC.

TABLE 20: Kings Mountain belt rocks and feldspars.

YC-1 Metatonalite at the Southern Gold mine. $35^{\circ}03'$N, $81^{\circ}26.25'$W.

YC-2a Metatonalite near the Bar Kat mine. $35^{\circ}03'$N, $81^{\circ}27.5'$W.

YC-3 Crystal-lapilli metatuff unit of Murphy and Butler (1981). $35^{\circ}5.7'$N, $81^{\circ}26.5'$W.

YC-5 Schist of Kings Creek in Kings Creek barite mine open pit. $35^{\circ}4.2'$N, $81^{\circ}26.1'$W.

APL81-21 Pegmatitic phase of Cherryville Quartz Monzonite, Moss mine. On the Inner Piedmont side of the Kings Mountain belt - Inner Piedmont boundary. $35^{\circ}12.25'$N, $81^{\circ}23'$W.

APL81-22 Spodumene pegmatite, Foote mine open pit, Kings Mountain, North Carolina. On Inner Piedmont side of Kings Mountain belt-Inner Piedmont boundary. 35°13.5'N, 81°20.5'W.

APL81-23 "High Shoals" granitic gneiss at Little Long Creek. 35°20'N, 81°13.1'W.

TABLE 21: These samples are described in the table.

TABLE 22: Rocks and massive pyrite from the Haile-Brewer block, South Carolina. Cyprus cores are in the possession of the Mineral Mining Company, Kershaw, South Carolina.

HB-3 Felsic volcanic rock on strike with Haile mine. On County Road 221, about 1.2 km NW of Kershaw. 32°30.6'N, 80°35.9'W.

HB-4 Felsic volcanic rock near county road 75, about 1.2 km W of Kershaw. 32°30.3'N, 80°35.9'W.

HB-7 Felsic volcanic rock. 34°38.75'N, 80°33.4'W.

HB-8 Felsic volcanic breccia. 32°37.3'N, 80°37'W.

8-549.5 Cyprus d.d.h. 8, 549.5'. Coarse-grained gray felsic tuff.

2-454 Cyprus d.d.h. 2, 454'. Fine-grained lapilli tuff.

7-327 Cyprus d.d.h. 7, 327'. Massive pyrite.

12-166 Cyprus d.d.h. 12, 166'. Massive pyrite.

TABLE 23: HB-3 is described under Table 22 and HB-11 under Table 24.

TABLE 24: Samples of other rock units in the Haile-Brewer block and adjacent areas.

Great Falls Granite

HB-9 34°32.4'N, 80°52.7'W. Behind Rocky Creek Hydroelectric plant in Great Falls. Same location as SC-150 in Fullagar (1971).

HB-10 34°31.5'N, 80°55.4'W. Same location as SC-151 of Fullagar (1971).

HB-11 34°32.2'N, 80°55.1'W. Same location as SC-107 of Fullagar (1971).

Libery Hill pluton

LG-101 34°27.1'N, 80°37.25'W. Porphyritic granite from Comolli Granite Company quarry.

LG-103 34°31.6'N, 80°42.6'W. Porphyrytic granite from Matthews International Quarry on Flat Rock Road, Kershaw County.

Pageland pluton

LG-201 34°40.1'N, 80°31.6'W. Porphyritic granite from 40 Acre Rock, Lancaster County.

Flat Creek diabase dike

DD-201 Flat Creek diabase dike. On U.S. 601, NE of

Midway. 34°38.9'N, 80°31'W.

TABLE 25: See notes for Table 26 (following).

TABLE 26: Hamme tungsten district and vicinity.

Tungsten Queen vein, Hamme district, Vance County, North Carolina. 36°30.5'N, 78°28.5'W.

PS-10701 Disseminated sulfides in quartz. NCDMR.

TC-1736-3 1735 stope. Sulfides in quartz vein. R.O. Rye, U.S. Geological Survey, Denver.

HW-144U, HW-181U, and HW-192U Samples of the Vance County pluton collected by J.E. Gair, U.S. Geological Survey, Reston. Samples were collected at 10 foot intervals from the vein NW of #6 shaft, 900 level. Sample numbers increase away from vein.

Vance County pluton

APL81-1 From "State Line" quarry. 36°32.5'N, 78°26.5'W.

APL81-2 From quarry in Crooked Run, NW of Henderson, N.C. 36°22'N, 78°27.6'W.

TABLE 29: Valley and Ridge galenas.

VR-01001 Gn disseminated in lower Silurian Tuscarora sandstone. Interstate 77 tunnel through Walker Mountain, Va. 37°2.3'N, 81°8'W. J.R. Craig, VPI.

NY-201 Shawangunk mine. Sp + gn in fracture filling quartz vein in Shawangunk conglomerate near Wurtsboro, New York. 41°35.7'N, 74°24.1'W.

NY-202 Shawangunk mine. Same as NY-201.

TABLE 30: Galenas from Scotland and Ireland

Aberfeldy district, Perthshire, Scotland.

L-79 Gn in qtz-celsian rock, west side of West Foss Estate.

L-80 Massive sulfide from central Aberfeldy district, Farragon Hill.

L-90 Approximately 5 cm wide gn vein in qtz-celsian rock, about 20 m from L-80, central Aberfeldy district.

Tyndrum, Scotland.

L-78 Sp + gn in fracture filling quartz vein.

Avoca mines, County Wicklow, Ireland.

L-77 "Galena boulder" in stringer ore, hanging wall side of East Avoca open pit.

TABLE 28: The only sample in this table that has not been previously described is from the Roxboro granodiorite

K81-8 Roxboro granodiorite. About 1.5 km south of Olive Hill, Person County, North Carolina. 36°24.6'N

79°02.6'W. Collected and K-feldspar separation by S. A. Kish.

APPENDIX B: ANALYTICAL PROCEDURES

The techniques described here are not new but are variations on methods worked out by various investigators through the years whose contributions have made this study possible. In particular, this study has benefited from advice on laboratory procedures from Maryse Delevaux, Lynn Fischer, Mark Huebner, and Loretta Kwak, all of the U.S. Geological Survey, Denver.

Mass Spectrometry

Most of the lead isotope analyses reported were made on National Bureau of Standards (NBS) Neir-type 12", 60° mass spectrometers at the U.S. Geological Survey, Denver, and at Florida State University. A few were run on a Micromass 54E mass spectrometer in semi-automatic mode, or on a NBS 12", 90° mass spectrometer. All lead analyses were made using the surface emission (silica gel) technique and are normalized to NBS Standard Reference Material 981, which was run periodically through the course of this study on each of the four mass spectrometers used for lead. All of the reported galena, K-feldspar, and whole-rock lead isotope ratios are averages of at least two complete runs made at 1200 ± 10°C per dissolution. In a few instances insufficient lead was recovered for more than one run. In these cases a fresh split was prepared for the second run.

Concentrations of uranium, thorium, and lead were determined by isotope dilution. Whole-rock uranium and thorium analyses were made on a 12", 60° NBS mass spectrometer. Zircon uranium analyses were made on a 6", 60° NBS mass spectrometer. Uranium was run with the ionizing filament at 2000°C and the sample filaments at about 2.0 amperes. Thorium was run with uranium, by turning sample filaments up to about 3.0 amps after completion of uranium runs.

Sulfur isotope analyses were made on the modified Nuclide 60 RMS mass spectrometer in the laboratory of Robert O. Rye, U.S. Geological Survey, Denver.

Lead isotope ratios are believed to be within 0.1% of absolute. U, Th, and Pb concentrations have an analytical error of about 1%. Sulfur isotope analyses are thought to have an error of about 0.1 per mil.

Dissolution Chemistry

All reagents, except as noted, were double sub-boiling point distilled. HBr and NH_4OH were suprapure grade. Water for sulfide, feldspar, and whole-rock chemistry was triple distilled whereas that used in zircon dissolution and U-Pb separation was five times distilled. The maximum lead blank in the chemistry for sulfides, feldspar, and whole-rock procedures was less than 30 ng/g and was negligible in all cases. Zircon procudures had a total lead blank of about 1 ng and all data is blank-corrected.

Sample preparation and chemistry (except for high Pb samples) was performed in positive pressure, "lead-free" laboratories. Ore, feldspar, and whole-rock samples were dissolved and evaporated in teflon tanks in a nitrogen atmosphere.

Galena

Galena was dissolved in 4:1 HNO_3 + $HClO_4$ and lead was electroplated as the dioxide on a platinum anode at about 2 volts. The plating was stripped with 1N HNO_3 plus a drop of H_2O_2 and taken to dryness. After adding dilute H_3PO_4 and allowing to evaporate, the sample was ready to run.

Hard-to-separate galenas were treated by one of two methods. 1) The sample was boiled in 50% $HClO_4$, and then filtered. After diluting with H_2O and a few drops of HNO_3, lead was electroplated as above. 2) The sample was leached with hot HCl, the leachate converted to bromide, and passed through the HBr ion exchange column to separate lead. After conversion to perchlorate, lead was electroplated as above. When significant Bi or Tl was present in any sample, it was passed through an HBr column before electroplating.

Sulfide minerals and "whole-ore"

Samples containing little or no pyrite were decomposed overnight in hot 6.2 N HCl. After evaporation, a few millileters of $7NHNO_3$ + 6.2 N HCl were added to dissolve any pyrite and HCl-insoluble sulfides present and the sample was again taken to dryness. The sample was redissolved with several ml of concentrated HF when silicate residue remained. After conversion to bromide, the sample was passed through 1.5-2.0 cm^3 (depending on sample size) brominated anion exchange column conditioned with 1.5N HBr. The columns were washed with two column-volumes of 1.5N HBr and then with four column-volumes of 1.5N HCl. Better separations were achieved when the resin was reconstituted by 1.5N HBr washed during sample loading. When uranium and thorium were to be analyzed, the dissolved sample was split before bromination. Lead was eluted with dilute HNO_3. After evaporation, the eluant was converted to nitrate/perchlorate and electroplated as for galena.

The nitrated/perchlorated eluant should be pure white. When it was evident by coloration that significant iron remained, the column procedure was repeated before electroplating. (Iron interferes with the electrical cell).

Pyrite-rich samples were treated in two ways: 1) as HCl-soluble and insoluble portions; and 2) as "whole-ore" samples. In the first method, the sample was heated overnight in hot 6.2N HCl, taking advantage of the insolubility of pyrite in HCl. The sample was centrifuged and the leachate (HCl-soluble fraction) decanted into a clean beaker. The leachate was dried, brominated, and passed through an HBr column for separation. The HCl-insoluble fraction (essentially, pyrite), was thoroughly washed to remove any traces of leachate and then heated overnight in concentrated HNO_3 with a few milliliters each of HCl and HF. After evaporation, the residue was converted to chloride and then bromide and passed through an ion exchange column.

The "whole-ore" method was essentially the same as that for the HCl-insoluble fraction. The sample was dissolved in concentrated HNO_3, HCl and HF, evaporated, converted to chloride, and then to bromide, and passed through HBr ion exchange resin.

Feldspar and whole-rock

The dissolution and analytic procedures used for feldspars and whole-rocks are essentially those described by Doe and Delevaux (1980). Where lead isotopes are reported for feldspar leachate, the first of two 5% HF leaches was used. The HF leaches were preceded by HCl and HNO_3 leaches. Feldspar residue analyses were made on the residue of a second HF leach. The residual material is considered to be the closest approach to primary lead isotope compositions (Ludwig and Silver, 1977).

Samples for whole-rock analysis were cut from the interior of the rocks, ultrasonically cleaned, powdered in a platiner mortar, and split into 2-3 gram fractions. Separate splits were used for lead isotope composition and U, Th, and Pb concentration analysis. Whole-rock and residual feldspar samples were dissolved in (10 ml/g) concentrated HF plus 2 ml HNO_3 and a little $HClO_4$. The solution was taken to dryness and then re-dissolved and evaporated in, successively, $H_2O + HNO_3 + HClO_4$ and then $H_2O + HNO_3$. After redissolution in 28 ml H_2O + 2 ml HNO_3, concentrated NH_4OH was added until pH=8.5. Lead, uranium, and thorium are carried with the precipitate. The sample was then centrifuged and the liquid fraction decanted and discarded. The precipitate was dissolved in 6.2N HCl and, for concentration runs, a split was taken for uranium and thorium analysis. Splits for lead analysis were taken to dryness, redissolved in 1.5N HBr, and passed through a 1.5cm^3 anion exchange bed conditioned with 1.5N HBr. The eluant was treated as described above: converted to nitrate/perchlorate and electroplated.

Uranium and thorium splits were taken to dryness, converted to nitrate, and passed through nitrate form anion exchange resin at 7N HNO_3. Uranium and thorium were eluted with 1N HCl and with H_2O.

Zircon

Size and magnetic fractions of zircon were separated and impurities left in the final stage were hand-picked. Before weighing the zircons were cleaned by successive HCl and HNO_3 leaches and by ultrasonic cleaning, ultra-pure water washes, and drying. The accurately weighed sample was decomposed using the Krogh (1973) method. Samples were "spiked" for uranium concentration determination after complete dissolution, then taken to dryness, re-dissolved and aliquoted. An aliquot (about one fourth) of the sample solution was "spiked" for lead concentration analysis. The remaining sample was processed for lead isotope composition analysis.

Lead was separated on HBr anion exchange columns, and uranium on nitrate columns, in essentially the same manner as previously described.

Sulfur extraction

Sulfur was determined as SO_2 which was made by mixing ground sulfide samples with CuO and reacting the mixture at 1025°C in quartz tubing. The reaction was allowed to proceed for fifteen minutes and SO_2 was collected in a liquid nitrogen-cooled trap. Where necessary, samples were further purified by passing through a methanol-liquid nitrogen "slush" trap.