A LEAD ISOTOPE STUDY OF MINERAL DEPOSITS

IN THE KOOTENAY ARC

by

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We accept this thesis as conforming
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ABSTRACT

Twenty-one galena specimens from 16 mineral deposits in the Kootenay district analysed isotopically in replicate have a linear relationship of isotopic compositions on a Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204} graph. Twelve of the galenas, including two from Sullivan mine (East Kootenay district), were analysed by an intercomparison technique; the first application of the intercomparison method to an anomalous lead suite. Intercomparison results verify the linear compositional pattern (slope = 0.1084 $\pm$ 0.0033). These results indicate that:

1. Kootenay arc leads are multi-stage leads.

2. Sullivan-type lead is the parent common lead from which the anomalous suite developed.

3. Kootenay arc mineral deposits formed during one major mineralizing episode.

Time of anomalous lead mineralization, t_m, is probably Jurassic as deduced from potassium-argon dates and crosscutting relations of ores and igneous rocks. Assuming t_m = 180 m.y. time of emplacement of uranium and thorium that produced the radiogenic component of the anomalous leads is approximately 1700 m.y., possibly the age of Lower Purcell strata of the East Kootenay district.

Lead isotopic compositions show no obvious correlations with age of wallrock, type of wallrock, geological nature of ore deposits, or minor element content of galena. Post-ore thermal metamorphism and hydrothermal alteration do not appear to have changed lead isotopic compositions. The

history of evolution of Kootenay arc anomalous leads is interpreted as follows:

1. Formation of source rocks containing uranium and thorium about 1700 m.y. ago.

2. Introduction of Sullivan-type lead into source rocks about 1340 m.y. ago.

3. Mixing of Sullivan-type lead with radiogenic lead formed by decay of uranium and thorium, and transportation and deposition of these "lead mixtures" to form anomalous lead deposits during Coast Range orogeny.

Geologic and isotopic data from Sullivan mine are reconciled most easily with an epigenetic origin of the Sullivan orebody, and probably with a genetic relation of Sullivan ore fluids with the source magma of Moyie Intrusions. Holmes-Houtermans model age for Sullivan ore, based on inter-comparison data, is 1340 m.y. Sullivan lead evolved in a source with $U^{238}/Pb^{204} = 9.02$, $Th^{232}/Pb^{204} = 36.71$, and $Th/U = 4.07$ (in terms of present day abundances).

A method of estimating volume of source rock of anomalous lead deposits is outlined. Calculations for Jersey, Reeves Macdonald and Bluebell mines indicate that the radiogenic lead component of these deposits could have been derived from 1 to 10 cubic kilometers of source rock containing 3 ppm uranium (and approximately 12 ppm Th) if only one-third to one-half of the radiogenic lead in the source were extracted during a period of concentration and mineralization.

Kootenay arc deposits can be divided into two classes on the basis of minor element contents of galenas. This division closely corresponds to the following geological types of deposits:

1. replacement deposits with no evidence of open space filling, and

2. deposits with evidence of open space filling and variable amounts of wallrock replacement.

Minor element contents of galenas from Salmo-type replacement deposits suggest but do not prove a fairly low temperature of mineral deposition.

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

ACKNOWLEDGEMENTS

CHAPTER I

INTRODUCTION

The Kootenay arc is a structural belt in southern British Columbia

(figure 1) that was first defined by Hedley (1955, p. 32) as:

> "..... a curving belt of heterogeneous, lime-bearing sediments
> bowed around the eastern margin of a major batholithic area and ...
> bounded somewhat arbitrarily on the east by underlying quartzites
> of early Cambrian age."

Only 15 to 20 miles wide, with a curved trend concave to the west, the arc

extends from south of the International Boundary at Nelway, B. C., through

Salmo mining district, Kootenay Lake, and Lardeau district to Revelstoke --

a distance of 160 miles. Probably it extends much farther north, for Suth-

erland-Brown (1957, p. 59), after studying similar strata and structures in

the Caribou district, 250 miles northwest of Revelstoke, concludes:

> "Even though the two districts are separated by a gap of 250
> miles, in which our knowledge is relatively slight, it is tenta-
> tively concluded that they are parts of the same geological prov-
> ince."

The eastern edge of the Kootenay arc in the Lardeau district is arbitrar-

ily taken as the base of a prominent exposure of Badshot limestone (Lower

Cambrian) known locally as the "Lime Dyke." This limestone bed can be traced

southward, paralleling the east shore of the north half of Kootenay Lake, to

Crawford Bay, whence the trend changes to south-southwest along a line extend-

ing from Crawford Bay to the town of Salmo. About midway between Crawford

Bay and Salmo, the Badshot limestone is interrupted by igneous intrusions.

Farther south, in Salmo district, the Reeves limestone, correlative of the
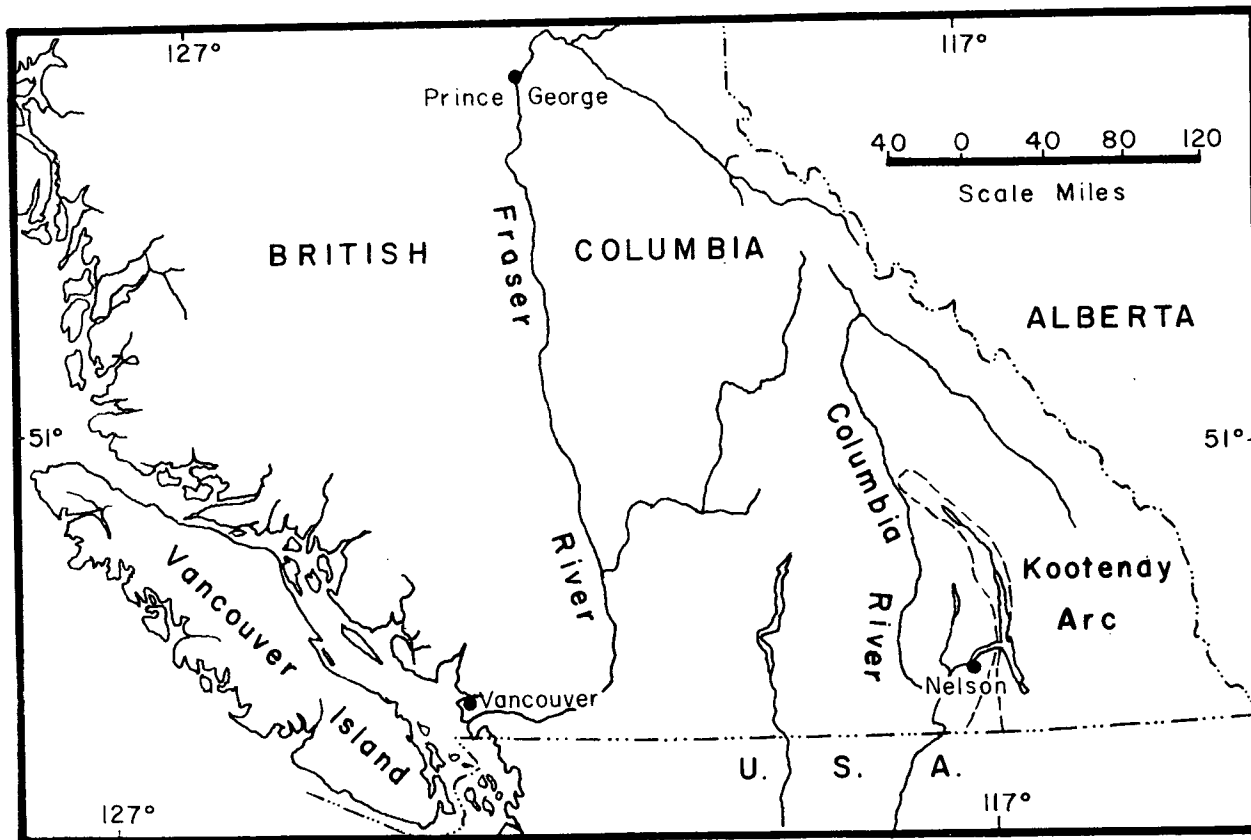
Fig. I-I: Location map showing the Kootenay Arc

Badshot limestone, does not outline the eastern boundary of the arc. In the

Salmo district the eastern limit of the Kootenay arc has never been defined

closely. Local usage of the term "Kootenay arc" is applied to Ymir, Salmo,

and Sheep Creek mining camps, implying that the eastern edge approximates the

117 degree west meridian.

The western edge of the arc is the eastern margin of the Kuskanax batho-

lith in the north and the Nelson batholith in the south. South of the city

of Nelson the western limit of the arc is roughly the eastern edge of Meso-

zoic volcanic rocks and corresponds closely to a group of granitic bodies

that are "satellitic" to the Nelson batholith (Hedley and Fyles, 1956).

Lead, zinc, silver, and gold deposits are abundant in the arc. The

earliest recorded commercial mining venture was at the Bluebell deposit

shortly after the "rediscovery", in 1868, of the showing known previously to

Indians and trappers. The venture was unsuccessful, but in 1882 the Bluebell

showing was re-investigated, and active exploration began in the Kootenay

district. By the late nineteenth century precious metals (gold and/or silver)

were being produced from Bluebell mine, several deposits in Lardeau, Slocan

and Ainsworth camps in the north, and Ymir camp in the south. The scene of

mining activity in the south soon shifted from Ymir southeast to Sheep Creek

camp which remained in production for several decades. Despite abundant lead

and zinc sulfides in many deposits in the Kootenay arc, mining was dependent

mainly on precious metals associated with sulfide bodies. During the late

1940's Salmo lead-zinc camp came into production, and since has greatly ex-

ceeded production of historic mining camps farther north.

The purpose of this investigation was to correlate lead isotope data

with the geological history of a mineralized region. The Kootenay arc appear-
ed a likely area for such an investigation because

    (1)   the area contains abundant mineral deposits in both similar
           and different geological settings;

    (2)   a number of prospects and operating mines were readily access-
           ible;

    (3)   despite the structural complexity of the region, the general
           geological history is reasonably well known; and

    (4)   previous exploratory lead isotope analyses at the University
           of Toronto indicated a wide range of isotopic compositions
           of lead from galena in different places along the arc.

The writer spent one month in the autumn of 1960 visiting mines in the

southern part of the arc collecting specimens for lead isotope and mineral-

ographic investigation. The summer of 1961 was spent doing geological mapp-

ing near Ainsworth, Kaslo, and in the South Lardeau district near Duncan Lake,

under the supervision of Dr. J. T. Fyles of the British Columbia Department

of Mines and Petroleum Resources. During the 1961 field season the writer

had several opportunities to accompany Dr. Fyles on field trips to several

parts of the Kootenay arc, including Salmo, Sheep Creek, Slocan and Ferguson

areas. A number of galena specimens used in this study were collected during

these field trips. The author benefited greatly from discussions in the

field with Dr. Fyles and mine geologists, concerning the geology of the arc

and of individual mines.

Presentation of material in this thesis is designed to:

    (1)   introduce the reader to the subject of lead isotope studies
           in relation to mineral deposits, and

    (2)   discuss a lead isotope case history in terms of geological
           history, using the Kootenay arc as an example.

Chapters II and III deal respectively with simple and complex histories of
lead in sulfide deposits, as inferred from lead isotope ratios. In both
chapters various "lead models" (hypothetical histories of lead isotope devel-
opment) are considered, followed by reference to possible geological process-
es that might produce observed patterns of lead isotope compositions. Gen-
eral geology of the Kootenay arc is reviewed in Chapter IV, and geology of
mining camps and deposits for which lead isotope analyses were made is summ-
arized in Chapter V. The remainder of the thesis is concerned primarily
with results of lead isotope studies of Kootenay arc galenas. Methods of
sample preparation and isotope abundance measurements are presented briefly,
and much space is devoted to interpretations of the lead isotope data. Pub-
lished isotope analyses from East Kootenay and Metaline districts are re-
viewed in light of more precise Kootenay arc analyses.

CHAPTER II

SINGLE STAGE (ORDINARY) LEADS

Lead has four stable isotopes of atomic masses, 204, 206, 207, and 208. The last three are identical to end members of U^{238}, U^{235}, and Th^{232} decay series, respectively, but Pb^{204} is not known to be produced by nuclear processes. Minerals contain lead with a wide range of isotopic compositions. Approximate relative abundances, expressed in atom percents are

$$Pb^{204}/Pb^{206}/Pb^{207}/Pb^{208} = 1.5/23.5/22.5/52.5$$

Holmes (1937) studied lead isotopes of galena indirectly by measuring atomic weights of ore lead. He determined a constant atomic weight of 207.21 for lead, regardless of geologic age, and concluded that lead developed in an environment free of uranium and thorium, presumably below the crust. Holmes' conclusion that the isotopic composition of lead in ore deposits is constant has been proven incorrect. Proportions of lead isotopes were found to vary in such a manner as to maintain an almost constant atomic weight. As a pioneer in lead isotope studies, Holmes evolved much of the terminology used today. He defined common lead as "the ordinary lead of commerce, which is the ore lead obtained from galena, cerussite, and other ores of lead"; radiogenic lead as "lead generated from the radioactive elements uranium and thorium"; and rock lead as "a mixture of common lead with the radiogenic lead generated in the rock material during geologic time." Primeval lead (primordial lead) is lead that was present in the earth at the beginning of geologic time.

Isotope ratios of common leads were first reported by Nier (1938) and Nier, Thompson, and Murphy (1941). They found a fairly consistent relation between lead isotopic compositions and ages of galena deposition and suggested that ore leads were mixtures of primeval lead and radiogenic lead. The isotopic composition of total radiogenic lead in an isolated or "closed" uranium-thorium system is time dependent. Hence mixtures of radiogenic lead and primeval lead separated from a source at various geological times would be expected to show some relation between composition and time of lead mineral formation.

Nier's data were used by several investigators in attempts to define the age of the earth (Holmes, 1946, 1947, 1949; Houtermans, 1946, 1947; Jeffreys, 1948, 1949; and Bullard and Stanley, 1949). All postulated that the majority of galenas analysed by Nier had simple histories wherein the total lead composition evolved gradually in a closed uranium-thorium-lead system by the addition of radiogenic lead to primeval lead. At some time lead was extracted from the system and deposited as a lead mineral after which there would be no further change of isotopic composition. Primeval lead was assumed to be of constant composition, and fractionation of lead isotopes negligible.

Equations employed in the mathematical treatment of common lead data can be derived from the radioactive decay equation

$$N_t = N_p e^{\lambda t} \tag{II-1}$$

where N_t is the number of atoms of a radioactive parent at time t, in the past, that would be reduced to N_p atoms at the present time. Lambda (λ) is the radioactive decay constant. Symbols used here and in all subsequent

Table II-1: Symbols and Constants Used

Isotope Ratio	at present $t = o$	at time t	at time t_o
Pb^{206}/Pb^{204}	a	x	a_o
Pb^{207}/Pb^{204}	b	y	b_o
Pb^{208}/Pb^{204}	c	z	c_o
U^{238}/Pb^{204}	$137.8V$	$137.8Ve^{\lambda t}$	$137.8Ve^{\lambda t_o}$
U^{235}/Pb^{204}	V	$Ve^{\lambda' t}$	$Ve^{\lambda' t_o}$
Th^{232}/Pb^{204}	W	$We^{\lambda'' t}$	$We^{\lambda'' t_o}$

Decay Constants	Value in 10^{-9}(years)$^{-1}$	Parent Atom
λ	0.1537	U^{238}
λ'	0.9722	U^{235}
λ''	0.0499	Th^{232}

$\alpha = U^{238}/U^{235} = 137.8$

$t_o = 4.55 \times 10^9$ years $(\pm .03 \times 10^9$ years$)$

equations are explained in Table II-1.

Let us consider the variation in amount, with time, of Pb^{206}. Total radiogenic Pb^{206} atoms formed from the beginning of geologic time to any time, t_1, is given by

$$Pb^{206} = U_o^{238} - U_{t_1}^{238}$$

$$= U_p^{238} (e^{\lambda t_o} - e^{\lambda t_1}) \qquad (II-2)$$

To obtain total Pb^{206} atoms present in a closed system at time t_1, Pb^{206} present in primeval lead must be added to Pb^{206} formed by radioactive decay. The amount of Pb^{204} is assumed to have remained constant, so we can write

$$\frac{Pb^{206}}{Pb^{204}} = \frac{Pb^{206}}{Pb^{204}} + \frac{U_p^{238}}{Pb^{204}} (e^{\lambda t_o} - e^{\lambda t_1}) \qquad (II-3)$$

| ratio at time t_1 | ratio of primeval lead | ratio change due to formation of radiogenic lead |

or, substituting symbols given in Table II-1:

$$x = a_o + 137.8V(e^{\lambda t_o} - e^{\lambda t_1}) \qquad (II-4)$$

In similar manner equations can be obtained for y and z, where y and z are respectively, Pb^{207}/Pb^{204} and Pb^{208}/Pb^{204} ratios at time t_1.

$$y = b_o + V(e^{\lambda' t_o} - e^{\lambda' t_1}) \qquad\qquad \text{(II-5)}$$

$$z = c_o + W(e^{\lambda'' t_o} - e^{\lambda'' t_1}) \qquad\qquad \text{(II-6)}$$

Equations (II-4) and (II-5) can be combined to give the Holmes-Houtermans "isochron" equation:

$$\frac{y - b_o}{x - a_o} = \frac{1}{137.8} \cdot \frac{(e^{\lambda' t_o} - e^{\lambda' t_1})}{(e^{\lambda t_o} - e^{\lambda t_1})} \qquad\qquad \text{(II-7)}$$

From this equation it is seen that compositions of leads with identical ages and simple histories must plot along a straight line or "isochron" passing through the composition of primeval lead.

Depending on which of Nier's data are used, various values of t_o, the age of the earth, will be obtained. Initial estimates of t_o ranged from 2.0 to 3.35 billion years. Early workers substituted approximate geologic ages of various leads of known isotopic compositions in the Holmes-Houtermans equation and solved for t_o and the isotopic composition of primeval lead. The method was not particularly successful because accurate geologic dates of the deposits concerned were not available and some of the leads are now known to be of multi-stage origin. If t_o and the isotopic composition of primeval lead were accurately known the Holmes-Houtermans equation could be used to date any lead minerals that fit the simple model.

Meteorites probably represent closed systems with respect to uranium,

thorium, and lead. Therefore, meteoritic leads should have compositions that plot on a zero isochron. Murthy and Patterson (1962) recently examined available lead isotope data for meteorites, and conclude in part that:

(1) primeval lead of meteorites, obtained from troilite, has the composition; x = 9.56, y = 10.42, and z = 29.71, with an uncertainty of about 1.5 percent of each ratio;

(2) lead in stoney meteorites has a wide range of compositions that group closely about a line (zero isochron) of slope 0.59 ± 0.01 on an x versus y graph; and,

(3) primeval lead of the earth and the terrestrial zero isochron correspond to meteoritic values (within limits of experimental error).

The age of the earth, calculated by substituting the slope of the meteoritic zero isochron in the Holmes-Houtermans equation is $4.55^{+}_{-} 0.03$ billion years.

Several attempts have been made to interpret common lead isotope abundances in terms of age of mineral deposition. Various histories of lead development have been proposed, and are reviewed briefly below. Common lead models are of two types:

(1) single-stage (ordinary) models involving lead that developed in a single uranium-thorium-lead system from the beginning of geologic time until the time of its final deposition as a lead mineral; and

(2) multi-stage (anomalous) models concerned with leads that existed in more than one uranium-thorium system prior to final deposition as lead minerals.

SINGLE STAGE LEAD MODELS

Holmes-Houtermans Model

Providing the age of the earth and the isotopic composition of primeval
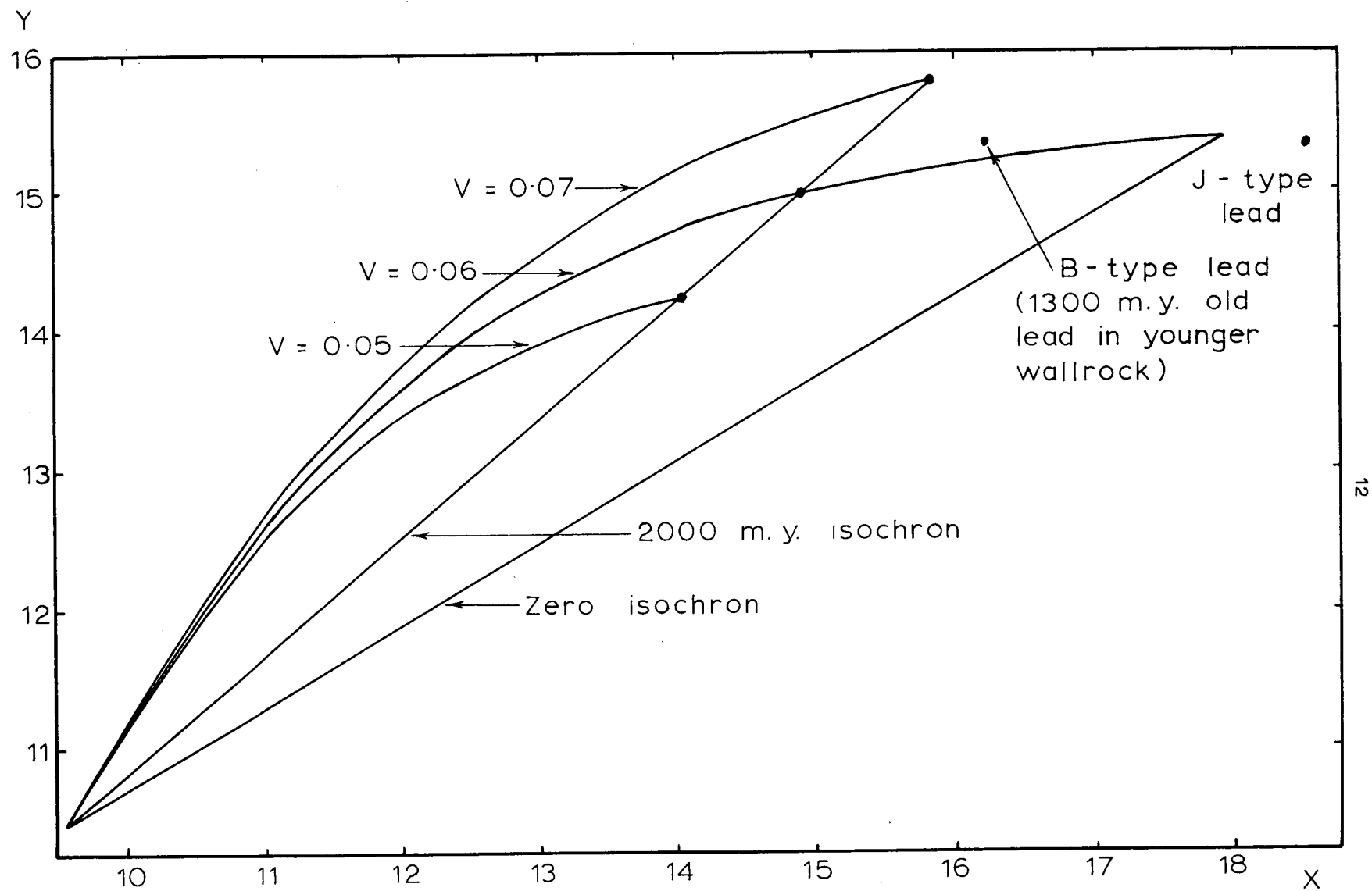
FIGURE II-1: HOLMES-HOUTERMANS MODEL FOR COMMON LEADS

lead are known, the Holmes-Houtermans equation (II-7) can be used to date leads with simple histories. The following assumptions are incorporated in the model:

(1) primeval lead and lead in troilite of meteorites have identical uniform isotopic compositions;

(2) leads developed within closed, uranium-thorium-lead systems in the earth's crust;

(3) different parts of the crust have their own characteristic uranium/lead and thorium/lead ratios;

(4) at various times lead was extracted from parts of the crust, concentrated, and deposited as lead minerals. The isotopic composition of a mixture of primeval and radiogenic leads at any given time would be "frozen" in lead minerals formed.

(5) no significant chemical or physical separation (fractionation) of lead isotopes occurred during or after mineral deposition.

If, at some time, lead were extracted from several zones with different uranium/lead ratios, then, on an x versus y graph the isotopic compositions should define a straight line (isochron) passing through the composition of primeval lead. Figure II-1 illustrates the basic concepts of the model.

Holmes (1949) realized that all leads would not have the simple history required by his model because of the probability that leads had existed in a number of different uranium-thorium environments before final deposition as lead minerals. However, he assumed that high and low U^{238}/Pb^{204} ratios for different stages in the development of a lead would compensate each other such that final isotopic compositions would give meaningful ages.

Certain leads, called J-type (Joplin) anomalous, are not explained adequately by the Holmes-Houtermans model. J-type leads have negative model ages. Anomalous leads of a second kind, B-type (Bleiberg), have model ages

older than their wall rocks. B-type leads are interpreted as old leads that have been remobilized without contamination by additional lead.

Some limitations to the Holmes-Houtermans model are given below:

(1) J-type leads are not explained;

(2) The existence of lead in several uranium-thorium environments prior to deposition as lead minerals would probably not produce a lead isotopic composition that could be dated meaningful by a single-stage model (Kanasewich, 1962a);

(3) compositions of certain suites of common leads have linear trends unrelated to primary isochrons. In particular, there appears to be a complete compositional gradation from B-type leads to J-type leads, suggesting that the distinction between the two types is unwarranted, or at least arbitrary.

The above limitations place severe restrictions on the application of the Holmes-Houtermans model to the problem of dating common leads. Insofar as the underlying assumptions are correct, leads that have had simple histories can be dated with confidence.

Russell-Farquhar-Cummings Model

Russell and others (1954) distinguish two classes of common leads, "ordinary" and "anomalous". Ordinary leads formed in single, closed, uranium-thorium systems prior to deposition as lead minerals; anomalous leads are considered mixtures in variable proportions of a single ordinary lead and a single radiogenic lead. A discussion of anomalous leads will be deferred to a later page.

The Russell-Farquhar-Cummings model has several basic assumptions in common with the Holmes-Houtermans model, and ordinary leads could be dated equally well by either model. Fundamentally the two differ in that Russell

and others consider the slight variations in U^{238}/Pb^{204} and Th^{232}/Pb^{204} values

calculated from ordinary lead compositions, to indicate a source region fair-

ly uniform with respect to uranium, thorium, and lead; specifically, the low-

er part of the crust and/or the mantle (cf. Alpher and Herman, 1951). The

concept of lengthy isochrons is rejected, and apparent variations in $U^{238}/$

Pb^{204} values are explained largely as resulting from

(1) experimental error, and

(2) our inability to distinguish certain anomalous leads which
     plot in the "isochron region".

The model for ordinary leads utilizes "best fit" curves of the type

$$x = a - 137.8V(e^{\lambda t} - 1)$$

$$y = b - V(e^{\lambda' t} - 1) \qquad\qquad\qquad (II\text{-}8)$$

$$z = c - W(e^{\lambda'' t} - 1)$$

(See Table II-1 for explanation of symbols)

Knowing the parameters a, b, c, V, and W, three ages of mineralization based

on the three radiogenic lead isotopes, can be determined from the foregoing

equations. The Pb^{207}/Pb^{204} ratio will not produce a meaningful age because

of the very slight change in this ratio over the past two billion years.

Ideally the two remaining ages should be similar if the model is correct.

Discrepancies in model ages could be due to: (1) experimental error, (2)

slight differences in V and W values from place to place in the system in

which ordinary leads develop, and/or (3) errors in the values of some of the

parameters used in age calculations.

The model is illustrated in Figure II-2, where time (of separation of

ordinary lead from its place of compositional evolution) is plotted against

x, y, and z values (after Russell and Farquhar, 1960). A single age of min-
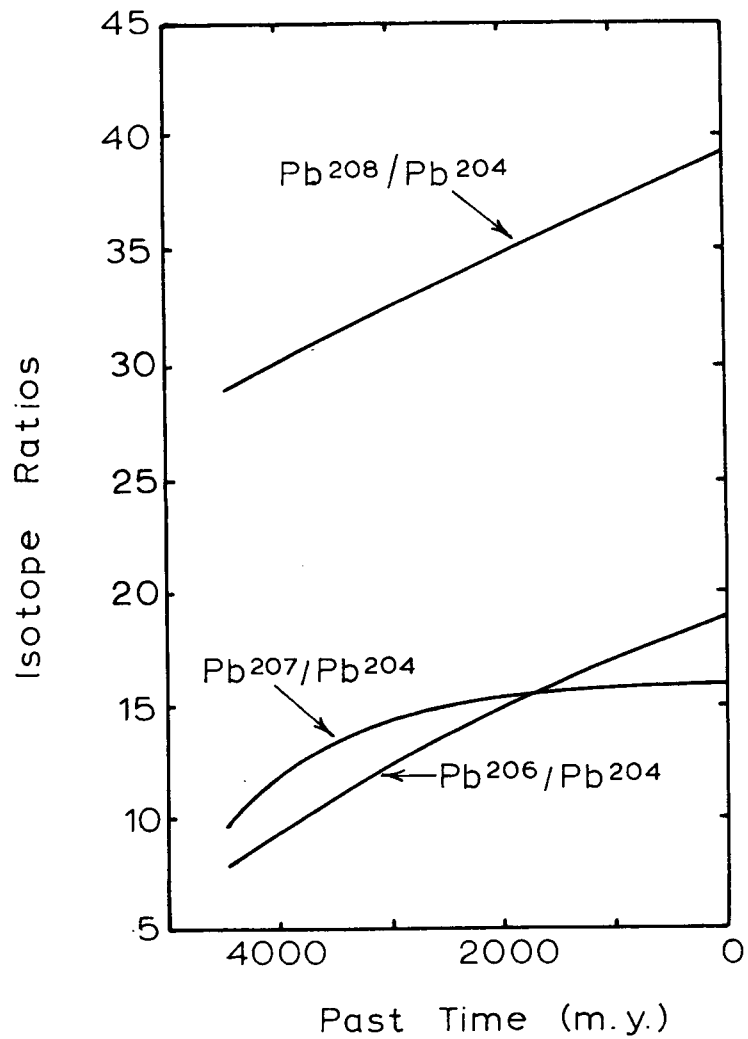
FIGURE II - 2: RUSSELL - FARQUHAR - CUMMING ORDINARY LEAD MODEL (after Russell and Farquhar, 1960)

eral deposition can be obtained graphically by finding the time corresponding

to the position of best fit on the curves of Figure II-2, for a given set of

x, y, and z values.

Estimated uncertainties in galena ages calculated on the above model

ranged from 780 m.y. for young leads to 180 m.y. for leads 3000 m.y. old

(Russell and others, 1954). These uncertainties are probably much too high

because:

(1) constants used in their calculation were not as accurately known
     as at the present, and

(2) much of the observed spread of isotopic compositions can be
     attributed to error in Pb^{204} measurement, and to our inabil-
     ity to distinguish some anomalous leads lying to the left of
     the zero isochron.

To summarize briefly, the Russell-Farquhar-Cummings model differs basic-

ally from the Holmes-Houtermans model in assuming the mantle or lower crust

to be the ultimate source of lead minerals, and in recognizing the signif-

icance of anomalous leads and effects of error in Pb^{204} measurement.

Russell-Farquhar-Stanton Model

The Russell-Farquhar-Stanton model (Stanton and Russell, 1959; Russell

and Farquhar, 1960a; 1960b) provides a means of dating "conformable" lead-

bearing sulfide deposits. The term "conformable" has been applied to massive

or disseminated, layered, sulfide deposits of principally pyritic or pyrrho-

titic character, whose more-or-less tabular or lenticular outlines parallel

layering in enclosing rocks. Country rock is commonly argillaceous or tuff-

aceous, and the deposits are thought by some authors (e.g. Stanton, 1960a)

to be genetically related to volcanic rocks that are, in places, closely associated with the ores. The Broken Hill deposit in Australia is the type of example of a "conformable" deposit (King, 1953). The word "conformable" has a genetic implication that has not yet been proven to apply to ore deposits and the term is used here in a descriptive sense only.

Stanton and Russell (1959) noted that conformable leads of a given deposit were of uniform isotopic composition and that lead of individual conformable deposits had, within limits of experimental precision, mean compositions that plotted on a single primary growth curve (Figure II-3). They inferred that the leads had developed by the gradual addition of radiogenic lead to primeval lead, in environments identical with respect to lead, uranium and thorium. The wide geographic distribution of conformable deposits that fitted the above pattern implied also that the uniform source was widespread. A subcrustal origin of the lead was postulated on the assumption that the mantle was uniform with respect to uranium, thorium, and lead. When first proposed, the model incorporated Stanton's sedimentary-volcanic theory of origin which can be summarized by the following brief quotation (Stanton and Russell, 1959, p. 594):

> ".....this combination of igneous (volcanism) and sedimentary factors may have led to the syngenetic development of sediments rich in sulfides, chiefly of iron, which later acted as precipitants for heavy metal halides expelled, principally during compaction and diagenesis, from associated tuff beds."

The present concept is that conformable sulfides were precipitated directly from sea water by the action of sulfate-reducing bacteria. Metals are assumed to be of volcanic origin, and no "significant" contamination by metals from other sources is thought to have occurred. This "volcanic-
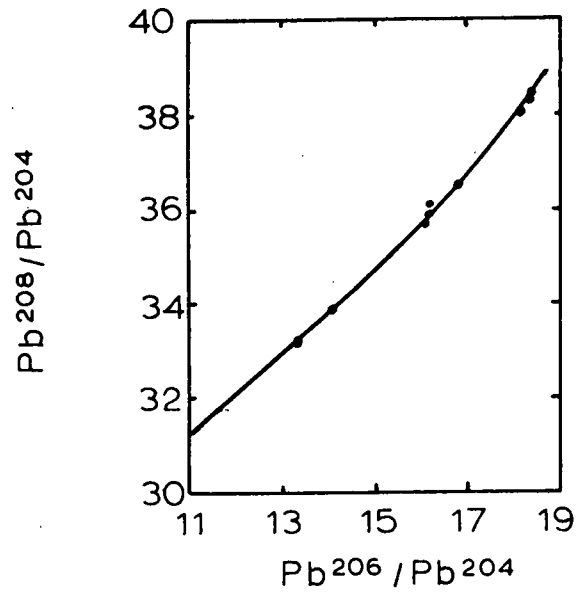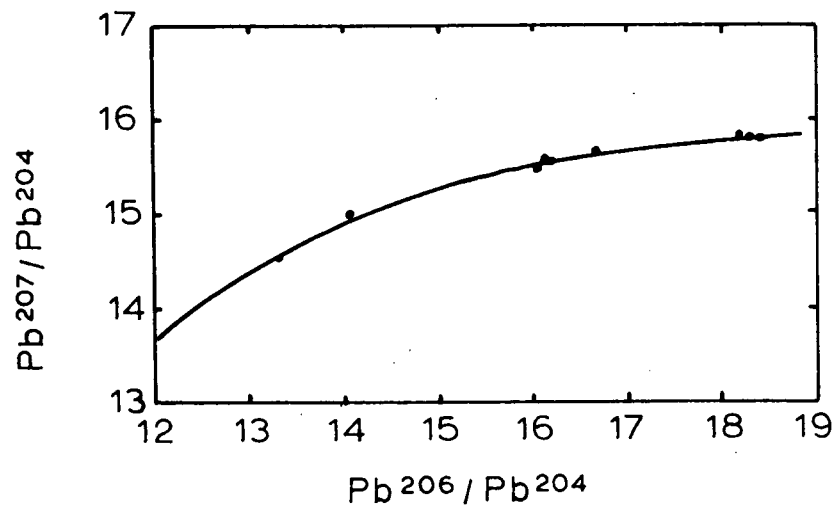
FIGURE II - 3: RUSSELL - FARQUHAR - STANTON
CONFORMABLE LEAD MODEL
(after Stanton and Russell, 1959)

syngenetic" theory of origin is an attempt to explain lead isotopes in terms
of ore-forming processes. Other theories of ore genesis that permit trans-
port of ordinary lead without contamination by crustal lead, would fit this
model equally well. Deposits are dated by the Holmes-Houtermans equation to
give model ages for times of syngenetic deposition. Minor variations are
recognized in U/Pb and Th/Pb ratios of the metals' ultimate sources. Figure
II-3 illustrates the closeness of fit of some conformable lead isotope abund-
ances to a single growth curve.

An alternative view of crustal derivation of extensively mixed lead is
presented by Shaw (1957, p. 573):

> "....it is not necessary to postulate a subcrustal source for
> galena deposits. The crust is admittedly heterogeneous, but crustal
> processes, especially gradation, diastrophism and volcanism, tend to
> restore homogeneity."

Hypothetical models of lead developed in frequently mixed sources, discussed
in some detail in a later section, suggest that unless extremely thorough
mixing of lead from various U/Pb environments occurred, a suite of crustal-
derived galenas formed contemporaneously would have significantly different
isotopic compositions.

At present it appears that homogeneity of lead isotope compositions of
conformable deposits, and the close fit of mean isotopic compositions to a
single growth curve, provide circumstantial evidence of subcrustal origin
of some lead.

DISCUSSION OF SINGLE-STAGE LEADS

Recognition of Single-Stage Leads

Single-stage (ordinary) leads are those leads whose compositions evolved

in single, closed, uranium-thorium-lead systems from the time the earth

formed until the time lead was extracted and deposited as lead minerals.

The definition is expressed mathematically by the Holmes-Houtermans equation

(equation II-7). Proposed criteria for recognition of single-stage leads

are based principally on constancy of measured isotope abundances in indiv-

idual deposits, and results of various calculations based on mean lead iso-

topic compositions. Tentative criteria (95 percent confidence limits) based

on precise intercomparison analyses are listed below (modified from Kanas-

ewich, 1962a).

(1) The isotopic compositions of a group of ordinary leads from an area should be constant within 0.3 percent.

(2) The Pb^{206}/Pb^{204} and Pb^{207}/Pb^{204} ratios of an ordinary lead should yield a U^{238}/Pb^{204} ratio of 8.99 ± 0.07.

(3) The Pb^{208}/Pb^{204} ratio of an ordinary lead should yield a Th^{232}/Pb^{204} ratio of 37.06 ± 0.97.

(4) The Th/U ratio (extrapolated to present-day values) of the source environment in which an ordinary lead developed should be 4.09 ± 0.09.

Geologic environments of deposition and theories of ore genesis are

especially important considerations in deciding whether or not a particular

deposit contains ordinary lead. Much of the present research in lead iso-

topes has been based on the possibility that "conformable" ore deposits re-

present uncontaminated mantle material (Russell, 1963, p. 58).

Ordinary Leads and Sedimentary Theories of Origin

Two theories of sedimentary formation of base metal sulfide deposits have been suggested that differ basically as to the source from which metals are derived. Under one hypothesis, metals are derived from volcanic emanations (Stanton, 1960a, 1960b); under a second, continental weathering and erosion provided the metals (Garlick, 1962). Some geologists (Davidson, 1961) feel that continental erosion could not supply sufficient metals to depositional sites where a sufficiently low rate of clastic sedimentation existed, to form large massive sulfide deposits. Volcanic emanations, on the other hand, commonly contain appreciable quantities of metals and sulfur (White, D. E., 1955; Stanton, 1962a). The source of lead in sulfide deposits of sedimentary origin must be known before lead isotope abundances can be evaluated properly.

Chow and Patterson (1962), studying lead in ocean sediments less than one million years old, found that very large areas (hundreds of thousands of square miles) are characterized by narrow ranges of lead isotopic compositions. Mean compositions in neighbouring regions differ significantly. Marine lead investigations indicate that denudation processes ending in marine deposition result in mixing analogous to an n-stage lead (Kanasewich, 1962a), and, ideally, would produce an "apparent" ordinary lead that could be dated by the Holmes-Houtermans equation to give the time of sedimentation. In the case of modern marine leads, an age of zero million years would be

expected if perfect mixing had occurred. Mean isotopic compositions of modern marine leads from various broad regions, give negative model ages ranging from -212 m.y. in the southwestern Atlantic, to -448 m.y. in the west-central Atlantic. The meaning of negative ages for modern sedimentary lead is not clear. Chow and Patterson (1962) suggest that the upper continental crust has a higher U^{238}/Pb^{204} ratio than the earth as a whole, and interpret the negative ages in terms of a two-stage model with leads having developed partly in an environment with a U^{238}/Pb^{204} ratio of 9.0 and partly in the continental crust with a U^{238}/Pb^{204} ratio of 11.3.

Kanasewich (personal communications, 1963) suggests alternative explanations:

(1)   the terrestrial zero isochron is not properly placed,

(2)   mantle lead has been evolving in a changing U^{238}/Pb^{204} environment as a result of differentiation, or

(3)   radiogenic lead is preferentially extracted during erosional processes, and marine lead is therefore not truly representative of crustal lead.

Whatever the true explanation of negative model ages, analyses of modern marine lead indicates that sedimentary lead in any one depositional basin is not necessarily representative of the mean isotopic composition of terrestrial lead. Table II-2 gives negative Holmes-Houtermans model ages for modern marine leads from several regions of the ocean floor. The wide range of calculated model ages for leads of approximately the same real age emphasizes the necessity of knowing the source of lead in an ore deposit before common lead model ages can be interpreted correctly.

If the theory of syngenetic origin of lead deposits were true, and lead were derived from volcanic emanations, model ages should be consist-

Table II-2: Isotopic compositions and model ages of lead in some modern marine
sediments (data from Chow and Patterson, 1962)

No.	Remarks	$\dfrac{Pb^{206}}{Pb^{204}}$	$\dfrac{Pb^{207}}{Pb^{204}}$	$\dfrac{Pb^{208}}{Pb^{204}}$	$\dfrac{U^{238}}{Pb^{204}}$	$\dfrac{Th^{232}}{Pb^{204}}$	Model age
46	Area B	18.70	15.66	38.74	3.86	8.74	−218
41	Area B	18.66	15.60	38.68	3.84	8.64	−269
35	Area B	18.66	15.69	38.96	3.98	8.80	−147
38	Area B	18.86	15.72	39.07	3.92	8.85	−257
40	Area B	18.71	15.65	38.76	3.86	8.73	−238
	Avg., area B	18.71	15.65	38.78	3.87	8.73	−240
100	Area G	18.98	15.67	39.07	3.84	8.75	−434
101	Area G	18.90	15.60	39.09	3.88	8.63	−471
94	Area G	19.09	15.63	39.23	3.84	8.66	−594
97	Area G	19.05	15.62	39.14	3.83	8.66	−566
100	Area G	18.94	15.70	39.13	3.90	8.80	−354
	Avg., area G	18.98	15.66	39.11	3.86	8.73	−448
	Avg., area C	18.66	15.64	38.59	3.82	8.71	−209

Table II-2: Isotopic compositions and model ages of lead in some modern marine
sediments (data from Chow and Patterson, 1962)   (Continued)

No.	Remarks	$\frac{Pb^{206}}{Pb^{204}}$	$\frac{Pb^{207}}{Pb^{204}}$	$\frac{Pb^{208}}{Pb^{204}}$	$\frac{U^{238}}{Pb^{204}}$	$\frac{Th^{232}}{Pb^{204}}$	Model age
	Avg., Area D	18.82	15.67	38.82	3.83	8.75	−302
	Avg., Area E	18.69	15.66	38.68	3.84	8.74	−212
	Avg., Area F	18.93	15.69	39.07	3.88	8.78	−362
	Avg., Area D	18.82	15.67	38.82	3.83	8.75	−302
	Avg., Area E	18.69	15.66	38.68	3.84	8.74	−212
	Avg., Area F	18.93	15.69	39.07	3.88	8.78	−362

Calculations based on Holmes-Houtermans equations.

Constants used are: $a_o = 9.56$; $b_o = 10.42$; $c_o = 29.71$; $t_o = 4.55$ b.y.

Area B, northeastern Pacific; Area C, west-central Pacific; Area D, southeastern Pacific;

Area E, southwestern Atlantic; Area F, east-central Atlantic; Area G, west-central Atlantic.

ently older than independent dates of periods of metamorphism in vicinities

of mineral deposits. Kanasewich (1962a) has shown that different geological

provinces of North America have ordinary leads consistently older than major

orogenic events (dated by the potassium-argon method). Potassium-argon ages

are commonly low due to argon loss, and the apparent differences in ages of

ordinary leads and periods of metamorphism does not necessarily support a

sedimentary theory of origin for deposits.

Ordinary Leads and Magmatic Theories of Origin

Stanton and Russell (1959) have referred to the probable ordinary nat-

ure of lead in magmatic deposits derived from depth. Ore deposits included

in, and spatially related to, intrusive bodies derived from the mantle

might well provide samples of mantle lead. Analyses of "uncontaminated"

lead genetically related to basic and ultrabasic masses could form an im-

portant test case for theories that have evolved from studies of conformable

leads. A. B. L. Whittles is presently engaged in the problem of measuring

isotope abundances of small amounts of lead in sulfides associated with basic

and ultrabasic rocks. One important aspect of such a study is that independ-

ent ages can be obtained for the parent rock by other dating techniques.

Bateman (1950) classifies magmatic deposits into early and late sub-

divisions. Sulfides are commonly concentrated as late magmatic deposits,

specifically as immiscible sulfide segregations and immiscible sulfide in-

jections. Blebs of immiscible sulfides probably will provide the best

samples of mantle lead, because if the genetic relation of sulfides and

enclosing rocks is correct, the sulfides have never been in contact with crustal rocks. Injected sulfide segregations may have suffered some contamination by crustal lead during metal transport from source rock to site of deposition. However, contamination might be negligible in a late magmatic sulfide injection that has not migrated far from its parent rock. Its lead might be dated by a single-stage model.

Recent investigations of strontium isotopes indicate that common strontium ratios can be used to determine whether intrusive rocks come directly from the mantle or are derived from crustal material (Hurley, 1960). Common strontium studies could aid in evaluating lead abundances of mineral deposits associated with igneous intrusions, particularly intermediate and acid types.

Frequently Mixed Heterogeneous Systems

Proponents of the Holmes-Houtermans model assume that crustal processes are adequate to homogenize sections of the earth's crust and produce lead of uniform isotopic composition. The lead is presumed to be an "apparent" ordinary lead, in the sense that it can be dated by the Holmes-Houtermans equation (Holmes, 1949; Shaw, 1957). In reality, such leads are, by definition, homogenized multi-stage leads that only coincidentally have isotope ratios amenable to dating by single-stage models.

The concept of mixing of crustal leads has been investigated by several authors (Russell, 1963; Kanasewich, 1962a; Russell, Kanasewich and Ozard, unpublished manuscript) in terms of hypothetical stages of development.

Lead was assumed to have developed in a uniform U-Th-Pb environment with
U^{238}/Pb^{204} ratio of 9.03 from a primeval composition 4550 m.y. ago to a lead
of uniform isotopic composition at a time 3000 m.y. ago. Sixty hypothetical
ordinary leads with a composition of a 3000 m.y. old ordinary lead were then
assumed to have been emplaced in new U^{238}/Pb^{204} environments. The new
U^{238}/Pb^{204} values were chosen randomly from a binomial distribution with a
mean of 9.03 and a standard deviation of 0.58 (6.4 percent). In one case
the leads were assumed to have developed in a second environment until the
present, at which time lead was extracted and a mineral deposit formed.
Calculated compositions of these hypothetical leads plotted along a line on
a Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204} graph. The lead history in this case is
analogous to a two-stage anomalous lead to be discussed in a later section.

If the 3000 m.y. interval is divided into a number of equal intervals,
and at the beginning of each new interval lead is emplaced in a new randomly
chosen U^{238}/Pb^{204} environment, final mineralization will result in a multi-
stage lead. Figure II-4(b) illustrates the distribution of final isotopic
compositions for an 11-stage (ten equal time intervals within the 3000 m.y.
period) lead. A comparison of Figure II-4(a) and II-4(b) illustrates the
general conclusion that as the number of stages increases the spread of
compositions along a line decreases, and the scatter of compositions on
either side of the line increases. Russell (1963, p. 57) has stated:

> "these calculations do not show that it is impossible to
> explain the observed abundances of lead on the basis of a fre-
> quently mixed heterogeneous system, but only that the degree
> of heterogeneity must be extremely limited and the mixing fre-
> quent if the process is not to be readily revealed by spurious
> age values."
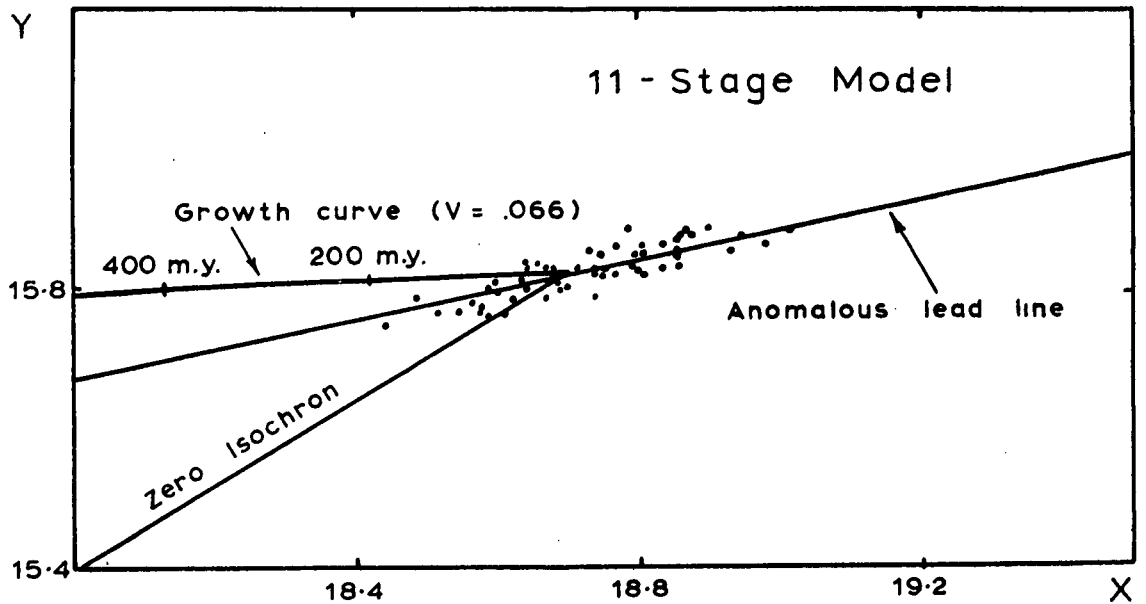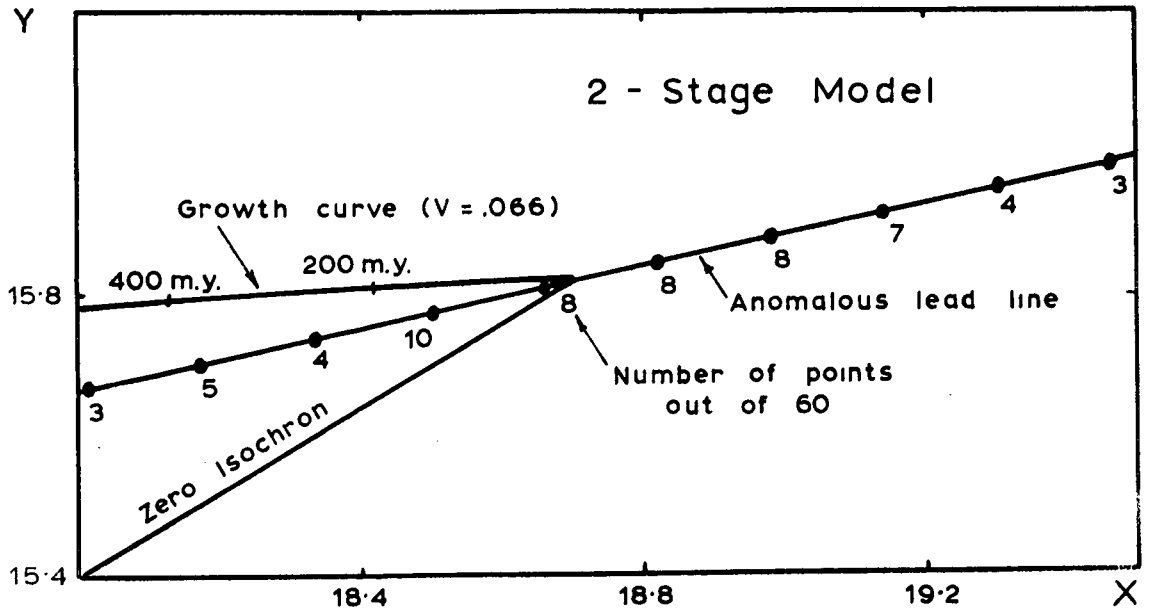
FIGURE II - 4: FREQUENTLY MIXED HETERO-
GENEOUS SOURCE

Summary

There are very stringent restrictions as to geologic processes that could produce leads that can be dated by single-stage models. The most acceptable processes for the emplacement of ordinary leads are:

    (1)   sedimentary lead derived almost exclusively from island arc vulcanism.

    (2)   syngenetic deposits (immiscible sulfide segregations) genetically related to basic and ultrabasic intrusions, and

    (3)   epigenetic deposits genetically and spatially related to basic and ultrabasic intrusions.

Other geologic settings can be imagined that would indicate ordinary leads, but available evidence suggests they are the exception rather than the rule. If the crust and mantle have the same over-all U^{238}/Pb^{204} ratio, perfect mixing of crustal material would produce an apparent ordinary lead, dateable by single-stage equations for mantle material. Acid to intermediate igneous intrusions derived from the mantle might contain ordinary lead in genetically associated sulfide deposits.

CHAPTER III

MULTI-STAGE (ANOMALOUS) LEADS

ANOMALOUS LEAD MODELS

Holmes-Houtermans Anomalous Leads

Holmes (1947) first recognized the existence of a group of "anomalous" leads that did not appear to fit the simple history postulated by the Holmes-Houtermans model. Anomalous leads, named J-type anomalous for the Joplin, Tri-state, mining district, are identified by negative Holmes-Houtermans model ages. A second group of "anomalous" leads, B-type anomalous first noted in a Bleiberg, Austria, galena specimen, is characterized by Holmes-Houtermans model ages older than host rocks. B-type leads are generally interpreted as old leads that have been remobilized and redeposited without contamination by lead of different composition. B-type leads can be identified only where age of host rocks is fairly well known.

Recent research into anomalous lead isotope abundances suggests that in certain lead suites a complete gradation in isotopic compositions exists between J-type and B-type leads, and that any distinction between the two is arbitrary. In some cases an old lead might have been remobilized without contamination. Presumably this would occur only near the site of original "old lead" deposition. Possible examples of B-type leads are small veins of galena in dated Tertiary intrusions of the Coeur d'Alene district (Long, Silverman and Kulp, 1960). This "Tertiary" lead has a model age of about

1400 m.y.

Cannon--"Exceptional Leads"

Cannon and others (1961) present an empirical classification of lead dependent on the plotted positions of isotope abundances on a triangular chart with apices Pb^{206}, Pb^{207}, and Pb^{208}. Lead-204 is ignored and coordinates are calculated on the basis of $Pb^{206} + Pb^{207} + Pb^{208} = 100$. Four classes of lead are distinguished: ordinary lead, U-lead, Th-lead and J-lead.

Cannon recognized the importance of Pb^{204} but omitted it from his classification because of its low precision of measurement. However, to deal graphically with all stable lead isotopes, Cannon's triangular graph must be supplemented by another graph that takes into account Pb^{204}. The method most commonly used to illustrate relations of the four stable lead isotopes employs two cartesian plots, Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204}, and Pb^{206}/Pb^{204} versus Pb^{208}/Pb^{204}. In view of high precision of Pb^{204} measurement in recent analyses, and the simplicity of presentation and ease of mathematical treatment of lead abundances plotted on cartesian coordinates, the added complexity of triangular plots appears to serve no useful purpose.

Some type of grouping of lead isotope abundances independent of genetic implications is desirable for reference purposes until an appropriate genetic classification can be established; however, no genetic implications should be read into Cannon's empirical classification. Leads plotting in any of the four fields listed above could have had complex histories of de-

velopment in two or more U-Th environments.

Russell-Farquhar Anomalous Leads

Anomalous leads are considered leads formed by "the addition to some ordinary lead of an additional amount of radiogenic lead in a way that is unaccountable by the simple (Holmes-Houtermans) formula" (Russell and Farquhar, 1960)". The basic assumption is that anomalous leads are mixtures of variable proportions of two components, an ordinary component and a radiogenic component. Mixing of the two components is thought to occur during mineralizing epochs related to periods of orogeny.

The general nature of the model is explained readily by reference to Figure III-1. The composition of ordinary lead and the U^{238}/U^{235} ratio evolved from the time the earth formed (t_o) to times t_1 and t_2 respectively. Ordinary lead deposition in the crust occurred at time t_1 either as massive or widely disseminated minerals. At time t_2 uranium and thorium from the mantle were introduced into a crustal environment. Radiogenic lead evolved from time t_2 to t_3 by the radioactive decay of uranium and thorium. At time t_3 orogeny occurred, radiogenic lead and ordinary lead were mixed, and the resulting anomalous lead was deposited as an ore mineral. Therefore, no change took place in lead isotope ratios.

Original uranium, thorium, and ordinary lead-bearing minerals could have been deposited in identical or different environments. In the latter case, ordinary lead-bearing solutions are thought to have extracted radiogenic lead from wallrocks as these solutions moved through the crust to

sites of anomalous lead deposition. Regardless of the mixing mechanism, mixtures of variable amounts of only two lead components, each of uniform composition, will plot along a straight line (anomalous lead line) on a Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204} graph. The slope R of the anomalous lead line defines the Pb^{207}/Pb^{206} ratio of the radiogenic component and is the basis for the Russell-Farquhar mathematical treatment of anomalous leads.

According to this model the uranium-derived part of the radiogenic lead component, generated between time t_2 and t_3 has a composition given by the slope R of an anomalous lead line. If the assumption is made that the radiogenic lead formed instantaneously (i.e. $t_2 = t_3$) a maximum possible age t_r of anomalous lead mineralization can be calculated (Appendix I, equation 2). A more realistic view is that the radiogenic component evolved during a time interval t_2 to t_3. Assuming that anomalous lead mineralization occurred at the present time ($t_3 = 0$ m.y.), a maximum value t_u for the time of uranium-thorium emplacement in the crust can be calculated (Appendix I, equation 3). If geologic information is such that some limit can be placed on the time of anomalous lead mineralization, a closer approximation of the time of uranium-thorium deposition in the crust can be calculated approximately. Large errors are commonly attached to calculated ages because of low precision in the determination of R. Errors can be minimized by utilizing a precise intercomparison technique for isotope analyses and by choosing specimens for analysis that give the longest possible length of anomalous lead line.

Additional information can be obtained from a Pb^{208}/Pb^{204} versus Pb^{206}/Pb^{204} plot. A linear relationship should exist between ordinary and anomalous leads if the anomalous leads are mixtures of two uniform compon-

FIGURE III-1: DIAGRAMATIC PRESENTATION OF THE RUSSELL-FARQUHAR ANOMALOUS LEAD MODEL

34
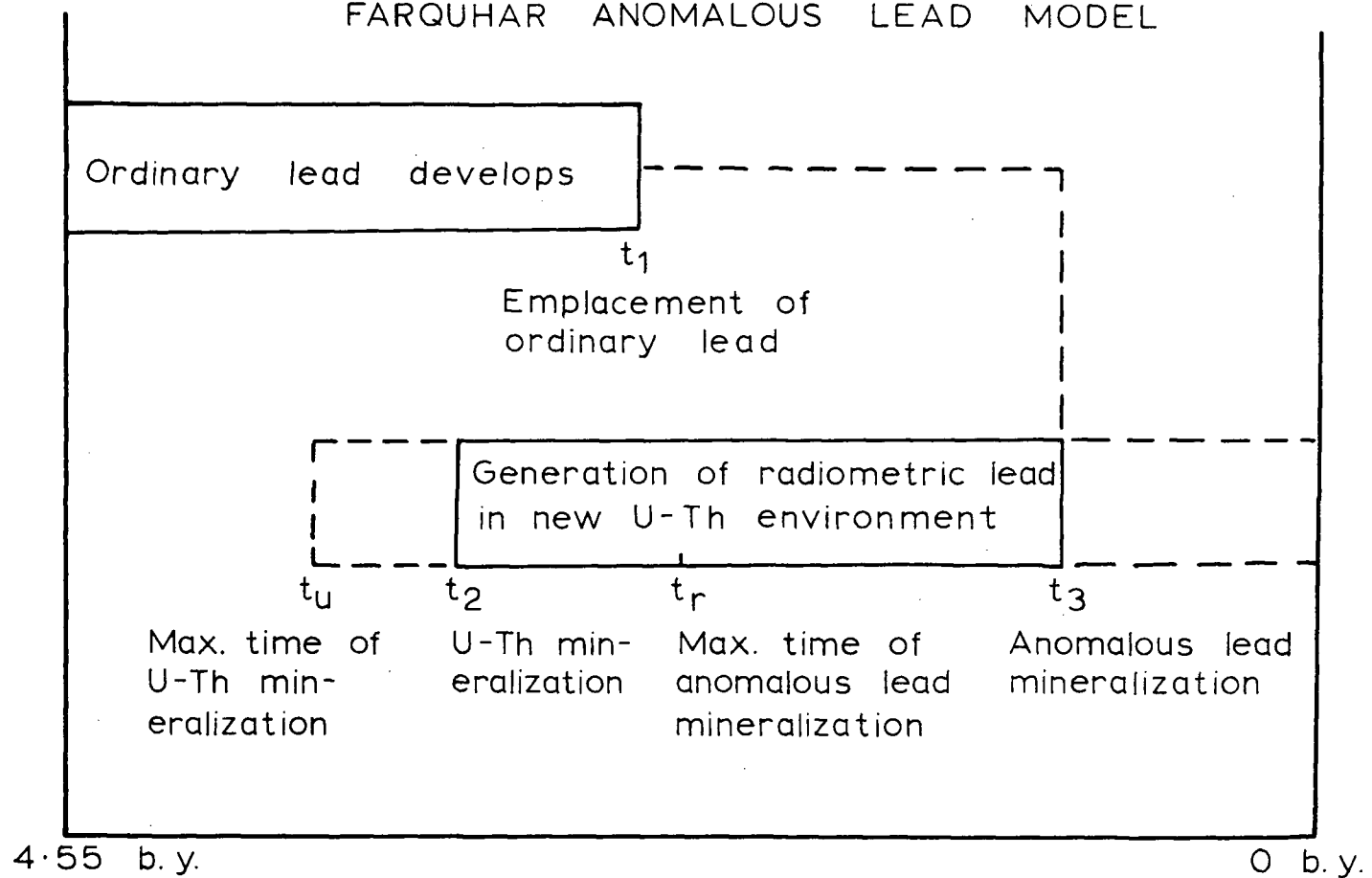
ents. The slope R' of such a line can be used to calculate the Th^{232}/U^{238} ratio of the source region of the radiogenic component of an anomalous lead suite (Appendix I, equation 4). In practice, linear patterns are not as clearly defined as those on the Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204} plot, and the scatter in the Pb^{208}/Pb^{204} versus Pb^{206}/Pb^{204} plot is attributed to variable Th/U ratios in crustal rocks from which anomalous leads are derived.

One important feature of the Russell-Farquhar model is that calculations are independent of the genesis of the "uniform" starting common lead (at time t_1). The common lead component may seem to be ordinary but a homogenized multi-stage lead would produce linear patterns that could be treated as above.

To summarize briefly, the model provides a maximum age of anomalous lead mineralization and certain characteristics of the source rocks of the radiogenic component. Refined calculations are possible if geological evidence places close limits on either the time of anomalous lead mineralization or the time of uranium-thorium emplacement in a crustal environment.

Kanasewich Multi-stage Model

Kanasewich (1962a, 1962b) proposed an anomalous lead model that is an extension of the Russell-Farquhar anomalous lead model. Figure III-2 is a diagrammatic representation of the Kanasewich two-stage model. Uranium, thorium, and ordinary lead evolve from the beginning of geologic history until some time t_1 when they are injected into the crust in different proportions from place to place. Anomalous leads are generated in new Pb-U-Th

FIGURE III-2: PICTORIAL REPRESENTATION OF KANASEWICH
TWO-STAGE LEAD MODEL

No change in lead
isotopic ratios

Pb

Anomalous leads
develop in different
U-Th-Pb environment

Pb, U
Th

t_2

Anomalous lead
mineralization

Ordinary lead develops

t_1

Ordinary lead, uranium
and thorium emplaced
in upper crust

4·55 b. y.

0 b. y.

36
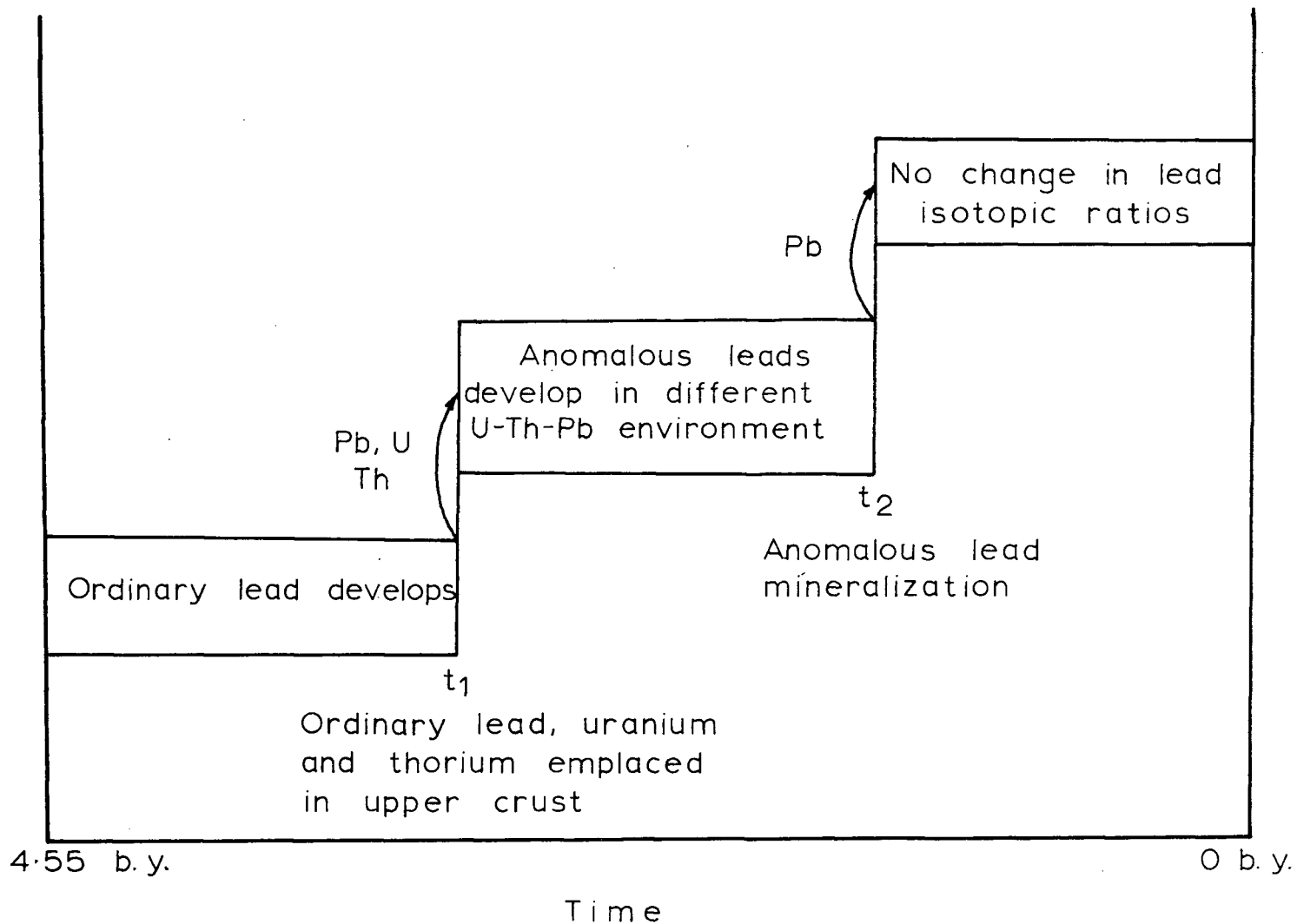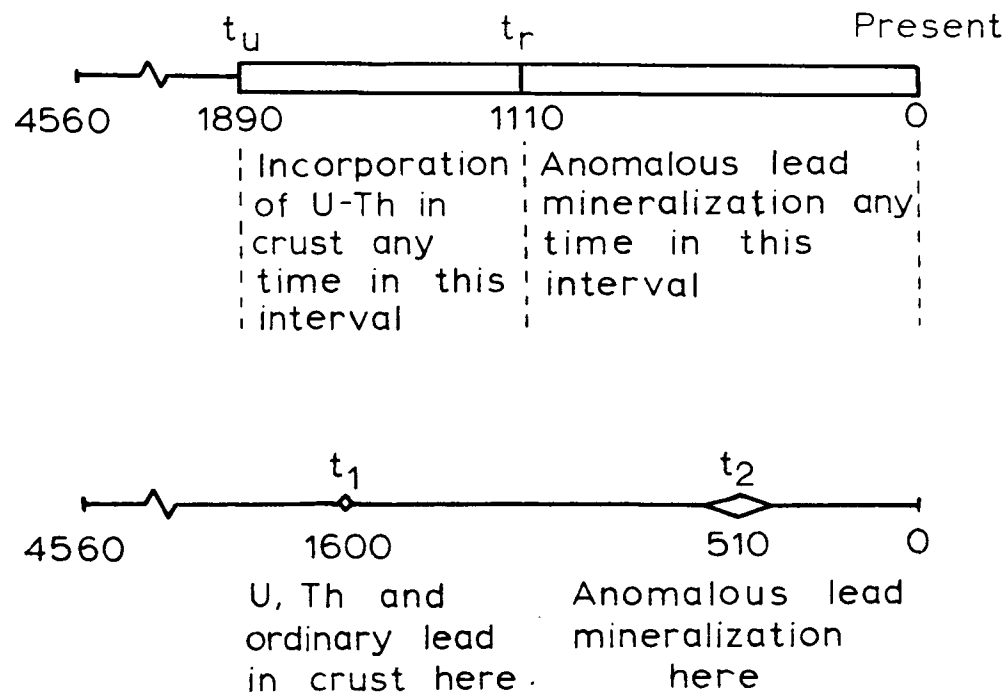
Time

FIGURE III-3: COMPARISON OF RUSSELL-FARQUHAR MODEL
AND KANASEWICH MODEL FOR DATING
ANOMALOUS LEADS FROM BROKEN HILL,
AUSTRALIA (after Kanasewich, 1962b)

environments until the time of anomalous lead mineralization, t_2, after which time no further changes in lead isotope compositions occur. Such anomalous leads are two-stage leads in that they develop in two distinctly different Pb-U-Th environments. Providing that an appreciable range of U/Pb ratios existed during the second stage of development, the anomalous lead isotope abundances will plot along an anomalous lead line passing through the composition of the ordinary lead developed during the first stage. The anomalous lead line is, in reality, a <u>second stage isochron</u> rather than a line representing mixtures of various proportions of two different leads.

The time of ordinary lead, and uranium and thorium mineralization is estimated from the isotopic composition of the ordinary lead using the Holmes-Houtermans (isochron) equation, and the time of anomalous lead mineralization is readily calculated (Appendix II).

The model has been presented as a two-stage growth process, but in general terms, can be considered an n-stage or multi-stage growth process (see discussion of frequently mixed source, Chapter II). Mathematical development of the model is given in Appendix II.

The model has been applied with apparent success to several suites of anomalous leads (Kanasewich, 1962b). Figure III-3 contrasts mathematical results obtained by interpreting Broken Hill anomalous leads according to the Russell-Farquhar model and the Kanasewich model.

A GENERAL DISCUSSION OF CERTAIN TYPES OF MULTI-STAGE LEADS

Multi-stage leads include many types: mixtures of two ordinary leads,

mixtures of an ordinary lead and variable amounts of a radiogenic lead, mixtures of a homogenized anomalous lead and variable amounts of a radiogenic lead, and so on. Recent research (Russell and Farquhar, 1960; Kanasewich, 1962a) suggests that numerous anomalous lead suites can be interpreted effectively as two-stage leads, consisting of mixtures of an ordinary lead and variable amounts of a radiogenic lead. Geological consideration suggests that a somewhat analogous type, mixtures of a homogenized multi-stage lead with variable amounts of a single radiogenic lead, should occur. Consideration will be given to those multi-stage leads thought to be mixtures of a radiogenic lead component and a common lead component, the common lead component being either an ordinary lead or a homogenized multi-stage lead. Both of the foregoing types can be interpreted quantitatively in terms of the Russell-Farquhar model although the former can be interpreted more specifically with the Kanasewich modification of the Russell-Farquhar model.

Multi-stage lead models must explain the variability of isotope ratios in individual deposits, and even within single crystals (Austin and Slawson, 1961). They must explain, also, the constant lead isotope composition of individual deposits, and variations from one deposit to another. At least two processes can account for such compositional variations in terms of multi-stage lead histories:

    (1) a multi-stage growth process by which radiogenic lead
           develops in an environment containing common lead
           (Kanasewich, 1962b), and

    (2) mixing of lead from different environments (Stanton and
           Russell, 1959).

Combinations of the two processes are inevitable.

Ore-bearing solutions, passing through crustal rocks, might effectively mix leads from more than one environment. Emanations from depth, containing common lead (ordinary or anomalous) of uniform isotopic composition, could extract radiogenic lead from crustal rocks prior to final lead deposition. The quantity of admixed radiogenic lead would be expected to change as new solution channelways became available (Slawson and Austin, 1962).

The assumption that radiogenic lead, in preference to common lead, would be selectively extracted from the wallrocks of solution channelways requires explanation. Experiments by Tilton and others (1955) show that one-third to one-half of the radiogenic lead in such minerals as apatite, sphene and monazite is readily available to acid leaches in the laboratory. This may be due to destruction of crystal lattices (metamictization) accompanying radioactive decay of uranium and thorium, possibly with associated hydration, expansion and fracturing of crystals (cf. Robinson and others, 1963). Because the crystal lattices of most uranium- and thorium-bearing minerals do not accept lead atoms, radioactive decay in such minerals would release radiogenic lead. On the other hand, lead is strongly held in silicates where it substitutes for potassium, particularly in potash feldspars.

Slawson and Austin (1962) interpreted a suite of 59 New Mexico leads in terms of a mixing process whereby emanations containing lead of uniform isotopic composition, extracted variable amounts of radiogenic lead from channelways during passage through a Precambrian basement complex.

Multi-stage growth processes are analogous to the "frequently mixed source model". Lead periodically is introduced into new uranium-thorium environments and eventually deposited as a lead mineral. A simple geolog-

ical model would be lead derived from a thick sequence of basic volcanic rocks several hundreds of millions of years after their deposition, perhaps during a period of regional metamorphism. Lead in basic volcanic rocks derived from the lower crust or mantle is probably ordinary at the time of extrusion, and changes in lead isotopic composition would occur after extrusion as radiogenic lead was generated. If local variations in U/Pb and Th/Pb ratios existed, extracted lead would have a range of composition plotting on an anomalous lead line and could be interpreted by the Kanasewich two-stage model. Lead in Yellowknife gold-quartz veins (Boyle, 1961) can be interpreted in such a manner (see later discussion on lead isotopes and metamorphic theories of ore genesis).

A somewhat similar multi-stage history can be envisaged for lead in a sedimentary sequence, except that such lead would be more-or-less homogeneous multi-stage rather than ordinary. Lead extracted from a sedimentary sequence several hundreds of millions of years after deposition would have a range of compositions, dependent on the U/Pb and Th/Pb ratios in various beds of the sedimentary sequence, that, in the absence of complete homogenization, would plot along an anomalous lead line.

The history of a multi-stage growth process can be summarized as follows:

(1) syngenetic deposition of uranium, thorium, and lead (ordinary or multi-stage),

(2) gradual change in _total_ lead isotope composition as radiogenic lead evolved, and

(3) local homogenization of lead, extraction by some unknown process from zones characterized by a variety of U/Pb and Th/Pb ratios, and deposition as a lead mineral. Extreme

homogenization would result in all the extracted lead
being of uniform but anomalous isotopic composition.

The method of concentration of lead from its growth environment might

be such that it is either completely homogenized, or enriched in the radio-

genic component. In either case, calculations and numerical results are

unaffected. Validity of calculations rests on the validity of applying the

Russell-Farquhar model to a particular set of lead isotope data.

MULTI-STAGE LEADS AND THEORIES OF ORE GENESIS

Lead Isotopes and the Magmatic Hydrothermal Theory

Lead isotopes may be well mixed in magma chambers. Rock lead isotope

analyses for part of the southern California batholith (Patterson and others,

1956) indicate a uniform lead isotope composition throughout. Igneous rocks,

derived directly from sima or mantle, that have undergone no assimilation of

upper crustal material would contain ordinary lead of uniform isotopic com-

position. Acid to intermediate intrusions formed by anatexis of upper crust-

al material in orogenic belts would contain multi-stage lead. Whether or

not melting of upper crustal rocks would result in complete homogenization

of lead isotopes is a matter of conjecture. Much more work remains to be

done to prove the ability of a magma formed from crustal rocks to homogenize

lead isotopes. A tentative conclusion is that, locally, lead is uniformly

mixed, but that different parts of a melted volume of rock have leads of

different compositions.

Isotopic compositions of multi-stage leads throughout a sedimentary unit are dependent on composition of syngenetic leads, U/Pb and Th/Pb ratios, and age of sediments. Analyses of syngenetic lead in modern marine sediments (Chapter II) implies that large oceanic areas have lead of a limited range of compositions, and that the range of compositions in one oceanic area differs significantly from that in another area. If variations of lead isotope composition occur in an ancient sedimentary unit, these must be due to different U/Pb and Th/Pb ratios within that unit. If such a sediment were melted, and only locally homogenized, lead isotope compositions would plot rather closely on an anomalous lead line, the length of the line depending on variations in U/Pb and Th/Pb ratios. In consequence, contemporaneous anomalous lead deposits derived from a single magma formed by anatexis need not have identical isotopic compositions. Also, any syngenetic lead forming one end of an anomalous lead line, being a multi-stage lead, need not plot on the primary growth curve.

An anomalous lead suite formed as suggested above can be treated mathematically with the Russell-Farquhar anomalous lead equations. If the age of mineralization is known, the time of uranium-emplacement in the original sedimentary sequence, that is, the approximate time of sedimentation, can be calculated.

Two published examples of rock lead and ore lead studies illustrate attempts to discover a possible genetic link between ore deposits and igneous rocks. Murthy and Patterson (1961) found lead in ore deposits of Butte, Montana, to be of constant isotopic composition. However, because lead in one specimen of quartz of an associated igneous intrusion differed

significantly in its isotopic composition, the authors concluded that lead

minerals could not have been derived from nearby igneous rocks.

Doe (1962) studied lead in ore deposits and igneous and metamorphic

rocks near Balmat, New York. The ores contained lead of uniform isotopic

composition with an approximate model age of 1,000 m.y. (Grenville orogeny).

Lead in igneous rocks, when corrected for radiogenic lead added between the

time of Grenville orogeny and the present, had isotopic compositions signif-

icantly different from ore lead.

Much more work remains to be done to decide whether the premise that

lead isotope homogenization occurs in a magma is true, or whether the diff-

erence noted between ore lead and spatially associated igneous rock lead

truly indicates the two are unrelated genetically. Two lines of investig-

ation are required:

(1) representative rock lead analyses from different parts of
batholiths are desirable to test the degree to which mix-
ing of lead isotopes occurs in magmas, and

(2) ore lead from contact metasomatic deposits adjacent to
intrusive "parent" rock should be analysed for comparison
with common lead in silicates of the "parent" rock.

Anomalous Leads and Metamorphic Processes of Metal Concentration

Some authors think that sulfide ore deposits have been concentrated

from crustal rocks during periods of regional metamorphism and granitization

either by secretion from immediately adjacent wallrock (Boyle, 1961), or by

concentration from huge volumes of crustal rock having extremely low metal

contents. It has not been proven that metals can move great distances dur-

ing metamorphism, but impressive support has been presented for local lateral secretion (Knopf, 1929; Wanless, and others, 1960; Boyle, 1961). However there is no general agreement on a mechanism of metal transport and concentration during regional metamorphism and granitization. Sullivan (1948) believes transport of metals and metal sulfides takes place as vapors; Goodspeed (1952) states that water derived from rocks during granitization (metamorphic water) carries metals in solution; and Boyle (1961) suggests that some vein materials are derived from immediately adjacent wallrock. Regardless of the mechanism of metal transfer and concentration, lead in deposits formed by secretion processes can be treated as multi-stage lead. The general history of such a lead has been outlined by Shaw (1957).

Lead concentrated during periods of regional metamorphism would be a mixture of two components:

(1) syngenetic lead of the source rock -- such lead might have a composition similar to an ordinary lead the same age as the source rock; and

(2) radiogenic lead formed by decay of uranium and thorium between the time of source rock deposition and the time of mineralization.

Variable proportions of these two lead components in different samples of lead minerals would have compositions plotting on an anomalous lead line. Two times are involved in the mathematical treatment (Appendix I): t_1, the time of emplacement of uranium and thorium (the approximate time of source rock deposition); and t_2, the time of lead mineralization (during a late phase of regional metamorphism). In practice it might be difficult to define either t_1 or t_2, but one must be known before the other can be calculated. If neither t_1 nor t_2 is known, a maximum age of lead mineraliz-

ation can be determined. Independent isotope dating of the time of meta-
morphism may provide an estimate of t_2. If the lead had only two stages of
development, t_1 and t_2 can be determined graphically by the intersection of
an anomalous lead line with the primary growth curve. Where ordinary lead
is associated with hypothetical source rocks, t_1 can be estimated from the
isotopic composition of such lead.

Syngenetic lead in a basic volcanic sequence probably closely approxi-
mates an ordinary lead, and its history is analogous to a two-stage model
of the sort proposed by Kanasewich (1962a, 1962b). In a sedimentary seq-
uence, syngenetic lead is anomalous, although probably more-or-less homogen-
eous in isotopic composition, and could be of considerably different compos-
ition than ordinary lead of the same age as the sedimentary host rock.

When a source rock formed, lead would occur in minerals other than those
that contain uranium and thorium. Thus at some later time some minerals
would contain common lead and other minerals radiogenic lead. Recrystall-
ization during metamorphism would expel lead from U-Th-bearing minerals.
Such lead would join common lead in new minerals, and the result would be
local mixing of lead isotopes.

If all "metamorphic" hypotheses of sulfide ore formation can be consid-
ered in the above manner, lead isotope studies might be used to test which
hypothesis would best explain a particular ore deposit or group of deposits.
Assuming that some vein minerals are derived from immediately adjacent wall-
rock as suggested by Boyle, there should be some correlation between lead
isotope abundances and types of wallrock. There is no reason to believe
that volcanic rocks and slates, for example, would have identical U/Pb and
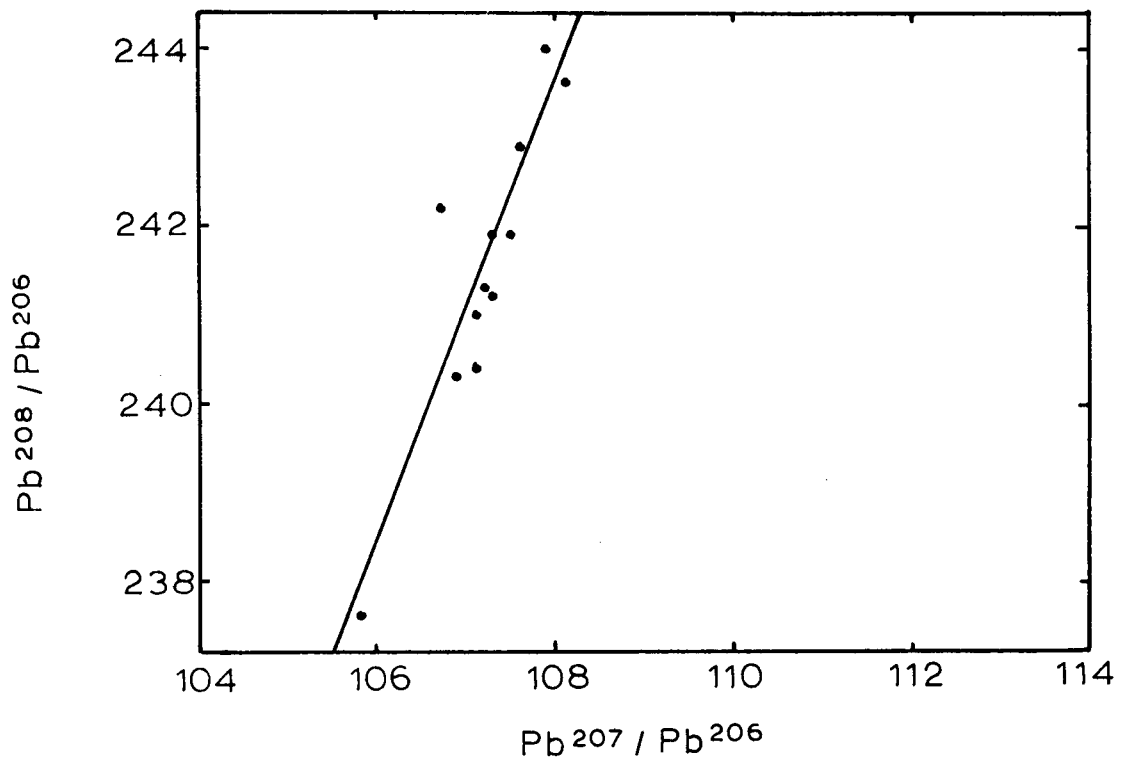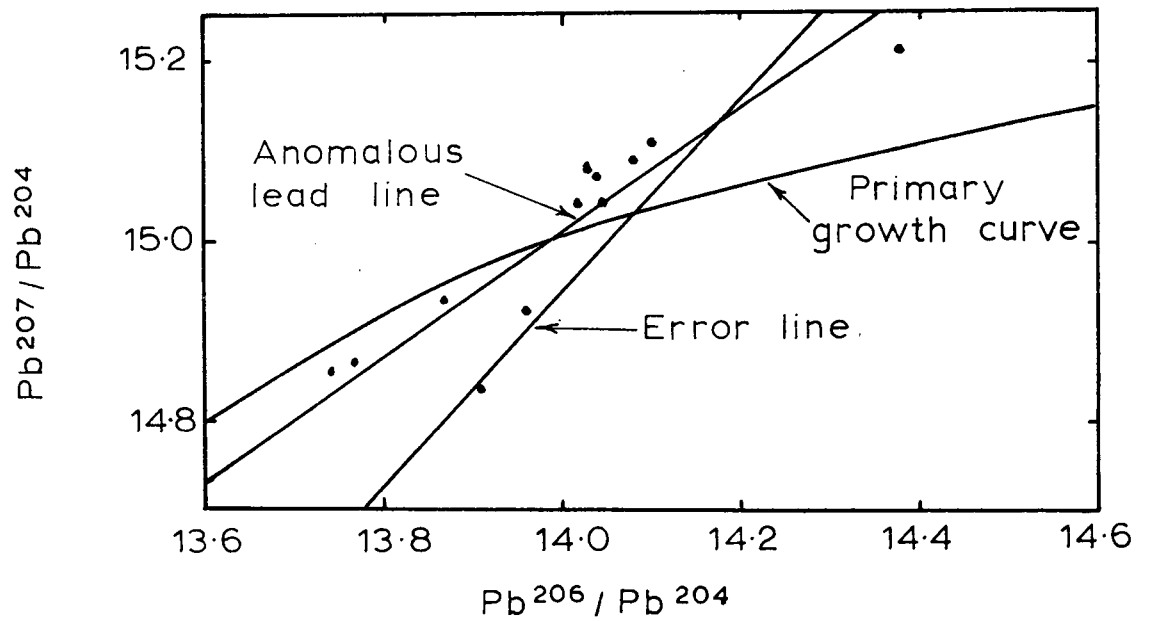
FIGURE III - 4: YELLOWKNIFE LEAD ISOTOPE DATA

Th/Pb ratios, and lead minerals derived from such rocks would have different isotopic compositions. Correlation of isotopic compositions with rock types would probably have to be made on a statistical basis because variations in U/Pb and Th/Pb ratios are possible within a single large geologic unit.

The veins of the Yellowknife district, N. W. T., that occupy shear zones in a thick metamorphic basic volcanic sequence, are interpreted by Boyle as originating, in part, by lateral secretion from adjacent wallrock. Twelve lead isotope analyses are available for the Yellowknife district (Russell and Farquhar, 1960, p. 140-142). The x, y, and z values have been multiplied by 0.99166 so that the compositions are in their correct positions relative to U. B. C. analyses (Figure III-4). These leads have been interpreted by Kanasewich (1962a, p. 80) as:

> "......indicating ordinary lead, uranium, and thorium being ex-
> tracted from a deeper source and placed in a crustal environ-
> ment between 2,800 and 2,900 m.y. ago. The lead isotopes dev-
> eloped in a crustal source for a short period of time. From
> the slope of the anomalous lead line, final mineralization
> appears to have occurred less than 300 m.y. after the formation
> of the ordinary leads."

A second interpretation is possible if it is assumed that lead were derived from enclosing volcanic rocks at the time of metamorphism. Volcanic rocks were extruded at time t_1, contained ordinary lead, and had variable U/Pb and Th/Pb ratios from place to place. The total lead composition changed with time as radiogenic lead was generated. At time t_2 the rocks were metamorphosed and lead homogenized, extracted by some unknown process, and deposited in the form now found. Lead isotope compositions of vein material should plot on an anomalous lead line, that, if extended, would cross the primary growth curve at two points representing the time of lava

extrusion and the time of anomalous lead mineralization. Unfortunately the anomalous lead line is extremely short, and this, combined with a slight scatter of analyses about the line, results in a large possible error in slope determination upon which mathematical calculations are based. However, calculated results are given herein to illustrate an alternative interpretation. The slope of the anomalous lead line (Figure III-4) is 0.6954 ± 0.0946. Assuming the time of anomalous lead mineralization to be 2,860 m.y. (the approximate intersection of the anomalous lead line with the primary growth curve), the time of volcanism is calculated to be $3,700 \pm 300$ m.y. Thus, lead isotope data does not exclude volcanic derivation of lead in gold-quartz veins of the Yellowknife camp.

Sullivan's hypothesis of long distance diffusion of elements can be tested in a manner similar to Boyle's local lateral secretion hypothesis. Time of mineralization, t_2, is equated with time of nearby granite emplacement, assuming that the granite provided heat for diffusion of metals. Provided an anomalous lead line exists, so that its slope can be estimated, and an independent date is available for the time of granite emplacement, t_1, the age of uranium emplacement (age of deposition of source rock) can be calculated (Appendix I). Conversely, if t_1 and the slope of an anomalous lead line are known, the time of mineralization can be calculated.

If the derivation of lead-bearing hydrothermal solutions from rocks during metamorphism (i.e. metamorphic waters) is a valid process (cf. Goodspeed, 1953), and contained lead is of uniform isotopic composition, the lead history can be considered in a manner identical to that of magmatic hydrothermal fluids discussed in a preceding section. In view of a fore-

going argument for the selective extraction of radiogenic lead by hydrother-mal solutions, the possibility exists that metamorphic waters might not con-tain lead of a homogeneous composition, but could be variably enriched in radiogenic lead. This might explain many "highly radiogenic" "J-type" leads.

Discussion

Theories of origin of ore deposits are not mutually exclusive, and it is worthwhile to inquire into possible criteria from lead isotope studies that might support one theory or another. From the foregoing discussion of multi-stage leads and theories of ore genesis, no truly definitive charac-teristics emerge to prove one theory exclusively. However, certain general characteristics of multi-stage leads appear to favour one origin over an-other. Unless complete homogenization of lead has occurred, a suite of anomalous leads formed by any of the commonly accepted theories of ore genesis probably will plot along an anomalous lead line. The scatter of compositions about the line is dependent on the precision of lead isotope analyses and the number of stages of development involved in the lead hist-ory.

Differences of lead isotope compositions in a single deposit suggest that either mixing of lead isotopes occurred during passage of ore-bearing solutions through wallrock or that lead concentration involved metamorphism. Uniform lead isotope compositions in individual deposits, but different com-positions among genetically related deposits, favours a magmatic hydrother-mal theory of origin involving local thorough mixing of lead isotopes. An-

omalous leads highly enriched in the radiogenic component are readily ex-
plained by a metamorphic process wherein heterogeneous proportions of common
and radiogenic components are extracted.

CHAPTER IV

GENERAL GEOLOGY OF THE KOOTENAY ARC

Much of the Kootenay arc has been mapped geologically on a regional

scale (Walker, Bancroft and Gunning, 1929; Little, 1960; Walker, 1934;

Cairnes, 1934; Drysdale,1917) but relatively little detailed work has been

done. During the past 10 years the British Columbia Department of Mines and

Petroleum Resources has undertaken detailed geological studies in several

mining camps along the arc. These projects have greatly increased our know-

ledge of structure and stratigraphy of the region, particularly of Lower

Paleozoic strata. The studies are significant because of the importance of

stratigraphy in determining structure, and the importance of structure in

localizing mineral deposits (Fyles, 1962a; Hedley and Fyles, 1956).

REGIONAL SETTING OF THE KOOTENAY ARC

East of the Kootenay arc is a large area of Precambrian rocks including

Purcell and Windermere systems, that crop out in a region of Mesozoic(?) up-

lift known variously as Purcell arch, Purcell geanticline and Purcell anti-

clinorium (Figure IV-1). Purcell strata are mainly fine-grained argillac-

eous rocks with a maximum exposed thickness of about 45,000 feet near the

eastern edge of the Kootenay arc (Rice, 1941, p. 7). The boundary between

Upper and Lower Purcell is placed at the top of a volcanic unit up to 300

feet thick known as Purcell lava. Purcell lavas are most abundant in east-
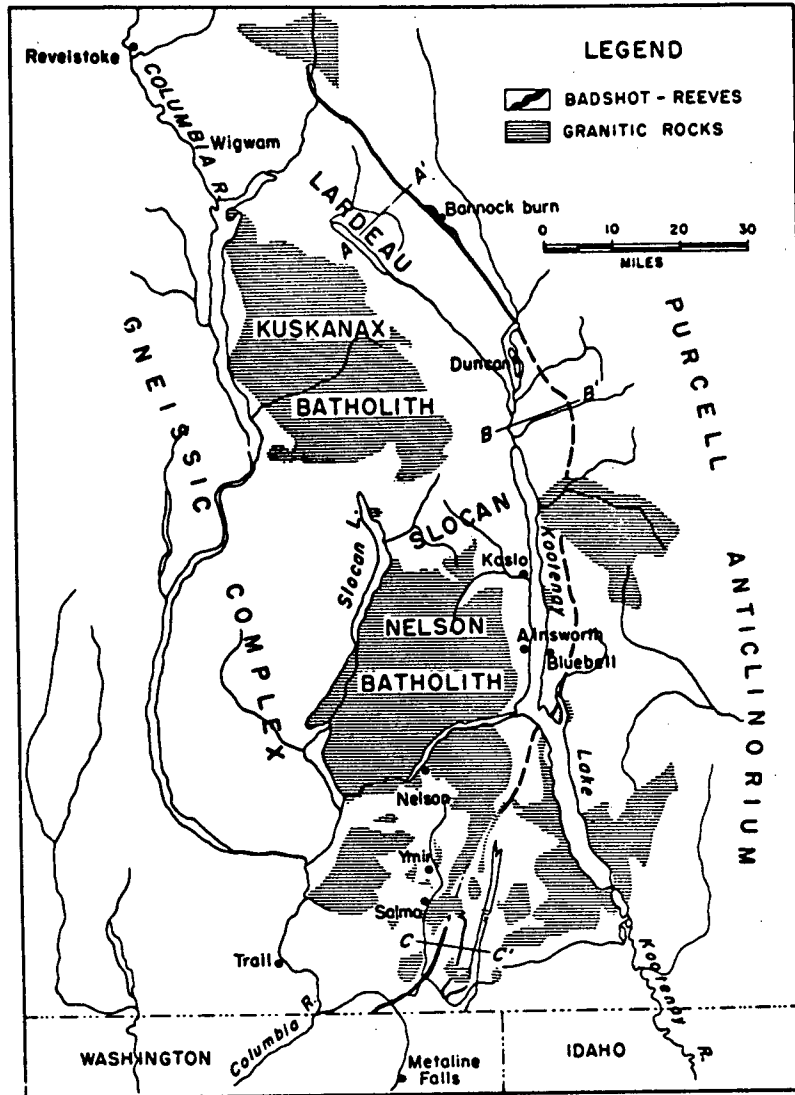
FIG. IV-1: REGIONAL SETTING OF THE KOOTENAY ARC.
(after Fyles, 1962b).

ern exposures of Purcell rocks. Near the Kootenay arc tuffaceous rocks that occur in the Kitchener-Siyeh formation are lithologic equivalents of Purcell lavas. The Purcell system is unconformably overlain by the Windermere system. Windermere equivalents in the southern Salmo district grade without break into Cambrian strata and the Precambrian-Paleozoic boundary is placed arbitrarily within a thick unit of quartzite.

West of the arc is an area underlain mainly by two large "granitic" masses -- Nelson and Kuskanax batholiths. Nelson batholith is dated at about 170 m.y. (Leech and others, 1963), approximately mid-Jurassic on the Kulp time scale. Most geologists who have worked in the Kootenay arc feel that the main intrusions are either Jurassic or Cretaceous in age (Little, 1960). Cairnes considers Kuskanax batholith younger than the Nelson and this is supported by two potassium-argon age determinations of 66 and 90 m.y. on biotite and musovite respectively, of a cogenetic pair (Leech and others, 1963).

West of the area of batholithic intrusions is a region of strongly metamorphosed and deformed rocks known as Shuswap terrane. Shuswap rocks have been divided into two groups, a lower division, Monashee group, and an upper division, Mount Ida group. Monashee rocks are mainly medium- to coarse-grained, quartz-feldspar-biotite gneiss with minor amounts of quartzite, schist, marble and calcareous gneiss. Mount Ida rocks are principally sedimentary and volcanic strata that have undergone low grade metamorphism. Each group is more than 50,000 feet thick. Age of Shuswap terrane is controversial. Jones (1959, p. 132) reviews different suggested ages, including Windermere, Purcell and Archean. At present there is not enough concrete

evidence to specify either age of deposition of Shuswap rocks or age of

major metamorphism and deformation. Potassium-argon results indicate that

the latest metamorphic effects occurred during the Tertiary period.

Probably much of the present character of the Kootenay arc reflects

effects of Mesozoic orogeny. Structural character of the arc, however, is

not entirely the result of Mesozoic deformation and intrusion. Fyles and

Hedley (1956) state:

> "Although the Nelson batholith occupies the central bow in
> the Kootenay arc, and the sedimentary structures are affected
> by it, the arc is not solely the result of intrusion. Structures
> attributable to intrusive forces along the north batholithic marg-
> in are superimposed upon earlier regional structure of northwest
> trend. The arcing of the sedimentary formations appears to be a
> structure of great antiquity that perhaps localized intrusions
> and certainly was modified by it."

White (1959) suggests that original folding of the ancestral Kootenay arc

occurred during "Caribou" orogeny (mid-Paleozoic).

STRATIGRAPHY

Strata in the Kootenay arc comprise a structurally conformable success-

ion of rocks ranging in age from Precambrian to Mesozoic. Precambrian rocks

are not abundant in the arc. Mathews (1953, p. 17) described the Three

Sisters formation in Sheep Creek area. This formation is variable in thick-

ness, being about 5,000 feet near the International Boundary and thinning

to the north. The rocks are coarse-grained greenish sandstones and some

pebble conglomerates. This formation, thought to be of late Proterozoic

age, tentatively is correlated with Windermere rocks (Little, 1960, p. 23).

Table IV-1: Paleozoic formations in the Kootenay arc.
(after Fyles, 1962b)

SALMO DISTRICT			LARDEAU DISTRICT	
Formation(Member)	Lithology	Group	Formation	Lithology
Milford (Carb. to Triassic)	Argillite, chert, and limestone.	Milford		Slate, chert, and limestone.

Disconformity

Formation(Member)	Lithology	Group	Formation	Lithology
Active (Ordovician)	Slate and argillite.	L A R D E A U	Broad-view	Grit, phyllite, minor volcanic rocks
			Jowett	Mafic flows and pyroclastics
			Sharon Creek	Dark grey siliceous argillite
Nelway (Middle Cambrian)	Limestone and dolomite.		Ajax	Grey quartzite
			Triune	Dark grey siliceous argillite
Laib (Lower Cambrian) — Upper Laib	Phyllite and schist; minor quartzite and limestone.		Index	Grey and green phyllite and minor limestone
Emerald	Black argillite			
Reeves	Grey limestone		Badshot	Grey limestone
Truman	Phyllite and argillite; minor limestone.		Mohican	Phyllite and minor limestone
Reno (Lower Cambrian)	Micaceous quartzite	H A M I L L	Marsh Adams	Micaceous quartzite
Quartzite Range (Lower Cambrian)	White and micaceous quartzite.		Mount Gainer	White and micaceous quartzite

Detailed mapping across several sections of the Kootenay arc show that lithologic sequences are remarkably similar along the arc, an important factor in correlation in view of the almost complete absence of fossils. Correlation of Paleozoic lithologies in northern and southern parts of the arc, and characteristic rock types, are given in Table IV-1 (Fyles, 1961, 1962b). Base of the Cambrian is arbitrarily taken at the base of the Quartzite Range formation (Hamill group). A few fossil localities in Reno, Laib, Nelway and Active formations are the basis for dating the Lower Paleozoic section.

Thicknesses of individual units vary from place to place along the arc. True thicknesses are difficult to establish because of extreme thickening and thinning of units resulting from structural deformation. In general, Cambrian and Ordovician rocks total about 10,000 feet in thickness.

Lower Paleozoic rocks consisting of fine-grained quartzites, micaceous quartzites, phyllites (in places limy or quartzitic), and limestones may represent a transition from eugeosynclinal to miogeosynclinal depositional environments (cf. Shaw, 1963, Figure 5). Lower Paleozoic volcanic rocks of the arc are confined to Broadview and Jowett formations in Lardeau district (Table IV-1).

Disconformably overlying Lower Paleozoic rocks is the Milford group of Carboniferous to Lower Triassic age. Rocks are predominantly fine-grained sedimentary types including argillite, micaceous quartzite, thin limestone beds, and chert. The Milford group is about 2,000 feet thick and is restricted to the western edge of the arc. Milford rocks correlate in part with the Upper Paleozoic Cache Creek sequence to the west. Detailed stratigraphic studies of Milford rocks have not yet been made.

In Slocan district about 6,200 feet (maximum thickness) of volcanic

flows and pyroclastic rocks of the Kaslo group overly Milford rocks and are,

in turn, overlain by an unknown thickness (perhaps 20,000 feet implied by

Hedley, 1952) of Triassic Slocan series. The Slocan series consists mainly

of argillites and slates with thin limestone layers and at least one tuffac-

eous stratum. Limestone is very abundant in exposures of Slocan rocks near

Ainsworth camp. The rocks are highly deformed and only a few detailed geol-

ogical investigations have been made (see Hedley, 1952).

Except in Slocan district, Mesozoic rocks are not present in the Koot-

enay arc. The unfossiliferous Ymir group crops out abundantly near the

southern and eastern borders of the Nelson batholith, and on the basis of

lithology has been correlated in part with the Slocan series. Recent stud-

ies by Frebold and Little (1962, p. 5) indicate that much of the Ymir group

probably correlates with the Archibald formation of Lower Jurassic age.

Outside the arc, west and southwest of the region of major exposures

of the Ymir group is an area underlain by 13,000 feet or more of Lower and

Middle Jurassic rocks (Frebold and Little, 1962) that includes about 9,000

feet of volcanic rocks.

STRUCTURE

Geological structure in the Kootenay arc is very complex and the struct-

ural history can be worked out only with a detailed knowledge of stratigraphy.

In parts of the arc where detailed mapping has been done, general geometry

of strata is fairly well known (see Fyles and Hewlett, 1959; Fyles and East-
wood, 1962). Structural geology of the arc is summarized by Fyles (1962b)
and is illustrated in Figure IV-2 by structural sections taken across northern,
central and southern parts of the arc. Locations of sections are shown in
Figure IV-1.

Fyles recognizes two major periods of folding in the Kootenay arc.
Oldest known deformation and associated structures are referred to as Phase
I, and the folds have N-shaped cross-sections illustrated by the Badshot
formation in the Trout Lake-Badshot Mountain section of Figure IV-2. At the
north end of Kootenay Lake Phase I folds are refolded in the shape of a back-
ward N, the characteristic pattern of Phase II folds. Phase I folds are
generally isoclinal whereas Phase II folds are commonly more open. Folds of
both phases plunge about 10 degrees in a northerly direction in the Ferguson
and Duncan Lake areas, and at low angles in either direction elsewhere in
the arc.

Near Salmo structural interpretation is complicated by granitic intrus-
ions, faults, and an abrupt swing of the regional structural trend. Granitic
intrusions interrupt but neither displace nor seriously deform regional
structures. In detail, though, both Phase I and Phase II structures are re-
cognizable and are similar in form to Phase I and Phase II structures in
Lardeau district. In Salmo camp the rocks are divided into three structural
belts separated by regional thrust faults. The Eastern belt is underlain
by rocks of the Quartzite Range, Reno and Laib formations deformed into the
Laib syncline on the east and Sheep Creek anticline on the west. West of
the Eastern belt is the Black Argillite belt of incompetent rocks of the
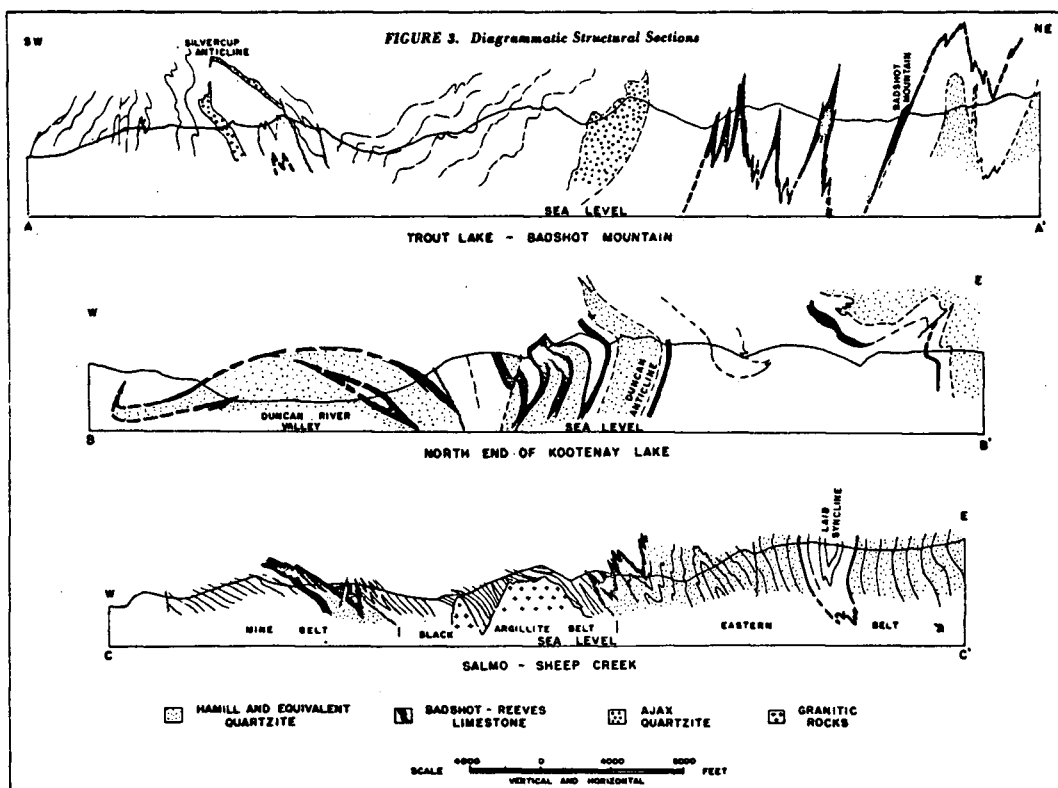
FIG. IV-2: STRUCTURE SECTIONS ACROSS KOOTENAY ARC (after Fyles, 1962b).

Ordovician Active formation folded into a complex syncline. Farther west is the Mine belt underlain largely by complexly folded members of the Laib formation. This belt contains the main sulfide ore deposits of the Salmo camp.

Extensive areas between the structural sections of Figure IV-2 are largely unmapped and interpolation of structures requires more study. Work in Ainsworth district shows that both Phase I and Phase II structures are present. The major recumbent fold in Slocan district is thought to be a Phase II structure.

Phase I and Phase II structures are the oldest known in the arc. They are intruded and in places warped by igneous rocks, and are cut by fault and shear zones. Time interval between Phase I and Phase II deformations is not known. Richardson (1961) ventures the opinion that the two sets of structures formed during one continuous period of deformation. An alternative interpretation is that Phase I structures were formed during mid-Paleozoic orogeny (Caribou orogeny of White, 1959), and Phase II structures developed during mid-Mesozoic orogeny. Sutherland-Brown (1957) found evidence of mid-Paleozoic orogeny in the Caribou district.

Detailed structural studies in the arc are important from the point of view of ore control and mineral exploration (Fyles, 1962a, 1962b). Phase I structures controlled distribution, continuity and thickness of rocks favourable for mineral deposition, but were not a major ore control. Replacement deposits commonly are confined to Phase II folds and related shear or fracture zones. Some veins are in fissures that may be younger than Phase II structures.

HISTORICAL GEOLOGY

During late Precambrian time much of southeastern British Columbia was covered by shallow seas. Rocks of Lower Purcell group (Table IV-2) are the oldest known in the area. These rocks were probably deposited in a seaway underlain by a metamorphic complex such as exposed in the Churchill province of the Canadian shield (Burwash, 1959). Hence, maximum age of Purcell strata is 1,800 m.y. (cf. Engel, 1963). Minimum age of Purcell rocks based on potassium-argon dating of intrusive rocks that cut the Aldridge formation (Hunt, 1961) is 1,500 m.y. A conservative estimate of extent of Lower Purcell seas is obtained by plotting areas underlain by outcrops of Lower Purcell strata (Figure IV-3). Western margin of the seas is unknown, but some information suggests they may have been more widespread than indicated by present outcrop areas of Lower Purcell rocks. A possibility that Monashee rocks of Shuswap terrane west of Kootenay arc correlate with Purcell strata is considered by Jones (1959, p. 132) who writes

> "A late Proterozoic age for the Shuswap rocks would make them equivalent to the Purcell series. The Purcell series is a thick assemblage (about 40,000 feet) of fine quartzite and argillite and is the oldest known assemblage of rocks in British Columbia. Dioritic igneous bodies known collectively as the Purcell intrusions or Purcell sills are included in the series and may also be of Precambrian age. The correlation of the Purcell series with the Monashee group has much to commend it. The Monashee group is lithologically similar to the Purcell series for, although the Purcell rocks are mostly unmetamorphosed, their known outcrops are sufficiently distant from the Shuswap terrane that metamorphic disparity is no difficulty in correlation. The Purcell sills, moreover, have ready counterparts in the pre-tectonic sills and dykes (the Three Valley intrusions) of the Monashee group."

Eardley (1962) considers that lithologic equivalents of Lower Purcell rocks

FIGURE IV-3: GENERAL DISTRIBUTION OF PRECAMBRIAN ROCKS IN SOUTHEASTERN BRITISH COLUMBIA

Magnesite Belt • Metaline • Salmo • Western • Divide • Cranbrook • Galton Range

Lower Cambrian

Upper Purcell

Windermere

Lower Purcell

Upper Purcell

?

?

?

Basement

Vertical Scale
(in feet)

0
10,000
20,000
30,000

B. C.

Divide
Cranbrook

Western

Salmo
Metaline

Galton Range

Waterton

WASH.

ID.

MONT.

B. C.

Magnesite Belt
Turtle Lake
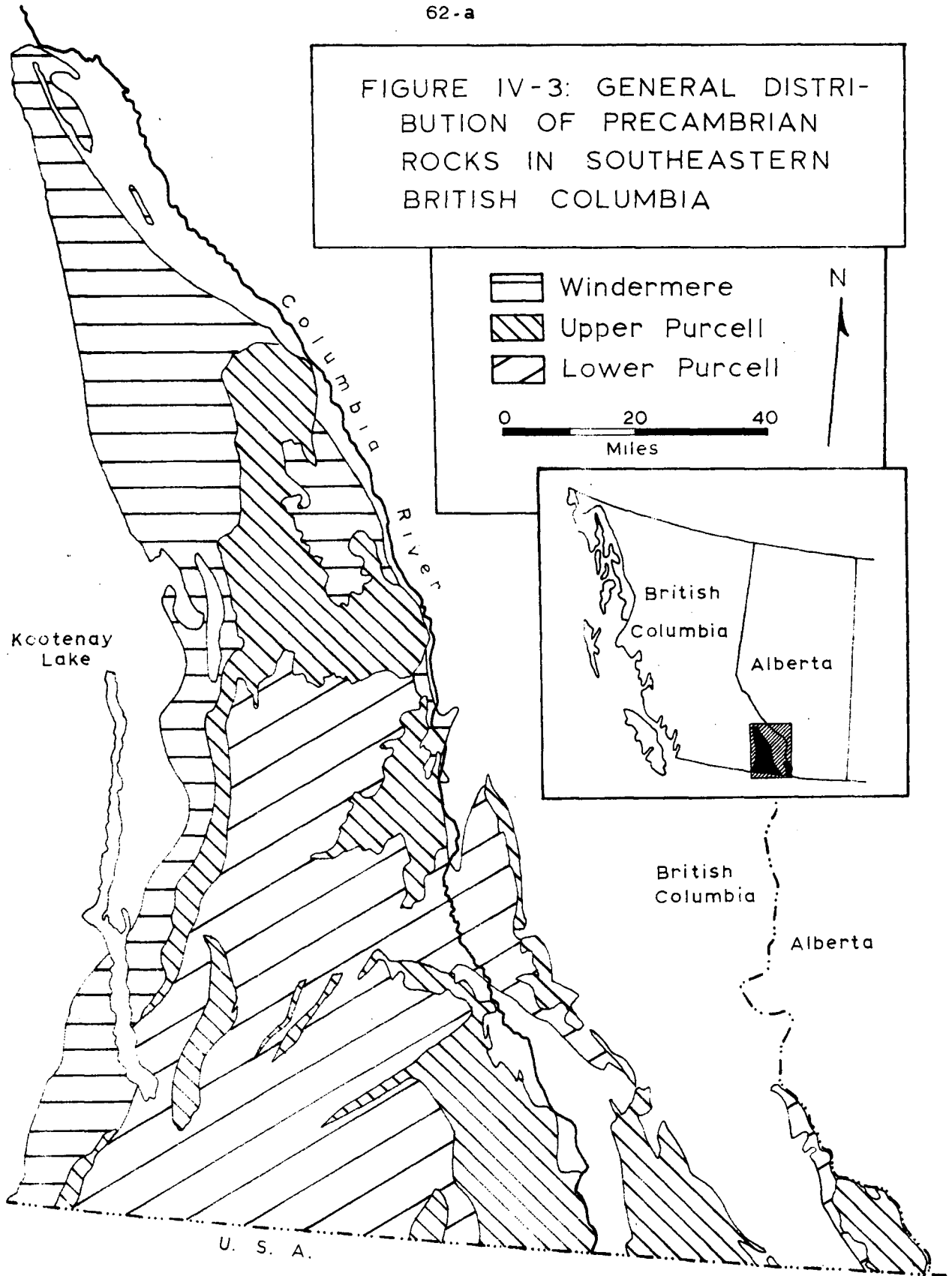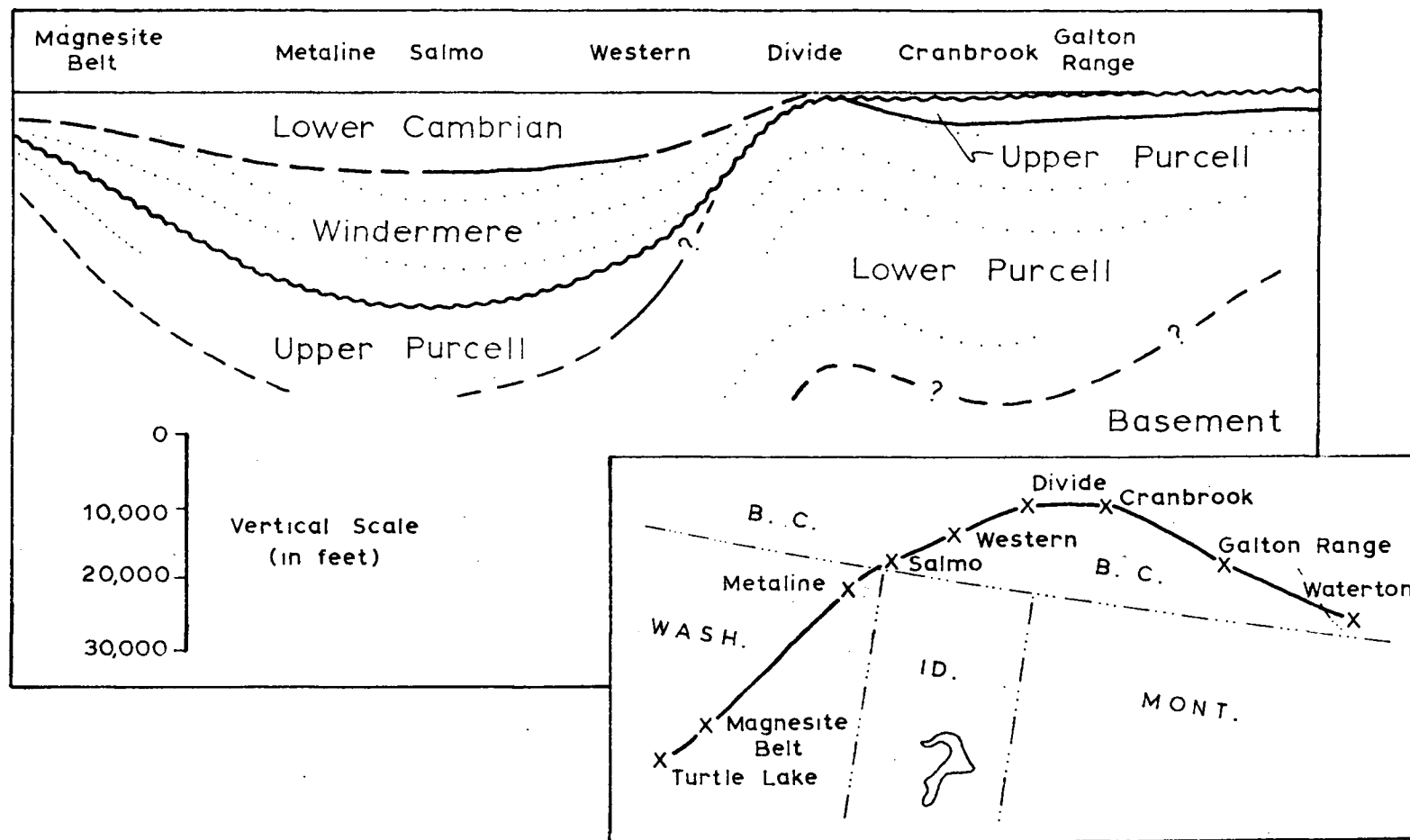
FIGURE IV-4: PRECAMBRIAN SYSTEMS, SOUTHEASTERN BRITISH
COLUMBIA (modified from Eardley, 1962)

TABLE IV-2

PRECAMBRIAN FORMATIONS IN SOUTHEAST BRITISH COLUMBIA

Lower Cambrian						
	Both conformable and unconformable					
WINDERMERE	Three Sisters					
	Horsethief Creek			Monk		
	Irene Volcanics	Leola Volcanics				
	Toby			Shedroof		
Unconformity						
UPPER PURCELL	Mount Nelson			Missoula		UPPER BELT
	Dutch Creek					
LOWER PURCELL	Siyeh			Striped Peak		LOWER BELT
	Kitchener			Wallace		
	Creston			Ravalli		
	Aldridge			Prichard		
	Fort Steele					

extend under the southern part of the Kootenay arc (Figure IV-4).

Base of Lower Purcell rocks has not been found, and in the area east of the Kootenay arc a minimum composite thickness of this system is about 5 miles. Most of these strata consist of fine-grained, argillaceous, clastic sediments. Only minor quantities of carbonate are present, although dolomite is fairly abundant in the Kitchener-Siyeh formation. Sediments were deposited largely in a shallow marine environment as shown by numerous ripple marks, mud cracks, salt crystal casts, and rain drop imprints. Some evidence for deep water deposition of Lower Aldridge strata has been found by staff geologists of Consolidated Mining and Smelting Company (A.C. Freeze, personal communications). Provenance is unknown (Rice, 1941, p. 13). Both eastern and western sources of clastic material have been suggested.

Volcanism marked the end of Lower Purcell time. Purcell lavas are found in eastern exposures of the Purcell system in thicknesses ranging up to 300 feet. Relict pillow structure suggests deposition in a submarine environment. West of Rocky Mountain Trench, Rice (1941) found minor amounts of pyroclastic rocks representing Purcell volcanism.

In general, Upper Purcell strata appear to overly Lower Purcell beds conformably in British Columbia and Alberta. However, Clapp and Deiss (1930) imply an erosional interval between Upper and Lower Belt rocks of Montana when they state, "...the limestone forming the base of the Miller Peak (formation) is traceable into Lolo Fork area 12 miles to the west, where it lies directly on Ravalli quartzite...". Wallace and Striped Peak formations are missing where Miller Peak formation rests directly on Ravalli quartzite. Although deposition of Lower and Upper Purcell strata appears to have been

continuous in British Columbia, part of Montana was a positive tectonic unit

for some of Lower Purcell time and may have provided some of the detrital

material in the upper part of Lower Purcell group.

Upper Purcell rocks contain more carbonates than Lower Purcell strata.

Fine-grained clastic sedimentary rocks, however, are common and predominate

in western exposures of Upper Purcell rocks (Reesor, 1957). Apart from a

greater proportion of carbonate rocks, Upper Purcell strata have similar

lithologies to Lower Purcell units. Abundant features of shallow water de-

position are common to both groups and conditions of deposition must have

been fairly uniform during formation of the entire Purcell system. Region-

al emergence occurred at the close of Purcell time as shown by unconform-

able relations of overlying Lower Paleozoic rocks. In Montana this emerg-

ence probably lasted longer than elsewhere, for that area appears to have

undergone uplift until the end of Lower Cambrian time. Deiss (1935) shows

that about 20,000 feet of Upper Belt sediments were removed prior to de-

position of Middle Cambrian quartzite. Westward, however, conditions dur-

ing Late Precambrian were different. Post-Purcell uplift is proven by un-

conformable relations of Upper Purcell to overlying beds. However, a

narrow subsiding trough formed in very late Precambrian time in which Wind-

ermere rocks were deposited.

Toby conglomerate at the base of the Windermere system probably repres-

ents a shoreline deposit "...of a sea that spread rapidly over the land,

roughly reworking the loose, superficial deposits." (Rice, 1941, p. 23). A

second period of Precambrian volcanism is indicated by Irene Volcanic form-

ation, which near its base is interbedded with Toby conglomerate. Maximum

thickness (more than 6,000 feet) of volcanic rocks occurs south of the International Boundary where volcanic activity probably was centered. Thicknesses decrease rapidly to the north. Overlying Irene Volcanic formation, or Toby formation where volcanic rocks are absent, are coarse sandstones and conglomerates of the Horsethief Creek and Three Sisters formations. Coarse detrital material of Horsethief Creek and Three Sisters formations probably was derived from adjacent land masses to the east and southeast (cf. Little, 1960, p. 107), particularly Montana Island (Deiss, 1940).

Windermere sediments were deposited in a narrow, north-northwesterly trending trough, more-or-less parallel to, but much more confined than, the Beltian geosyncline. Westward extent of this trough is unknown. White (1959) considered the Shuswap terrane a western facies of the Windermere sequence. Jones (1959, p. 132) implies a possible correlation of Windermere rocks and Mount Ida group of Shuswap terrane.

In much of Southern British Columbia sedimentation appears to have been continuous from Precambrian Windermere sediments to Cambrian beds (Figure IV-4). On the east flank of the Purcell geanticline, Windermere rocks are absent and Cambrian sedimentary rocks lie unconformably on Purcell system (Geol. Surv. Canada, 1957, p. 324). In Montana an unconformity separates Belt strata and mid-Cambrian rocks (Campbell, 1959; Kauffman, 1959). In Windermere map area Walker (1928) found Lower Cambrian strata resting on different members of Windermere system. In the Kootenay arc Paleozoic rocks are practically devoid of fossils. The Cambrian-Precambrian boundary is placed arbitrarily between Windermere system and Hamill group (Little, 1960, p. 24) and marks the beginning of stable conditions of sedimentation. Dur-

ing Lower Paleozoic time the Kootenay arc was a transition zone between eu-
geosynclinal and miogeosynclinal environments (cf. Shaw, 1963, Fig. 5).
Provenance of all Lower Paleozoic rocks has not been established. The Ham-
ill group, however, was derived from the east and southeast (Little, 1960,
p. 107). Evidence of Ordovician(?) volcanism is given by volcanic rocks
and tuffaceous sedimentary rocks in Jowett and Broadview formations in Fer̥g-
uson map area of Lardeau district (Table IV-1). Absence of mid-Paleozoic
strata from the Kootenay arc suggest that the area was tectonically positive
during the Silurian and Devonian.

During Pennsylvanian, or possibly as early as Mississippian, the area
was again inundated as part of the "Cache Creek submergence" of the western
Cordillera (Geol. Surv. Canada, 1957, p. 300). Apparently deposition con-
tinued uninterrupted into Lower Triassic when uplift and erosion occurred
followed by volcanism in a restricted region near Kaslo on the west shore
of Kootenay Lake (Cairnes, 1934). A maximum thickness of Kaslo volcanic
rocks of 6,200 feet indicates intense volcanism during Lower Triassic time.

Following Upper Triassic volcanism, the region was submerged and depos-
ition of Slocan (and possibly some Ymir) strata began. Structural complex-
ities make it difficult to estimate thicknesses of these beds although
Hedley (1952, p. 23) implies that the Slocan series is as much as 20,000
feet thick. Ymir group may be largely Lower Jurassic (Frebold and Little,
1962). Thus, extent of Triassic seaways is difficult to establish, although
Little, (1960, p. 108), indicates that a Triassic seaway did not extend as
far west as Rossland, B. C. Beginning in Lower Jurassic and continuing into
Middle Jurassic time, much of the area immediately west of the Kootenay arc

was deeply submerged and deposition of a eugeosynclinal sequence of sedi-
mentary and volcanic rocks occurred. A minimum thickness of 13,000 feet of
Lower and Middle Jurassic rocks has been measured west of Salmo, B. C.

Since Upper Jurassic time the region has been uplifted and eroded, the
only major depositional period being during the Pleistocene epoch.

Orogenic History of the Kootenay District

The earliest known intrusions in southeastern British Columbia are
Moyie sills of the East Kootenay district (Rice, 1941, p. 24). These in-
trusions, gabbroic to dioritic in composition, occur as thick sills and a
few dikes and stocks in more-or-less restricted stratigraphic positions in
the Purcell system. In the western part of the East Kootenay district most
intrusions are sills ranging up to 800 feet thick principally in the Ald-
ridge formation. East of the Rocky Mountain Trench, Moyie Intrusions are
found mainly in the Siyeh formation. Moyie Intrusions have been correlated
tentatively with Purcell lavas (Schofield, 1915, p. 69) and tuffs in the
upper part of the Kitchener-Siyeh formation, although no specific geologic
evidence other than similarities of composition have been found to support
this correlation. Recent potassium-argon dates on Moyie sills and related
metamorphic selvages range from 669 m.y. to 1580 m.y. (Hunt, 1961, p. 116).
Three distinct groupings of potassium-argon data exist with ages centered
about 1500 m.y., 1100 m.y. and 800 m.y. (Figure IV-5). Hunt (1961) inter-
prets this grouping of ages as indicating two separate injections of
"Moyie" magma about 1500 m.y. ago and 1100 m.y. ago, and attributes 800 m.y.
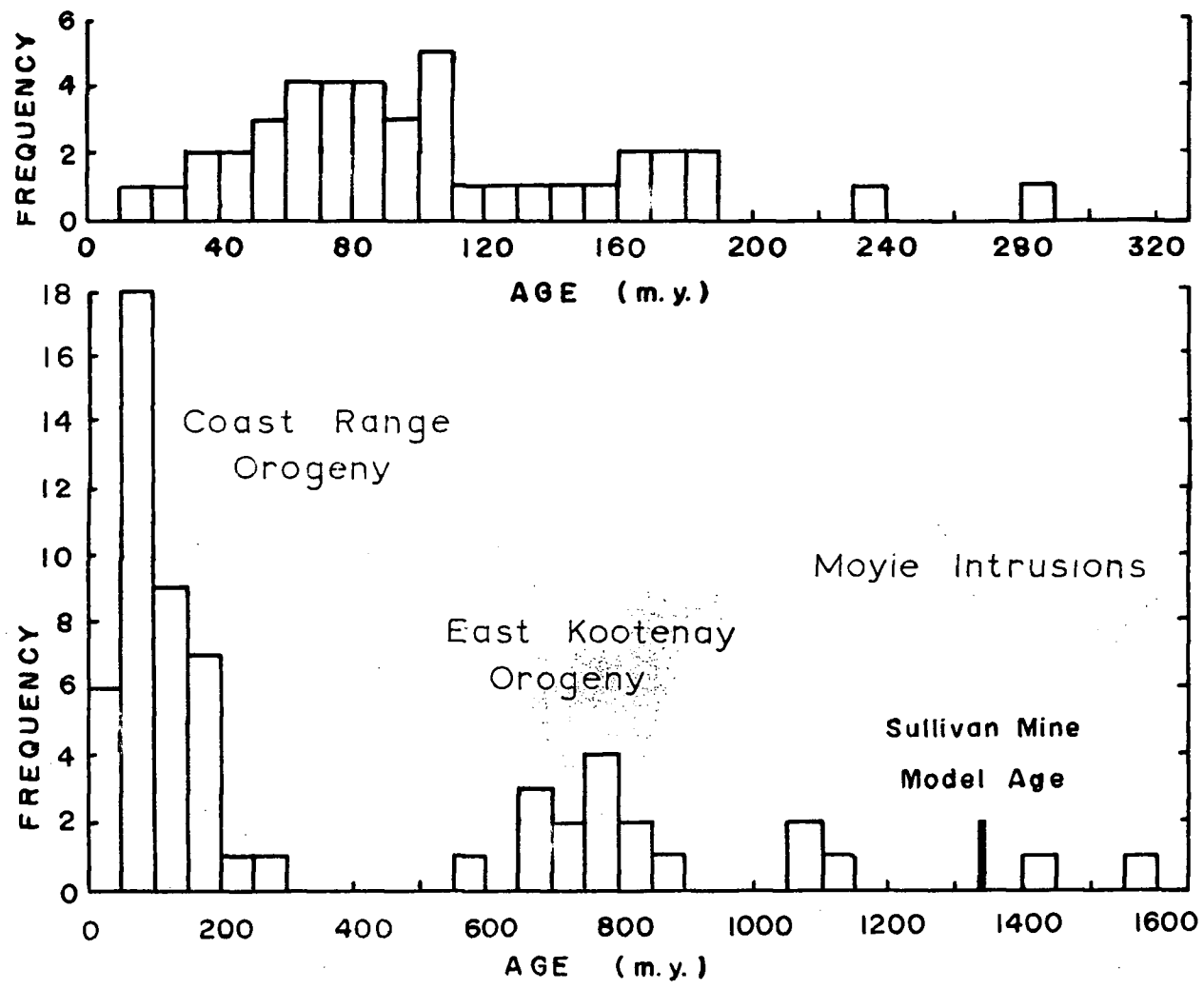
FIGURE IV-5: DISTRIBUTION OF POTASSIUM-ARGON
AGES FOR KOOTENAY ARC & VICINITY

ages to a later epoch of metamorphism. Moyie Intrusions, although originally interpreted as related to Precambrian orogeny, have been re-interpreted (Hunt, 1961; Leech, 1962) as being non-orogenic in origin.

Unconformable relations of Windermere rocks to underlying Purcell strata (Schofield, 1922; Walker, 1928; Reesor, 1957) was the main evidence of Precambrian orogeny. This disturbance was named "East Kootenay" orogeny by White (1959). Recent potassium-argon work (Hunt, 1961; Leech, 1962) fixes the probable time of this orogeny at about 800 m.y. Precambrian metamorphism, intrusion and folding (Leech, 1962; Leech and Wanless, 1962) are tentatively attributed to East Kootenay orogeny. Leech (1962, p. 6) states:

> "The Precambrian granitic intrusions and metamorphism reported here are concrete evidence of orogeny. Its age relative to the Windermere sequence must be determined from regional considerations because the rocks are not in contact. Nevertheless, because the pre-Windermere disturbance was much greater than the possible post-Windermere one, the intrusion and metamorphism are considered pre-Windermere and, less probably, intra-Windermere in age."

A mid-Paleozoic orogeny was recognized by Sutherland-Brown (1957, p. 62) in Cariboo district of British Columbia, where mildly deformed Permian strata unconformably overlie closely folded and regionally metamorphosed rocks (chlorite-muscovite grade) of early Cambrian age. White (1959, p. 67) calls this the "Caribou" orogeny and suggests that "original folding of the ancestral "Kootenay arc" was one effect. Within the Kootenay arc itself relatively little evidence exists of Paleozoic orogeny. Mid-Paleozoic tectonism is suggested by the absence of Silurian and Devonian rocks, although a few scattered outcrops of Devonian strata have been identified in Metaline district of northeastern Washington (Park and Cannon, 1943, p. 22). Upper Paleozoic formations are not abundant in the arc but in Lardeau district

the Milford group of probable Carboniferous to Lower Triassic age lies dis-
conformably on Lower Paleozoic rocks of the Lardeau series. North of Kaslo
the Milford group overlies highly metamorphosed rocks of the Lardeau series
but the nature of the contact is not known. Field studies by the writer
suggest differences in degrees of metamorphism of Milford and Lardeau rocks
in any one area. Thus, orogenic activity may have occurred between depos-
ition of the two units. However, relatively little is known about petro-
graphy, structure and stratigraphy of the Milford group and definite con-
clusions must await detailed studies. Potassium-argon dates supporting mid-
Paleozoic igneous intrusion have been found in several places in the Canad-
ian Cordillera(Baadsgaard and others, 1962; Lowdon, 1963) but none of these
intrusions are near the Kootenay arc.

Mesozoic orogeny in the arc probably began in late Triassic. Milford
rocks in Lardeau district disconformably overlie and are complexly inter-
folded with rocks of the Lardeau series (Fyles and Eastwood, 1962, p. 30).
In Slocan district, the Triassic Slocan series is intensely folded
(Cairnes, 1934, p. 57) but only slightly metamorphosed except near the
contact of the Nelson batholith.

The Nelson batholith appears to be the earliest major batholithic mass
formed during Mesozoic orogeny in the arc. Recent potassium-argon dates
(Leech and others, 1963) place the minimum age of the batholith at about
170 m.y., i.e. lowermost Middle Jurassic on the Kulp (1961) time scale.
Emplacement of the batholith followed intense folding of the Slocan series
(Cairnes, 1934). Hedley (1952, p. 33) believes "...that the development of
the complex Slocan fold and the emplacement of this (northern) part of the

Nelson granite must have been interrelated." Porphyritic granite and grano-
diorite with orthoclase phenocrysts are perhaps the most widespread and dis-
tinctive members of the Nelson plutonic assemblage. A non-porphyritic gran-
ite and granodiorite member of the Nelson batholith appears in some places
to merge with, and in other places to crosscut, porphyritic Nelson granite
(Cairnes, 1934, p. 65).

Little (1960, p. 86) concludes that, "...the lower limit of age is
post-Middle Jurassic.." and, "...the upper limit of the age of the Nelson
rocks can be set, with rather less confidence, as pre-Upper Cretaceous".
The post-Middle Jurassic lower age limit is based on the fact that non-
porphyritic Nelson granitic rocks crosscut the Hall formation of Middle and
Upper(?) Jurassic age (Little, 1960). As previously indicated the non-
porphyritic granitic rocks are in places younger than the porphyritic types.
Thus, early porphyritic phases of the Nelson batholith could be early Middle
Jurassic as suggested by 170 m.y. potassium-argon dates.

Small acid stocks are abundant around the northern and eastern margins
of the Nelson batholith. Cairnes (1934, p. 84), discussing stocks in the
Slocan-Kaslo region, states:

> "...excluding the intrusives related to the Kaslo series and
> certain dykes younger than the mineralized veins, the available
> evidence indicates that all the intrusive bodies are related in
> origin, though differing somewhat in age; all are younger than
> the Slocan series and older than the period of mineralization."

Little (1960, p. 84) points out that "...satellites of the Nelson batholith
are more varied in composition than those (rocks) of the batholith." The
time relations of individual stocks to the Nelson batholith are neither
clear nor consistent. Some stocks such as porphyritic bodies near the

←— Silver King mine (Mulligan, 1952, p. 13) are interpreted as early phases of the Nelson batholith. Potassium-argon work indicates that many stocks and small batholiths might be considerably younger than the Nelson batholith (Leech and others, 1963, p. 7-25).

Igneous activity in the Kootenay arc and vicinity continued into the Tertiary. Coryell intrusions cut the Sophie Mountain formation of Upper Cretaceous or Tertiary age. Potassium-argon dates of Coryell rocks range from 30 m.y. to 60 m.y. (Lowdon, 1961). Lamprophyre dikes occur in many places within the arc but are particularly abundant in Salmo district where they crosscut Coryell-type (syenitic) intrusions. Tertiary igneous activity was not as pronounced in the Kootenay arc as farther west near Trail, British Columbia (Little, 1960, p. 109).

CHAPTER V

DESCRIPTION OF MINERAL DEPOSITS STUDIED

INTRODUCTION

Mineral deposits in the Kootenay arc include lead-zinc fissure veins

and replacement deposits, silver-rich lead-zinc veins, and gold-quartz

veins with minor amounts of sulfides. This investigation and related

field work is restricted to vein and replacement deposits containing

appreciable amounts of lead and zinc distributed as widely as possible

along the arc. Only those deposits for which lead isotopic compositions

were obtained are described here. Fissure and replacement deposits from

four mining camps in the arc were studied (Figure V-1): Lardeau district

in the north, Salmo lead-zinc camp in the south, and Slocan and Ainsworth

camps in the central part of the arc. In addition, two deposits in rocks

of the Shuswap terrane, near the northern part of the arc, are included in

this investigation.

General features of mineral deposits of Lardeau, Ainsworth and Slocan

districts are reviewed first, followed by summaries of significant geolog-

ical features of deposits specifically dealt with in this investigation.

General features of deposits in Shuswap rocks are not considered because

of the scarcity of published data. As many detailed accounts of Salmo-

type replacement deposits are available (Fyles and Hewlett, 1957, 1959;

Whishaw, 1954; Rennie and Smith, 1957; Irvine, 1957; Warning, 1960), this

review is confined to general characteristics of Salmo-type deposits.

FIGURE V-1: LOCATION OF DEPOSITS STUDIED
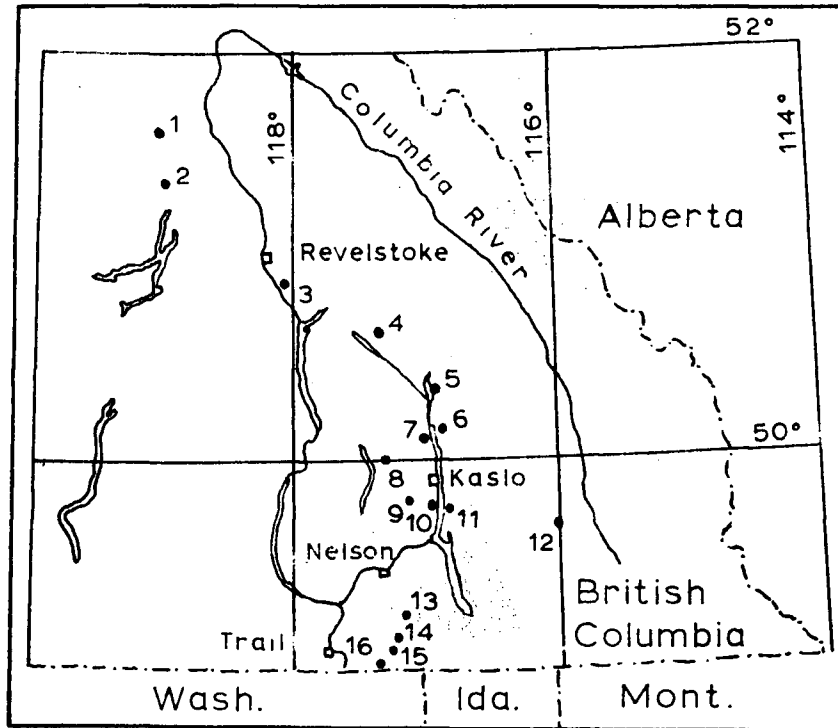
1 Ruddock Creek

2 Cotton Belt

3 Wigwam

4 Mollie Mac

5 Duncan Lake

6 Sal

7 Moonshine

8 Victor

9 Scranton

10 Lakeshore

11 Bluebell

12 Sullivan

13 Jackpot

14 H. B.

15 Jersey

16 Reeves Macdonald

LARDEAU DISTRICT

A wide variety of mineral deposits occur in the Lardeau map-area. Those of greatest commercial interest are mesothermal gold-quartz veins, silver-lead-zinc veins, and lead-zinc replacement deposits in limestone (Walker, Bancroft and Gunning, 1929, p. 20-26). Brock (1903, p. 56) recognized three geographic zones of mineral deposits separated by more-or-less barren ground, the "southwestern belt", the "central belt", and the "lime dyke belt". Gunning (Walker, Bancroft and Gunning, 1929, p. 27) suggests that Brock's "mineral belts" oversimplify the zonal pattern of ore deposits, and redefines the mineral belts more specifically. The western limit of mineral deposits is the eastern contact of the Kuskanax batholith. Farther east, in a zone extending from the south end of Trout Lake about 10 miles south along the west shore of Lardeau River, is a narrow zone of gold-quartz veins. Several miles west of, and parallel to Trout Lake, is a zone of gold-bearing lead-zinc-silver fissure veins, the most productive and most well-defined "mineral belt" in Lardeau district. This zone extends about 25 miles northwest from a point 4 miles east of the south end of Trout Lake. Farther east, near the eastern margin of the arc, is a zone characterized by galena-sphalerite replacement deposits in limestone. Other deposits occur east of the "lime dyke" outside the Kootenay arc as here defined.

Most of the galena-sphalerite replacement deposits are in limestone and most fissure deposits of economic importance are in argillaceous and schistose rocks. Relatively few mineral deposits are in quartzites, green-

stones or chlorite schists.

Concerning origin of sulfide bodies in the Lardeau district, Gunning
(Walker, Bancroft and Gunning, 1929, p. 31) writes:

> "The metalliferous (lode) deposits of the Lardeau map-area ...
> are believed to have formed by ascending heated solutions which
> originated during the final stage of consolidation of the magma
> or magmas that formed the Kuskanax batholith and other masses of
> igneous rock that more-or-less surround the district on three
> sides."

The abundance of quartz, albite, muscovite, and tourmaline in veins is off-
ered as support for a magmatic derivation hypothesis. However, Fyles and
Eastwood (1962, p. 57) write:

> "The source of the mineralization is not known. Early
> workers concluded that the mineral-bearing solutions originated
> from the final stages of consolidation of granitic rocks, princip-
> ally the Kuskanax batholith which lies several miles southwest of
> the (Ferguson) map-area. Direct evidence of this relationship has
> not been found. The exposed granitic masses are many miles from
> the central and lime dyke mineral belts in the Ferguson area, and
> there is no indication that granitic rocks lie beneath the deposits
> at any reasonable depth."

Detailed investigations by Fyles and Eastwood (1962, p. 55) indicate that
mineral deposits are mainly in folds, shear zones and fissures.

Gunning (Walker, Bancroft and Gunning, 1929) observed the following
features of Lardeau mineral deposits:

1. Simple mineralogy.

2. Complete gradation in mineralogy among well-defined types of
   deposits.

3. A similar paragenetic sequence in deposits throughout the
   district.

4. In any one deposit there is no mineralographic evidence for
   more than one period of mineralization.

Gunning concluded that deposition in any one deposit was a continuous process, and that mineralization throughout the Lardeau map-area was more-or-less contemporaneous.

Age of mineralization is uncertain. A maximum age is Triassic because rocks of the Milford group (Carboniferous to Triassic) are mineralized. Mineralized fissures crosscut folds probably formed during Mesozoic orogeny, but the precise age of orogeny is unknown. Gunning assumed that mineralization followed emplacement of the Kuskanax batholith, and is therefore probably Late Mesozoic or Early Tertiary in age.

Wigwam Showings

The Wigwam showings are on the north side of Akolkolex River, 14 miles southeast of Revelstoke. Pyrrhotite, pyrite, sphalerite and galena, in decreasing order of abundance, occur as replacements of partly silicified crystalline limestone. The limestone which strikes north 30 degrees west and dips 23 degrees northeast is underlain by a series of micaceous quartzites and overlain by carbonaceous schists. Extensive irregular silicification of the limestone has occurred.

Fyles (B.C. Dept. Mines, Ann. Rept., 1962) describes the showings, in part, as follows:

> "The sulphides are mainly in the siliceous parts of limestone. They are mostly very fine-grained and occur in layers parallel to the layering in the siliceous limestone. Some of the mineralization consists of scattered disseminated grains of sulphides; other mineralization is massive in layers a few feet thick, which locally contain rounded fragments of siliceous rock resembling incompletely

replaced breccia fragments. Locally fairly coarse-grained galena
and minor light brown sphalerite and pyrite occur in irregular
lenses in crystalline limestone."

The main siliceous zone is lenticular having a maximum width of 200

feet and a known length of one mile. Three poorly defined mineralized

lenses have been found within this siliceous zone.

Gunning (Walker, Bancroft and Gunning, 1929, p. 102) suggests a possible

structural control for mineral deposition:

> "Much minor folding is present, however, so that locally beds
> may be horizontal or folded into small anticlines. Of the numerous
> sulphide exposures examined, all but two occurred where the marble
> was lying much more flatly than the average and at several showings
> its attitude was essentially horizontal. Some shearing and random
> joints were observed but on the whole they seemed to have little
> influence on the deposition of sulphides. On the basis of a hasty
> examination it seemed evident that the siliceous mineralizing
> solutions ascending from below, had penetrated along bedding planes
> of the marble, effecting widespread silicification; that somewhat
> later, or towards the end of silicification, the sulphides had
> been introduced in a like manner. The latter, however, were de-
> posited most abundantly where the limestone was flat-lying or
> folded into minor anticlines."

Mollie Mac Showing

The Mollie Mac showing is a siderite-galena replacement deposit in

limestone, about two and one-half miles northeast of a settlement known as

Ten mile, in the Ferguson map-area (Fyles and Eastwood, 1962, p. 65).

Country rock of the mineralized zone is the Mollie Mac limestone, a grey,

fine-grained, crystalline rock 100 feet thick dipping steeply southeast,

within grey and green phyllites of the Index formation. Large sinuous re-

placement masses of siderite in limestone in places contain small amounts

of massive or disseminated galena. Pyrite and small quartz veins are distributed throughout the siderite masses. Sphalerite is rare and silver values are low. Within the mineralized zone are a few small galena veins.

Duncan Mine

The Duncan mine is on a peninsula on the east shore of Duncan Lake, near the geographic center of the Kootenay arc. Sulfide minerals occur in four roughly tabular bodies in dolomitic zones of the Badshot limestone, on the eastern limb of a major fold known as the Duncan anticline (Richardson, 1961). The Duncan anticline is an isoclinal fold whose axial plane subsequently was folded in the form of a curved sheet concave to the west. Long dimensions of ore shoots approximately parallel fold axes, plunging about 10 degrees in a north 20 degree west direction. According to Richardson this complex fold is the result of a single prolonged period of stress.

Ore minerals are pyrite, sphalerite, galena and pyrrhotite. Faults seem to have no influence on localization of ore. The main ore control appears to be the contact of dolomite and chert units of the Badshot formation.

Richardson (1961) describes the possible origin of ore as follows:

"...the deposits are of the telethermal type in that they were probably deposited under conditions of low intensity, possibly by rising hydrothermal solutions from an unknown widespread source at depth and that they were deposited prior to structural deformation and granitic intrusion."

The Duncan deposits have many features in common with ores of the Salmo camp to the south. Similarities of ores from Duncan mine and the

Salmo camp are listed below:

1. Simple ore mineralogy — principally pyrite, sphalerite and galena, with minor amounts of pyrrhotite.

2. Evidence of deformation of pyrite and sphalerite (Appendix IV).

3. Occurrence as replacement deposits in Badshot (Reeves) limestone of Lower Cambrian age.

4. Association with zones of dolomitization.

5. Low iron content of sphalerite.

6. Elongation of ore zones approximately parallel to fold axes.

7. Absence of copper minerals — especially tetrahedrite which is present in many fissure deposits in the arc.

8. A similar, distinctive trace element assemblage in galenas (Appendix III).

Sal Showings

The Sal showings on Mount Willet, 4 miles east of the north end of Kootenay Lake (at the southeastern extremity of the Lardeau map sheet of Walker, Bancroft, and Gunning, 1929), are somewhat similar to the Duncan Lake deposit. Three sulfide zones occur in dolomite and siliceous dolomite of the Badshot formation on the eastern limb of the southern extension of the Duncan anticline. Sulfides consist mainly of pyrite, sphalerite and galena. Little is known of the geology of the showings because they were discovered recently and only preliminary exploration has been done.

Moonshine, Right Bower Showing

The Moonshine property is about 1 mile south of the town of Lardeau on the west side of Kootenay Lake. The showing is a fissure vein in a thick, pale grey limestone bed similar in appearance to the Badshot limestone. The fissure strikes 26 degrees east of north and dips 62 degrees west. Present surface exposures of sulfides range from a fraction of an inch to 3 inches in width. Mined portions of the vein were up to 2 feet thick (B.C. Dept. Mines, Ann. Rept., 1952, p. A194-A195). Massive galena is common near surface and sphalerite is common at depth.

SHUSWAP TERRANE

Ruddock Creek Showing

Ruddock Creek showing is on Gordon Horne peak, at the head of Ruddock Creek, about 60 miles northwest of Revelstoke, B.C. Lead-zinc mineralization has been found intermittently over a 2-mile distance in a calcareous layer interbedded with schists and gneisses of the Shuswap complex.

Dark brown sphalerite, pyrrhotite and galena occur in relatively continuous layers a few feet to a few tens of feet thick. In some places the mineralized rock is recrystallized mylonite or breccia. Mineralized breccias consist of angular fragments of quartzite with some interstitial sulfides. Fluorite, barite, epidote and amphibole occur in places in the mineralized zone.

Schists and gneisses dip gently to the southwest. Mineralized layers are characterized by small attenuated folds that plunge gently to the northwest.

Cotton Belt Showing

The Cotton Belt showing is about 18 miles north of Seymour Arm, a small town on the shore of Shuswap Lake. Sphalerite, galena and minor amounts of chalcopyrite, pyrrhotite and magnetite occur in a layered skarn deposit, part of a mica schist-quartzite-marble sequence of the Shuswap complex. Gold and silver have been recorded in assays.

Sulfides occur as disseminations and stringers in a persistent layer ranging in width from 2 inches to 16 feet, that has been traced on surface a distance of about 3 miles. The mineralized layer parallels bedding in the area, striking about north 30 degrees west and dipping about 40 degrees southwest.

AINSWORTH MINING CAMP

The Ainsworth camp, on the central west shore of Kootenay Lake, was first mapped geologically by Schofield (1920). Further detailed work was carried out by Eastwood (1952) and Fyles (1961 and 1962 — unpublished).

Schofield mapped the Ainsworth and the overlying Slocan series as a homoclinal sequence striking slightly west of north and dipping moderately

to the west. However, the structure of the area is much more complex than initially recognized by Schofield. Fyles has mapped intense isoclinal folds in the lower part of the Ainsworth series, and finds the region has undergone at least two periods of deformation. The Ainsworth series, including quartzite, mica schists and crystalline limestones, may correlate with the lower part of the Lardeau series, the Badshot formation and the Hamill group, respectively.

Ore deposits have been classified (Schofield, 1920, p. 30) as:

1. Fissure veins
   (a) cutting bedding at an angle
   (b) parallel to bedding

2. Replacement deposits in limestone.

Ore bodies are not generally large and are commonly in limestone units in both the Slocan and Ainsworth series. Ore minerals are mainly galena and sphalerite in a gangue of calcite, siderite, quartz and fluorite. Other sulfides present are pyrite, pyrrhotite, chalcopyrite and marcasite.

Age of mineral deposition is not well established. Deposits seem to be about the same age as lamprophyre dikes that are younger than the Nelson batholith. Eastwood (1952, p. A149) reports quartz veins that cut lamprophyre dikes near the Highlander mine, south of Ainsworth. ~~Conversely, he found dikes cutting the veins.~~ In common with many pioneer geologists in the Kootenay arc, Schofield (1920, p. 36) genetically relates the ores to the Nelson batholith.

(

Lakeshore Showing

The Lakeshore showing of Western Mines Limited, is about one and three-quarter miles north of Ainsworth and one-half mile west of Kootenay Lake. Sulfides occur in a jointed zone, 35 to 40 feet wide, in the Lardeau series. Ore minerals are most abundant where the jointed zone crosses limestone, and to a lesser degree, hornblende schist (Powelson, 1957). Joints strike approximately east and have nearly vertical dips. Individual mineralized joints are not persistent, and rarely exceed a few inches in width (Bourne, 1953). Major sulfide concentrations were controlled by fractures with slight replacement of wallrock.

Massive and disseminated sulfides include principally galena, sphalerite and pyrrhotite, with minor amounts of arsenopyrite and pyrite. Calcite and quartz are the main gangue minerals, and knebelite and minnesotaite(?) occur locally. The showing is similar in character to the Bluebell deposits, 3 miles to the east, except that replacement of limestone is less extensive.

Bluebell Mine

The Bluebell mine is at Riondel on a peninsula on the east shore of Kootenay Lake, about two and one-half miles east of Ainsworth. Sulfides occur as fairly extensive replacement bodies in the Bluebell limestone, 100 to 150 feet thick, that strikes northerly and dips 35 degrees west under Kootenay Lake. Replacement zones extend into the limestone host from joints in the crests of three gentle anticlinal warps with centers spaced at about

1500-foot intervals, and trends that parallel the dip direction of the Blue-
bell limestone. Most ore is concentrated near the hanging wall, possibly
due to a damming effect on mineralizing fluids of the hanging wall quartzite
and pegmatite sills in the upper part of the Bluebell limestone (Irvine,
1957). However, in some ore shoots replacement is most extensive near the
footwall.

Ore minerals are principally galena, sphalerite and pyrrhotite, with
minor amounts of pyrite, arsenopyrite, chalcopyrite and magnetite. Gangue
is commonly host rock and quartz, but in places, knebelite and minnesotaite(?)
occur to the exclusion of quartz. Mineralized joints especially apparent
near the footwall of the Bluebell limestone, and small vugs common near the
hanging wall, indicate some filling of open spaces, but most production
zones owe their extensive nature to replacement.

Concerning origin of Bluebell ore Irvine (1957, p. 97) states:

> "Ore deposition is probably related to one or another of the
> granitic bodies which surround the mine, but so far no direct
> evidence links the deposits to any one body."

Pyrrhotite and sphalerite geothermometers give 490 and 495 degrees centi-
grade respectively for minimum temperature of ore formation (Arnold, 1962,
p. 85).

SLOCAN DISTRICT

Mineral deposits in the Slocan district occur mainly in the Slocan
series and the Nelson batholith as veins with variable degrees of wallrock

replacement. A few deposits, such as the Whitewater and Lucky Jim (Hedley, 1945), are replacements of thin limestone units in the Slocan series. Ores are divided into "dry" ores in which precious metals are the only important constituents, and "wet" ores containing argentiferous galena, argentiferous tetrahedrite, and sphalerite.

Abrupt changes in mineralogy occur with increased vein depth, implying that steep geothermal gradients controlled mineral deposition (Cairnes, 1934). A rough parallelism commonly exists between surface topography and mineral zones. Wet ores are generally enriched in sphalerite at depth. Commercial sulfide deposits normally bottom in the zinc-rich zone.

All deposits are in faults, joints, breccias or combinations of such structures. Deformation was contemporaneous with ore deposition -- early minerals are commonly fractured and veined by late minerals in the paragenetic sequence. Some deposits were deformed subsequent to ore formation and are characterized by gneissic and steel galena, and "trails" of sphalerite fragments in recrystallized galena (Uglow, 1917).

Cairnes (1934) classifies fissure veins on the basis of mineralogy as follows:

Type 1: Barren or nearly barren quartz veins occurring in all types of wallrock. Minor quantities of pyrite and pyrrhotite are commonly present and the wallrock is generally silicified.

Type 2: Quartz veins with silicified wallrock. The veins contain 2 or more of the following ore minerals: pyrite, pyrrhotite, chalcopyrite, arsenopyrite and gold.

Type 3: Typical silver-lead-zinc "wet" ores that charact-
eristically occur in the Slocan series. Sulfides
are sphalerite, galena, tetrahedrite, pyrite and
minor quantities of pyrrhotite and chalcopyrite.
Gold is rare. Gangue is commonly quartz and sider-
ite, either of which can be most abundant. Small
amounts of calcite are present. Vertical zoning
is a characteristic feature of these "wet" ores.
Veins commonly are enriched in sphalerite at depth.
Iron sulfides commonly predominate below the sphal-
erite zone, and in places, contain gold.

Type 4: Dry ores in which silver is the metal of chief import-
ance. Galena and sphalerite are the common sulfides,
and quartz is the gangue. The deposits generally
occur in the Nelson batholith although a few are
found in the Slocan series near the igneous-sediment
contact.

Type 5: Dry ores in which silver, and in a few cases silver
and gold, are the only metals of economic importance.
Minerals present include argentite, stephanite, ruby
silver and native silver. Stibnite, pyrite, chalco-
pyrite and galena are commonly present in small
amounts. The deposits occur in the Nelson batholith,
small stocks, and the Slocan series.

Cairnes (1934) interprets the veins as having formed during a single
period of mineralization throughout the course of which the composition of
the ore-forming fluid changed continuously. Temperature of deposition is
thought to have decreased from Type 1 veins to Type 5 veins. Ore solutions
are assumed to have been derived from the Nelson batholith. A more caut-
ious view is expressed by Hedley and Fyles (1956):

"No evidence has been found that any one deposit is genetically
related to a specific part of the (Nelson) batholith. If ore sol-
utions were derived from some magmatic chambers, the chambers must
be sought far beyond the limits of practical exploration. The ob-
served relations between intrusion and ore are physical rather than
chemical."

Hedley (1952, p. 60-61) "...agrees that some veins may show decrease in
silver and lead and increase in zinc with depth but disagrees (with Cairnes)

that the pattern is such as to prove that a steep geothermal gradient...."
existed. In the Sandon area, Hedley found no evidence for a temperature
control of mineral deposition, but found abundant evidence for structural
control.

Obvious structural controls of mineral deposition are fissures of sev-
eral types. Locations of ore shoots are controlled by the nature of fissures
and apparently by the nature of wallrock. Ore is not commonly found in
shear zones, but generally occurs in shattered zones and clean-cut fissures
in brittle rocks. Cross fractures are an important ore control, and ores
rarely occur in areas of extensive gouge (Hedley, 1952, p. 55).

A geological reconstruction of mineralization and structural deform-
ation of the Sandon area (Hedley, 1952) closely delimits the time of miner-
alization. Hedley showed that faults were initiated during the closing
period of folding. At least part of the mineralization is younger than
the Nelson batholith, and intrusion of the Nelson batholith post-dates a
major period of Mesozoic folding. As fissures would not persist long in the
incompetent Slocan sediments, mineralization must have been closely related
in time to late stages of folding, i.e. shortly after emplacement of the
Nelson batholith.

Victor Mine

The Victor mine is about 5 miles due east of New Denver, B. C., on the
northeastern slope of Idaho Peak, in Carpenter Creek valley. Ore occurs in
a fissure in incompetent quartzitic and limy slates of the Slocan series.

Fine-grained, porphyritic, pre-ore sills, locally termed "porphyry", are abundant. The fissure strikes southwest and dips 70 degrees southeast. Most of the fissure is a single "break", but in some places it "splits", and in other places is a highly jointed zone. The deposit is essentially a mineralized normal fault with apparent relative movement of the hanging wall and footwall of less than 10 feet (Sharp and Pedley, 1956), although several periods of displacement in various directions produced the present configuration. Width of mineralized parts of the fissure range from a fraction of an inch to about 8 feet. Galena, sphalerite, pyrite and tetrahedrite are the abundant ore minerals. Chalcopyrite and pyrrhotite are present locally in minor amounts. Gangue is mainly quartz and siderite with minor amounts of calcite.

Mineralization and movement along the fissure were contemporaneous. Veining relations observed underground indicate that ore-bearing fluids were introduced intermittently with renewed movements along the fissure. Movement continued after mineralization was completed producing gneissic and "steel" galena. Bedding faults offset the vein.

Metal distribution apparently is related to lode width. In general, galena is the dominant mineral in wide sections, and sphalerite is more abundant in narrow sections. Only one exception to the above relationship is known, the lower, eastern part of the mine has siderite vein-filling up to 7 feet in width. Silver occurs with galena. Recently Pedley (personal communcations, 1962) noted that silver is concentrated in the crestal zone of a major fold cut by the fissure.

The fissure is the essential ore control, but ore shoots within the fissure are localized in zones of steeply dipping, thin bedded argillites and quartzites, where the fissure was apparently deflected from its normal course. Steep dipping, favorable rocks commonly occur on the limbs of small folds cross-cut by the fissure.

Scranton Mine

The Scranton mine is in Kokanee Glacier Park, 11 1/2 miles by road, west from a point on the Nelson-Kaslo highway 8 miles south of Kaslo. Four showings, Pontiac, Sunset, Grandview and Sunrise, from east to west, occur along a northeast-trending fissure system over a distance of about 7,000 feet. Wallrock is the Nelson granite. Abundant minerals, in order of deposition, are quartz, pyrite, sphalerite and galena. Two veins were observed at the portal of the Scranton mine (Sunset showings); one consists of quartz and pyrite, and the other of quartz, pyrite, sphalerite and galena. Sulfides are coarse-grained, show "crustification banding" and some comb structure. Maximum width of veins is about 2 feet, although widths of a few inches or less are most common. Some silicification of wallrock has occurred. This deposit is typical of "dry" Slocan ores, and is commercially important for its gold and silver contents.

SALMO LEAD-ZINC CAMP

Several types of mineral deposits occur in the Salmo district:

1. Tungsten skarn deposits.

2. Lead-zinc fissure deposits with attendant replacement.

3. Lead-zinc replacement deposits in limestone (Salmo-type deposits).

Tungsten deposits are not considered here but they appear to be contact metasomatic deposits related to satellites of the Nelson batholith (Ball, 1954) and are younger than the lead-zinc mineralization. Fissure-controlled lead-zinc deposits are few in number and are not important economically.

Lead-zinc replacement deposits of the "Salmo-type" are the important ore deposits in the district. Numerous detailed accounts of the geology of individual deposits are available in the literature and will not be reviewed here. General characteristics of Salmo-type deposits, including Reeves Mac-donald mine, H. B. mine, Jersey mine and Jackpot showings, are discussed in the following pages.

General Characteristics of Salmo-type Deposits

Stratigraphic Environment

All producing lead-zinc deposits in the Salmo camp occur in the Reeves limestone of Lower Cambrian age. Most deposits occur near the base of the Reeves limestone, but at various stratigraphic horizons. Non-productive sulfide showings have been found in the Nelway formation (Middle Cambrian)

and also in the Active formation (Ordovician).

Structural Control of Sulfide Deposits

On a regional scale, Salmo-type orebodies are closely related to the
footwall side of the Argillite fault, a folded thrust fault with steep to
moderate easterly dips whose strike closely parallels the regional struct-
ural trend in the southern part of the arc. (Fyles and Hewlett, 1959, p.57).
A commonly held view among field geologists in the area is given by Warn-
ing's (1961) statement, "...that this (Argillite) fault has exerted a con-
trol on ore deposition."

Mineralized zones are closely related to Phase II folds. Ores at the
Reeves Macdonald mine are localized around the hinge of a tight anticline
overturned to the north (Pollock, 1961). At the H. B. mine sulfides are
related to shears and breccia zones superimposed on the Mine syncline, a
Phase I isoclinal fold with steeply dipping axial plane. Orebodies at the
Jersey mine are on the upper, warped limb of a large recumbent anticline
overturned to the west. Structural control of mineral deposits is further
emphasized by parallelism of elongate ore zones and major fold axes.

Some zones, such as the X-1 at the H. B. mine, are related to flat
fault breccias (Warning, 1961). At the Jersey mine (Fyles and Hewlett,
1959, p. 119) the A-zone is a mineralized flat-lying fault breccia. Smith
(1961) notes that F-zone sulfides at the Jersey mine appear "...to be con-
trolled in part by an involved system of near-bedding plane faults." An
illustration of "breccia ore" at the Jersey mine is given by Fyles and

Hewlett (1959, plate XVl).

Dolomite-Ore Association

A close spatial relationship exists between sulfide mineral deposits

and dolomite in the Salmo camp (cf. Hewett, 1928). The term "dolomite en-

velope" is commonly used to describe the relationship, but is not true in

the strictest sense because, in places such as the Reeves Macdonald mine,

sulfides extend outward from the dolomite zone into limestone (Pollock,

1961). Alternatively, in many places large areas of dolomite are unminer-

alized. Dolomite zones are normally many times the size of sulfide zones.

Two types of dolomite are distinguished:

1. textured dolomite (layered, mottled, etc.).

2. massive or poorly layered dolomite.

Generally, the two types form separate masses. All dolomite, with the ex-

ception of an insignificant quantity in minor late fractures, is very fine-

grained. Sulfides occur in textured dolomite.

Origin of the dolomite is controversial. Green (1954, p. 28) states

that much of the dolomite formed as a primary sediment or as a diagenetic

replacement of Reeves limestone. More recent work (Fyles and Hewlett,

1959) suggests that dolomite zones in the Reeves limestone are epigenetic

replacement. Positions of dolomite zones relative to the base of the Reeves

limestone vary. Fyles and Hewlett (1959, p. 86) state:

"On a local scale dolomite transgresses boundaries of
the Reeves member."

Dolomite formed prior to sulfides and both ore and dolomite are cut by granite and lamprophyre dikes. In places, such as at the Jackpot showing, the Hidden Creek stock (a possible satellite of the Nelson batholith) metamorphosed dolomite. Fyles and Hewlett (1959, p. 86) consider that regional relationship of dolomite zones and the argillite fault and general parallelism of dolomite zones with fold axes provide evidence of structural control of dolomitization.

Mineralogy

Salmo-type deposits contain simple sulfides — mainly pyrite, sphalerite and galena. Locally pyrrhotite is abundant. Some of the pyrrhotite, at Reeves Macdonald mine and Jersey F zone, for example, appears to be a product of thermal metamorphism of pyrite. Chalcopyrite is the only other sulfide identified by the writer, and occurs in negligible quantity, generally associated with either pyrrhotite or sphalerite.

Relative amounts of common sulfides vary considerably from one ore zone to another, and even within individual ore shoots, although no systematic zonal arrangement of sulfides has been recognized. At the Jersey mine, the lead:zinc ratio ranges from 1:1.1 in the G zone to about 1:6 in the E zone. The Jersey A zone has a lead:zinc ratio of 1:5 if the "footwall lead band", a layer of nearly pure galena about 1 foot thick, is not included. Inclusion of the "footwall lead band" in ratio calculations results in an overall lead:zinc ratio of 1:2 for the A zone (Smith, 1961). Fyles and Hewlett (1959, p. 82) state:

"Sphalerite is commonly the most abundant sulphide, but
in parts of the Jersey A orebody and in zones of breccia at the
H. B., galena is more abundant. In much of the ore at the H. B.
and in some at the Reeves Macdonald mine, pyrite is more abund-
ant than sphalerite."

Gangue is mainly dolomite, some calcite and a little quartz. At the

H. B. mine talc and tremolite occur in some of the ore zones. According to

Warning (1960)...

"Evidence from thin section study indicates that the tremo-
lite-talc.........is pre-ore, and that the presence of these in
altered zones was not necessary for the formation of ore."

In places at the Jackpot mine serpentine, diopside, tremolite and forsterite

are associated with sulfides.

Trace Element Data

Sphalerite varies in color from pale yellow to red-brown, and is gen-

erally low in iron except where thermally metamorphosed. Pale yellow sphal-

erite at the Reeves Macdonald mine contains about 0.1 percent iron; brown

sphalerite at Jersey mine contains from 2-10 percent iron (Fyles and Hewlett,

1959, p. 83).

Cadmium is a minor but persistent constituent of Salmo-type ores. It

probably occurs in solid solution in sphalerite. Cadmium:zinc ratios

(pounds per pound), calculated from production figures, are 0.59×10^{-3},

0.70×10^{-3} and 0.81×10^{-3} for Reeves Macdonald, Jersey and H. B. mines

respectively. No reason for the increase in Cd:Zn ratios from south to

north is apparent.

Eight galena specimens from replacement deposits in the Salmo camp

were analysed for the following trace elements: Bi, Sn, Cu, Tl, Ag, Sb, Cd,

Zn, Mo, Co, In, Au, Te, As, Ga, and Ge. Two of the galenas had been therm-

ally metamorphosed and have trace element contents notably different to the

remaining six specimens. Table V-1 gives the range of trace element con-

tents in six galenas, and specific values for the two thermally metamorph-

osed specimens (CX-42 and JP-7). The following elements were not detected

(detection limits given in brackets): In (1 ppm), Au (10 ppm), Te (100 ppm),

As (10 ppm), Ga (1 ppm) and Ge (1 ppm). From a consideration of data in

Table V-1, these points are considered significant:

1. The strongly chalcophile element copper is present much
   below its average crustal abundance of 45 ppm.

2. Tin is present in only slightly greater amounts than its
   average crustal abundance despite the Kootenay arc being
   part of a tin metallogenetic province (cf. Warren and
   Thompson, 1945; Lang, 1961).

3. Silver is present in sufficiently low abundances that it
   could occur entirely in solid solution in galena.

4. High abundance of thallium in some galenas (crustal abund-
   ance of thallium is less than 1 ppm).

5. Antimony has from 1.5 to 2 times the atomic abundance of
   silver in the same galena specimen (for unmetamorphosed
   specimens).

A more detailed discussion of trace elements in Kootenay arc galenas is

given in Appendix III.

Evidence of Late Movement of Sulfides and Gangue

White (1950, p. A174) and Green (1954, p. 15) describe coarsely crys-

talline veinlets containing dolomite, calcite, quartz and small amounts of

Table V-1:   Quantitative trace element data for galenas from
replacement deposits in the Salmo district.

Element	Detection Limit ppm	Six Galenas		CX-42 ppm	JP-7 ppm
		No. of galenas in which element not found	Range of concentrations where found		
Bi	1	4	15- 25 ppm	1400	60
Sn	1	2	5- 35 ppm	200	60
Cu	0.1	0	0.3- 13 ppm	500	217
Tl	1	3	9-140 ppm	7	150
Ag	0.1	0	5-700 ppm	3000	340
Sb	5	1	87-780 ppm	36	3230
Cd	5	0	93-490 ppm	93	87
Zn	5	0	.011%-6.0%	.06%	N. D.*
Mo	0.1	6	--	250	N. D.*
Co	0.5	5	0.5 ppm	0.7	N. D.*

*   (N. D.)   not detected.

Quantitative spectrographic analyses. Analyst: R. Hibberson, B. C.
Dept. of Mines and Petroleum Resources.

sulfides, that occur in fractures cross-cutting structures and ores in the
Salmo camp. The writer has observed late veinlets at Reeves Macdonald and
Jersey mines, and suggests that they might have formed in connection with
a rise in temperature that probably accompanied emplacement of granitic
bodies.

Age of Mineralization

Salmo-type deposits have been shown to post-date dolomitization (Fyles
and Hewlett, 1959, p. 86) and evidence has been put forward previously to
suggest that dolomitization was a structurally controlled epigenetic pro-
cess. If the foregoing interpretation of origin of dolomite is correct,
dolomitization was either a syn-orogenic or post-orogenic process. The
time of Phase I deformation in the Salmo district is not known precisely
but is probably not older than mid-Paleozoic. Phase II folds deform the
Triassic Slocan series, and are in turn cut by the Nelson batholith. Hence,
Phase II folds were formed during mid-Mesozoic, probably Lower Jurassic.

Salmo-type deposits are spatially related to Phase II structures.
Mineralographic evidence (Appendix IV) from Jersey and Duncan mines indic-
ates that pyrite, the earliest mineral deposited was, in places, fractured
prior to deposition of sphalerite and galena. Therefore, mineralization
may have occurred during a late stage of development of Phase II folds
and can be dated tentatively as Lower or Middle Jurassic.

White (1961) mapped the Jackpot showings and concluded that mineral
deposition preceded intrusion of the Hidden Creek stock. At the Jersey
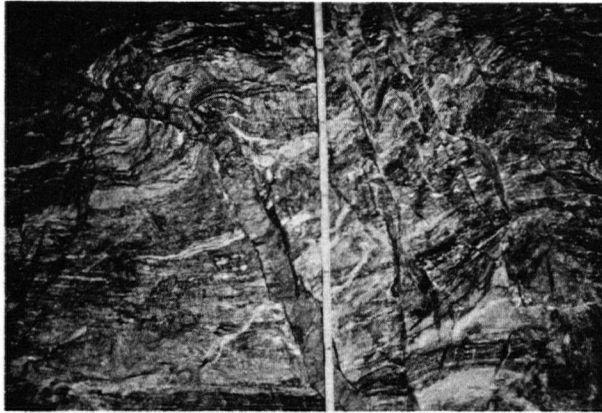
FIG. V-2: Granite dike cutting and including layered sphalerite-
dolomite ore, Jersey E zone. Maximum width of dike is
3 inches. Photo courtesy of T. S. Smith.

mine Rennie and Smith (1957, p. 122) report that two granite dikes cut the E ore zone. One of these dikes, examined by the writer, contain an angular inclusion of sphalerite-bearing dolomite (Figure V-2) similar to the ore zone adjoining the dike. Fyles (personal communications) who mapped surface exposures of the Emerald stock (at the Jersey mine) found some dikes were apophyses of the stock. No dikes have been found that cut the stock. Therefore it is likely that the dikes that cut ore in the Jersey mine are contemporaneous with the Emerald stock. The age of the Emerald stock is unknown, but it is thought to be slightly younger than, and genetically related to, the Nelson batholith. Hence a minimum age of mineral deposition is about 170 m.y., the approximate age of the Nelson batholith.

CHAPTER VI

EXPERIMENTAL PROCEDURE AND RESULTS

Choice of Specimens for Lead Isotope Analyses

The purpose of this investigation was to determine as precisely as possible the isotopic compositions of lead in galenas from the Kootenay arc, and to explain these results in terms of the geologic history of the arc. Lead showings are abundant in the arc and there was little difficulty in obtaining galena specimens from several mining camps (see Figure III-1).

Deposits in the Salmo camp were particularly easy to study because most are in production and have extensive, accessible workings, the geology of which is reasonably well understood. In addition to specimens of galena representative of the major replacement deposits of Salmo-type, certain galena specimens were obtained that illustrated the occurrence of that mineral in special associations, viz:

1. veinlets of "remobilized" sulfides and gangue (RM-1);

2. metamorphosed galena ore at the contact of a lamprophyre dike (CX-11); and

3. metamorphosed galena ore at the contact of a granite dike (CX-42).

Two galena specimens from showings in the Shuswap terrane were analysed. Although Salmo-type deposits were studied in greatest detail, other deposits in rocks of different lithologies and possible ages are included in the investigation.

After the first twelve isotope analyses of Kootenay arc galenas had

been made and results plotted, it became necessary to analyse galena from

the Sullivan mine in the East Kootenay district. Two galenas were taken

from mineralogical collections of Sullivan ore in the Department of Geology,

University of British Columbia. Previous isotope investigations by the

Geological Survey of Canada and the University of Toronto, that indicated a

uniform isotopic composition for Sullivan lead, justified use of museum

specimens.

Apart from Sullivan galenas, specimens were collected specifically for

this investigation by either the writer or J. T. Fyles from all active and

some inactive mining operations along the arc. These specimens are believed

to be representative of their respective mineral deposits. A description of

specimens analysed isotopically is given in Appendix V.

Method of Investigation

Specimens were examined in polished sections to determine

1. position or positions of galena in the paragenetic
   sequence, and

2. effect of contact metamorphism on certain specimens
   of sulfides.

From microscopic examination of about 150 polished sections it was evident

that in every deposit galena occurs at only one place in the paragenetic

sequence. In all deposits this sequence was:

Pyrite (and/or pyrrhotite)—Sphalerite—Galena

Field studies suggest that galena in veinlets that cut replacement deposits in Salmo camp has been "remobilized" by subsequent igneous activity and does not constitute a later stage of lead mineralization (Chapter V). A detailed mineralography of Salmo-type ores is given in Appendix V.

Most galena was separated as cleavage fragments and finely ground in an agate mortar. Where sulfides were fine-grained and intimately intergrown, mixed sulfides were pulverized. The sulfides were treated with HCl and KI to form lead iodide which in turn was transformed to tetramethyl lead by reaction with methyl magnesian bromide (Grignard reagent). The resulting solution of tetramethyl lead in ether was further purified by a gas chromatographic technique (Ulrych, 1960). A more detailed discussion of chemical preparation of samples for mass spectrometric analyses is given in Appendix VI.

Lead tetramethyl was analysed isotopically on a 90° sector, 12 inch radius, direction focussing mass spectrometer constructed in the Geophysical Laboratory of the University of British Columbia (Kollar, 1960).

The first sixteen analyses when plotted on a Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204} graph, had a linear trend that probably included an anomalous lead line. Because the points were scattered and the anomalous lead line comparatively short, its slope was poorly defined. Consequently it was decided to make precise intercomparison analyses of specimens at various points along the linear trend. Provided contamination between samples can be avoided, the intercomparison technique will give a precision of about 0.1 percent. Previously, R. G. Ostic and E. R. Kanasewich had attempted intercomparison analyses of ordinary leads of widely different compositions,

and showed that with extreme care memory effects of preceding samples in the
mass spectrometer could be eliminated. This is the first intercomparison
study of an anomalous lead suite.

Intercomparison Technique of Mass Spectrometry

An intercomparison loop, shown diagrammatically below, allows the
analysis of two lead tetramethyl samples every 3 days.
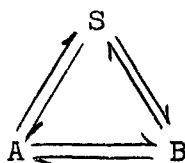
Samples are analysed according to the following pattern:

First day	AAAA	SSSSSSS	AAAA
Second day	SSSS	BBBBBBB	SSSS
Third day	BBBB	AAAAAAA	BBBB

Each capital letter represents an up-mass and a down-mass scan of the lead
trimethyl spectrum. Three analyses are carried out each day, one sample
being analysed twice, at the beginning and end of the day. From the re-
sults of the first day, sample S (standard) is compared with sample A.
Similarly, on the second day B is compared with S, and on the third day
A is compared with B. The result of analyses over a 3-day period is a set
of differences between isotopic ratios of samples A, B and the Standard.
Details of the calculations are given in Appendix VII. Ideally the differ-
ences obtained should sum to zero. In practice an error is obtained that

is distributed evenly over analyses for the three days. This "loop closure error" shows that short term mass spectrometer variations of measured peaks are not linear with time. Distribution of the loop closure error around the loop partly offsets the effect of non-linear variation. As loop closure errors are generally less than one tenth of one percent of the isotope ratios involved, no great bias can result from the equal distribution of error over the entire loop.

The standard S, for the U. B. C. laboratory is Broken Hill No. 1 or another sample that has been intercompared with Broken Hill No. 1. Intercompared analyses are probably within 0.1 percent of their correct positions relative to the standard sample. The accuracy of their compositions is deemed good because the fixed composition of the Broken Hill standard is the mean of numerous U. B. C. analyses, and is close to the mean of analyses by other laboratories (Russell, 1963, p. 49).

A possible source of error in the intercomparison method is contamination of a sample by the previous sample analysed. In this work the technique used to minimize contamination was as follows:

1. Sample A was recovered from the mass spectrometer in a breakseal tube by vacuum distillation and the mass spectrometer was pumped out for one-half hour.

2. A split of Sample B, the new sample to be analysed, was introduced into the mass spectrometer and left for one-half hour to "contaminate" the mass spectrometer with the new sample to be analysed.

3. Sample B was pumped from the mass spectrometer and a new split of the sample was introduced for analyses.

The procedure is time-consuming but apparently effective in eliminating cross-contamination of samples. When samples were analysed before and

TABLE VI-1:   Kootenay Arc Lead Isotope Results

No.	Mine	Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}
*282	Duncan Lake	19.563	15.949	40.425
*284	Jackpot	19.140	15.891	39.728
*286	HB Mine	19.289	15.947	40.081
*288	Jersey Mine	19.281	15.938	40.006
*291	Sal A Zone	19.537	15.942	40.307
*293	Reeves Macdonald	19.199	15.913	39.869
*300	Jersey Mine	19.273	15.923	40.027
*318	Mollie Mac	18.497	15.839	38.844
*321	Sullivan Mine	16.632	15.643	36.599
*323	Sullivan Mine	16.633	15.633	36.555
**283	Jersey Mine	19.310	15.937	40.106
**317	Moonshine	19.384	15.888	40.062
182	Lakeshore	17.803	15.727	38.919
237	Bluebell	17.743	15.728	38.608
285	Reeves Macdonald	19.248	15.911	39.943
287	Jersey Mine	19.271	15.933	40.012
289	Cottonbelt	18.610	15.869	38.838
290	Wigwam	18.403	15.826	38.749
292	Ruddock Creek	18.651	15.832	38.573
294	Victor Mine	18.954	15.884	39.725
295	Scranton Mine	19.062	15.901	39.568

*   Precise intercomparison analysis

** Intercomparison analysis without loop closure

after a sample of notably different composition, the analyses were ident-
ical within normal limits of error.

Experimental Results

Measured lead isotope abundances are listed in Table VI-1. Precision
is about 0.1 percent (standard deviation) for precise intercomparison anal-
yses, about 0.2 percent for intercomparison analyses without loop closure
errors, and about 0.3 percent for non-intercompared results.

Figure VI-1 illustrates variations in measured isotopic compositions
of two specimens analysed several times over a period of about one month
(Table VI-2). The range of measured ratios is about 0.1 percent. Apparent
variations in isotopic ratios with time are the result of instability of
the mass spectrometer, possible cross-contamination of specimens, and error
in peak measurement of trimethyl spectra. The small magnitude of composit-
ional variations shows that these sources of error are slight.
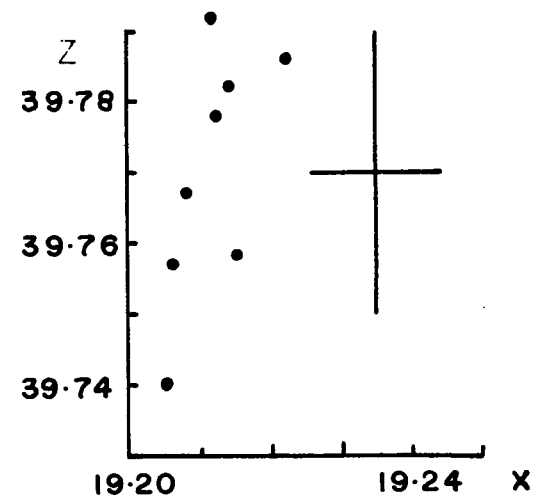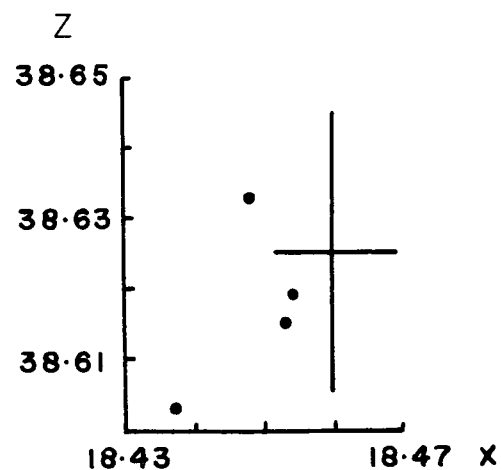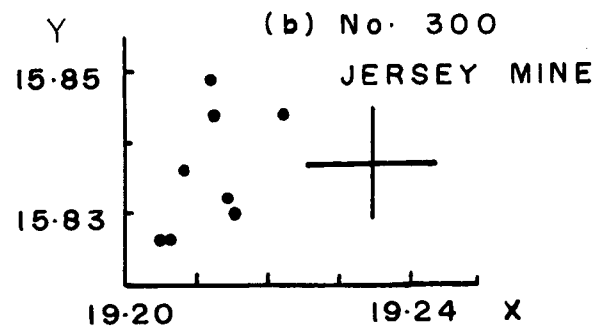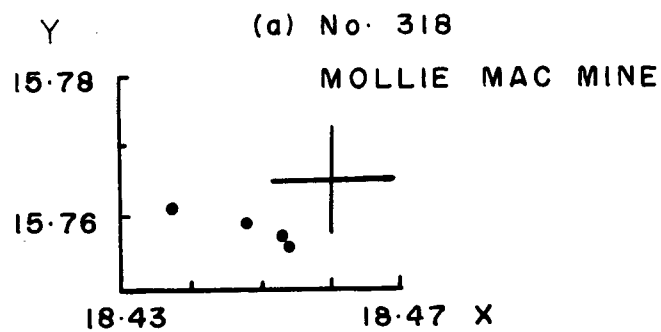
FIGURE VI-1: REPRODUCIBILITY OF ISOTOPE ANALYSES (CROSS REPRESENTS VARIATION OF 0.1 PERCENT)

Table VI-2:   Replicate analyses of two galena specimens
              showing variations in measured isotope
              ratios during September, 1962.

	Date	x	y	z
Specimen 300 Jersey Mine				
	~~September~~			
	Sept. 10, 1962	19.208	15.836	39.767
	Sept. 11, 1962	19.212	15.844	39.778
	Sept. 12, 1962	19.205	15.826	39.740
	Sept. 14, 1962	19.214	15.832	39.782
	Sept. 15, 1962	19.206	15.826	39.757
	Sept. 16, 1962	19.215	15.830	39.758
	Sept. 18, 1962	19.212	15.849	39.792
	Sept. 19, 1962	19.222	15.845	39.786
Specimen 318 Mollie Mac Mine				
	Sept. 18, 1962	18.437	15.761	38.603
	Sept. 20, 1962	18.448	15.759	38.633
	Sept. 21, 1962	18.454	15.756	38.619
	Sept. 22, 1962	18.453	15.757	38.615

CHAPTER VII

INTERPRETATION OF KOOTENAY ARC LEAD DATA

INTRODUCTION

Previous Kootenay Arc Lead Isotope Data

Prior to the author's study most available lead isotope analyses reported for Kootenay arc galenas had been done at the University of Toronto as part of a study of lead-bearing deposits in Canada. Early results (Russell and Farquhar, 1960; Farquhar, personal communications) are shown on a Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204} graph (Figure VII-1). Also plotted on Figure VII-1 are Toronto analyses of lead from Sullivan mine in East Kootenay district, and Minnesota and Lamont analyses of lead from Metaline district in northeastern Washington. The variation of isotopic compositions indicates that the leads are anomalous, but the scatter of compositions is too great for meaningful mathematical treatment.

More lead isotope data are available for Bluebell mine than for any other deposit in the arc. Kanasewich (1962, p. 104-110) shows that the apparent wide range of lead isotopic compositions of galena from the Bluebell mine are grouped closely about a line passing through the origin of the coordinate system (Figure VII-1). Such a line commonly indicates error in Pb^{204} measurement and is referred to as an error line. Recent unpublished analyses by Kanasewich show that Bluebell lead has a fairly
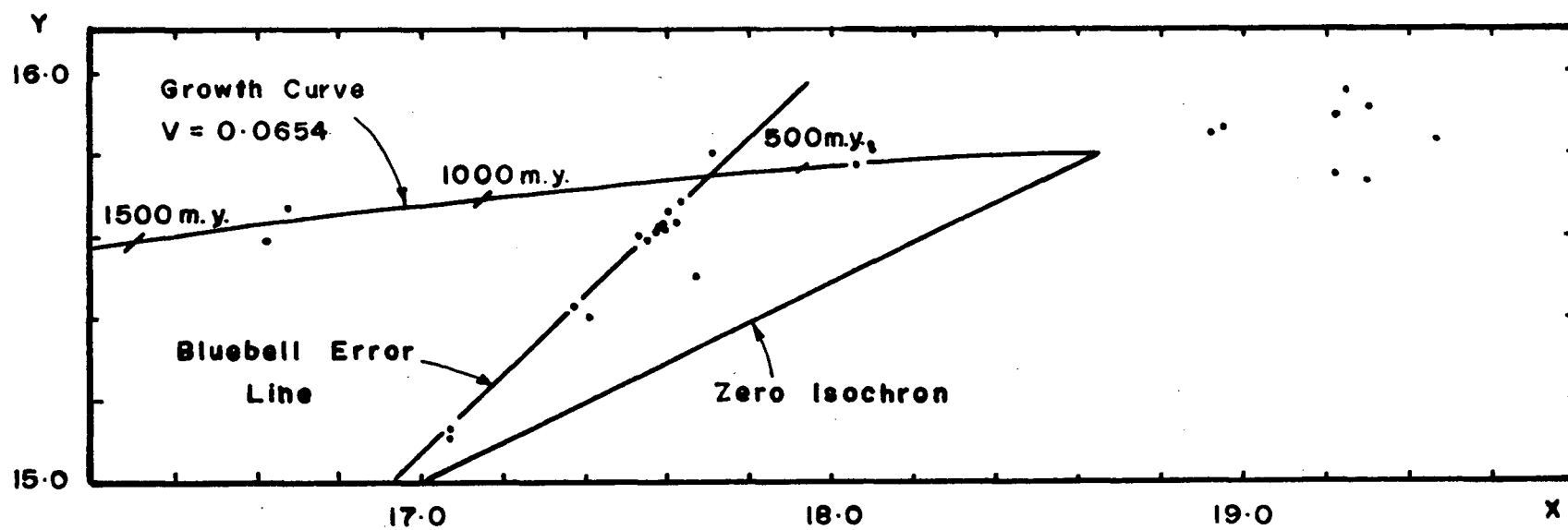
FIGURE VII-1: PREVIOUS LEAD ISOTOPE DATA FOR THE KOOTENAY ARC

uniform composition with a slight spread along an anomalous lead line. These latest results imply that some of the scatter of other early analyses is the result of measurement error of Pb^{204}.

East Kootenay Anomalous Leads

Figure VII-2 is a Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204} graph illustrating anomalous lead data from East Kootenay district, and the mean isotopic composition of 27 analyses of lead from the Sullivan mine (Leech and Wanless, 1962). Compositional distribution of anomalous lead data (Figure VII-2) and Sullivan lead data (Figure VII-7) indicate considerable Pb^{204} error. Leech and Wanless (1962, p. 268) treat East Kootenay data according to the Russell-Farquhar anomalous lead model but reject the model because:

1. plotted analyses are "non-linear", and,

2. a calculated least squares line does not pass through the composition of Sullivan lead.

In view of the possibility of Pb^{204} error these are not adequate reasons for rejecting the Russell-Farquhar anomalous lead model. Intercomparison analyses of 5 or 6 East Kootenay anomalous leads of different compositions would test for existence of an anomalous lead line.

U. B. C. Kootenay Arc Lead Data

U. B. C. lead isotope analyses of Kootenay arc and Sullivan galenas are plotted in Figure VII-3. A linear pattern is apparent in the diagram.
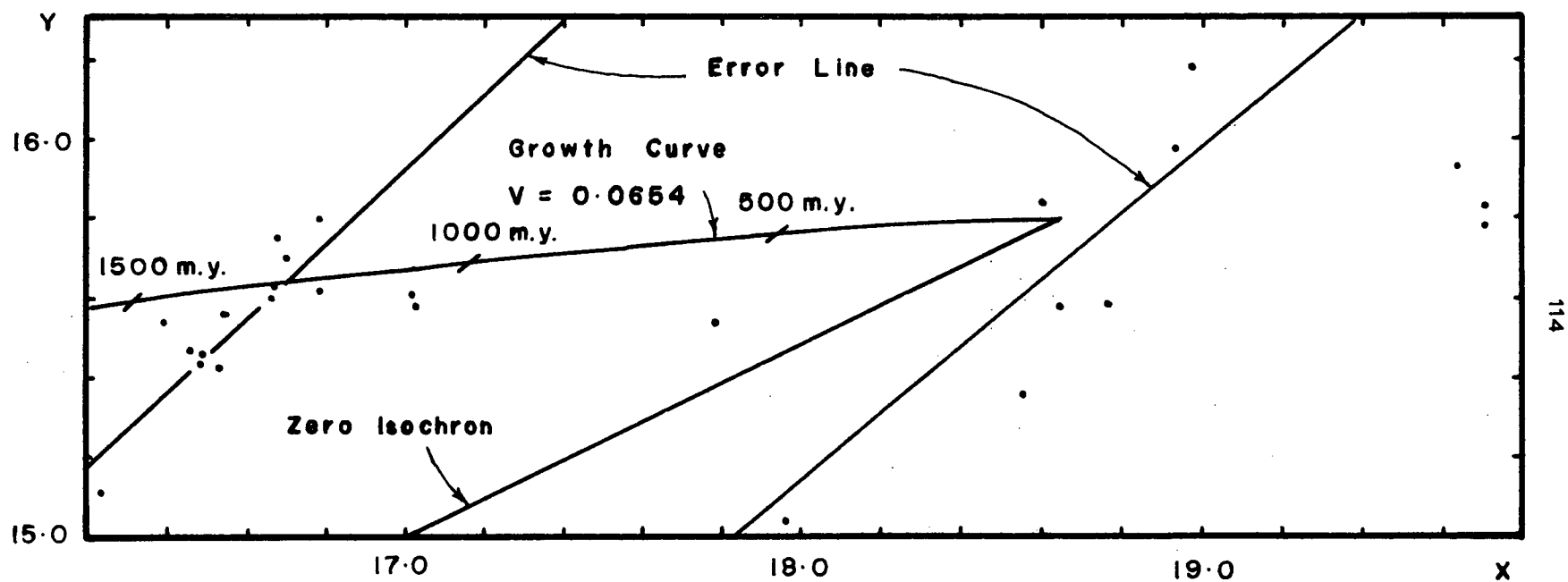
FIGURE VII-2: LEAD ISOTOPE DATA FOR EAST KOOTENAY DISTRICT
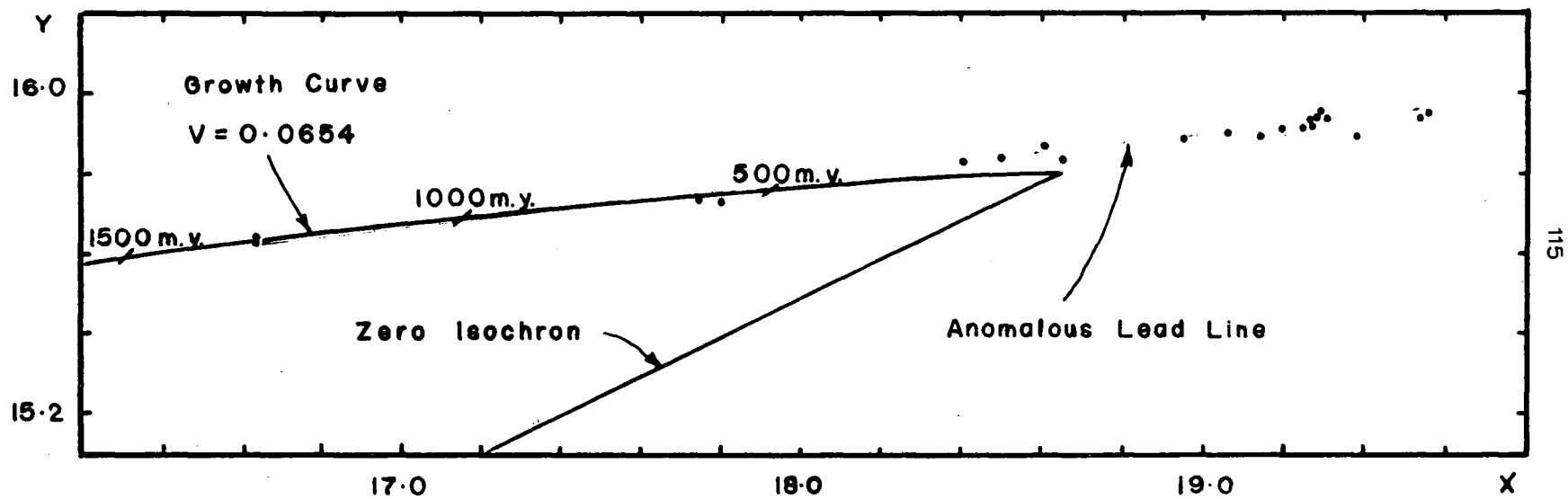
FIGURE VII-3: U.B.C. LEAD ISOTOPE DATA FOR THE KOOTENAY ARC

Slopes of least squares lines through the data have been calculated in two

ways to test the hypothesis that Sullivan lead plots on the Kootenay arc

anomalous lead line:

1. West Kootenay and Sullivan data treated together -- inter-
   comparison results with loop closures, intercomparison re-
   sults without loop closures, and non-intercomparison results
   given relative weights of 3, 2 and 1 respectively. Slope is
   0.1084 ± 0.0026. The same slope is obtained using inter-
   comparison data only.

2. Data were treated as in (1) above, except that Sullivan
   analyses were not included in the calculations. Slope is
   0.1174 ± 0.0062.

Both slopes were calculated by diagonal linear regression (Kanasewich, 1962b)

and lines were forced through centroids of the two sets of data. Because

the two slopes differ only by the sum of their respective standard deviat-

ions there is no reason to suppose that the slopes are different. Data are

compatible with the assumption that Sullivan lead plots on the Kootenay arc

anomalous lead line and the best estimate of slope is 0.1084 ± 0.0026. In

view of these data the writer feels that the much younger anomalous leads

of the Kootenay arc are in part derived from much older lead having the

Sullivan isotopic composition.

Interpretations that follow are based on the assumption that Kootenay

arc leads are mixtures of lead of composition similar to that in the Sullivan

mine (Sullivan-type lead) and a radiogenic component. This assumption is

supported by similarities in metal content of Kootenay arc lead-zinc depos-

its and deposits of the Sullivan-type. Geochemical similarities of the two

groups of deposits include:

1. Major metallic elements are lead, zinc and iron.

2. Deposits are strongly deficient in copper.

3. Silver is the only important precious metal.

4. High tin content of the ores was first recognized by Warren and Thompson (1945). Lang (1961) considers the Kootenay arc and East Kootenay district a tin metallogenetic province.

5. Thallium is commonly present in much greater concentrations than its mean crustal abundance (0.3 ppm).

The close fit of all leads analysed isotopically to a single anomalous lead line indicates that lead deposition throughout the arc occurred during a fairly short time interval. Precision of slope determination for the anomalous lead line gives a probable maximum time interval for mineralization in the arc of about 150 m.y. Maximum age of veins in the Slocan camp is 170 m.y. (Chapter IV). Hence, earliest probable time of lead mineralization in the arc is (170 + 150) 320 m.y. ago or, during Mississippian time. Some mineral deposits can be shown to have a much younger age, about Middle Mesozoic. However, there is little geological evidence to indicate age of deposition of Salmo-type replacement deposits, and here the 320 m.y. age limit may be significant. Salmo-type lead-zinc deposits occur in Lower Cambrian limestone so that a maximum age of deposition of 320 m.y. rules out a simple syngenetic origin.

Leads from several host rocks were analysed to test for possible correlation of lead isotopic composition and host rock. Those leads whose wallrock is Badshot formation, have a wide range of compositions. For example, leads from Bluebell and Duncan Lake deposits have the most dissimilar common lead isotopic compositions known in the Kootenay arc. Leads with Mesozoic

wallrock (Slocan series and Nelson batholith) have compositions similar to
lead of Salmo deposits. Leads from Shuswap rocks and the Mollie Mac lime-
stone have compositions approximately midway between Bluebell and Duncan
Lake leads. Judging from the wide range of isotopic compositions of leads
in the Badshot formation, and the variety of compositions within this range
of leads from other host rocks, there seems to be no apparent relation be-
tween wallrock and lead isotopic composition of galena.

Galenas from two geologically distinct types of deposits were studied:

1. deposits characterized by evidence of open space filling,
   with or without appreciable evidence of replacement, and

2. replacement deposits with little evidence of open space
   filling.

Galena from these two types of deposits have very different minor element
abundances (Appendix III). Leads from the two groups of deposits also have
overlapping ranges of isotopic compositions, and there seems to be no de-
finite relationship between geological nature and lead isotopic composition
of a deposit.

Lead isotope analyses of galenas from three deposits in the Shuswap terr-
ane plot on the Kootenay arc anomalous lead line. Single galena specimens
from Cotton Belt and Ruddock Creek showings were analysed in duplicate by
the writer (Table VI-1). R.M. Farquhar of the University of Toronto kindly
supplied 3 unpublished analyses of galenas from the River Jordan deposit
(see Riley, 1961). These results agree so well with Kootenay arc lead data
as to suggest similar histories for Kootenay arc and Shuswap deposits. This
implies that leads in both geological environments were derived from similar

source rocks and consist of similar components. Consequently, Sullivan-type lead may have had a widespread distribution, although not necessarily in ore-grade concentrations; and source rocks, probably Lower Purcell strata or rocks similar to those of the Churchill geological province of the Canadian shield (discussed in a later section), underlie the area containing Shuswap rocks. Little detailed information is available on Shuswap deposits and so few lead isotope data are available that it is dangerous to draw definite conclusions. Shuswap leads warrant further investigation.

Two specimens of thermally metamorphosed galena (CX-42 and CX-11) were analysed to test whether or not lead isotopic compositions were changed dur-ing metamorphism. Specimen CX-11 is coarse-grained galena from an aureole 1-2 inches wide at the contact of a lamprophyre dike. A few inches from the dike galena is fine-grained, and concentrated in layers in fine-grained dol-omite. Near the dike dolomite has a granular texture and coarse-grained galena occurs in anastomosing veinlets. Speciman CX-42 is a contorted mass of sulfides made up of monominerallic layers of galena, pyrrhotite and sphalerite, less than one foot from a 40-foot wide vertical granite dike in the Jersey E zone. Sulfides are cut by thin calcite-quartz veinlets with irregular bleached zones due to carbonatization of diopside in the green host rock. Both specimens of thermally metamorphosed galena have lead iso-topic compositions identical to two other galenas from Jersey mine (Table VI-1). Hence, metamorphism and hydrothermal alteration have not signif-icantly affected lead isotopic compositions of galena in the Jersey mine.

Thin fracture fillings that cross-cut layering in dolomite and small

tabular masses of coarse-grained gangue and sulfides are common in Reeves

Macdonald mine. These are thought to have formed later than the main sul-

fide mass during a period of granite intrusion. Fractures are discontinuous

and it seems unlikely that sulfides and gangue could have been derived from

a distant source. Hence, it is possible that material in these veinlets

and masses has been derived from the immediate vicinity of the veins and

may represent pre-existing ore material that was remobilized. To test this

possibility lead from a small dilation veinlet containing coarse-grained

calcite, quartz, and galena (RM-1) was analysed for comparison with typical

Reeves Macdonald lead (RM-5). The two analyses of lead are nearly ident-

ical and support the view that lead in veinlets was derived from fine-

grained ore by remobilization without contamination by lead of a different

composition.

HOLMES-HOUTERMANS INTERPRETATION

Holmes-Houtermans model assumes that leads can be dated using single-

stage equations, regardless of the history of a lead deposit, providing

only that a positive model age is obtained. Model ages for Kootenay arc

leads, calculated by the Holmes-Houtermans equation, are listed in Table

VII-1. The wide range of model ages for deposits formed at approximately

the same time (Middle to Late Mesozoic) implies that the Holmes-Houtermans

model is not applicable to Kootenay arc leads. The fact that a linear

relationship exists between model age and V must be considered coincidental

Table VII-1: Model age and geochemical nature of source rocks
of Kootenay arc leads interpreted according to
the Holmes-Houtermans model.

No.	Mine or Showing	Holmes-Houter-mans model age	Apparent Values		
			V	W	Th/U
282	Duncan Lake	-503 m.y.	.0668	38.31	4.13
283	Jersey	-317	.0667	38.42	4.15
284	Jackpot	-247	.0662	37.50	4.08
285	Reeves Macdonald	-305	.0664	37.90	4.11
286	HB	-287	.0669	38.54	4.15
287	Jersey	-292	.0667	38.25	4.13
288	Jersey	-293	.0668	39.22	4.12
289	Cotton Belt	136	.0663	36.79	4.00
290	Wigwam	240	.0658	37.22	4.07
291	Sal A	-492	.0667	37.96	4.10
292	Ruddock Creek	57	.0657	35.16	3.85
293	Reeves Macdonald	-263	.0665	37.92	4.11
294	Victor	-110	.0662	38.46	4.18
295	Scranton	-172	.0664	37.42	4.06
300	Jersey	-308	.0666	38.19	4.13
317	Moonshine	-447	.0661	37.38	4.08
318	Mollie Mac	184	.0659	37.18	4.06
182	Lakeshore	574	.0650	40.78	4.52
237	Bluebell	620	.0651	39.82	4.41

if the Holmes-Houtermans interpretation is accepted. If those leads with negative model ages are anomalous there appears to be no justification for excluding linearly-related compositions with positive model ages from the anomalous category.

Bluebell lead has a model age of 620 m.y. and if, as seems likely, mineral deposition post-dated Mesozoic metamorphism and deformation, the deposit could be considered a B-type lead. Kootenay arc leads support a suggestion made previously (Chapter III) that a complete gradation can exist between B-type and J-type leads, and that a distinction between the two types is arbitrary.

KANASEWICH MULTI-STAGE INTERPRETATION

According to the Kanasewich model ordinary lead, uranium and thorium mineralization are assumed to have occurred contemporaneously at a time approximated by the ordinary lead model age. Sullivan lead appears to be ordinary (see later section) and has a model age of 1340 m.y. Using this model age and the slope estimate of the anomalous lead line, an age of 730 $\pm$ 75 m.y. is calculated for the time of anomalous lead mineralization. However, many of the lead-zinc deposits in the Kootenay arc are of Mesozoic age. Consequently, the two-stage interpretation assumed in the above calculation must be extended to a 3-stage model, the last stage of which requires an uranium-thorium-free environment (Figure VII-4). A postulated 3-stage history is summarized as follows:

FIGURE VII - 4:

KOOTENAY ARC LEAD HISTORY -

KANASEWICH MULTI-STAGE MODEL

Remobilization and
redeposition of
anomalous leads

170 m.y.

Stage 3
U - Th - free

Anomalous lead

mineralization

730 m. y.

Stage 2
Radiogenic
component

t_o = 4550 m. y.

1340 m.y.

Stage 1: Ordinary lead develops

Ordinary lead
mineralization

4500   4000   3500   3000   2500   2000   1500   1000   500   0

AGE (m. y.)
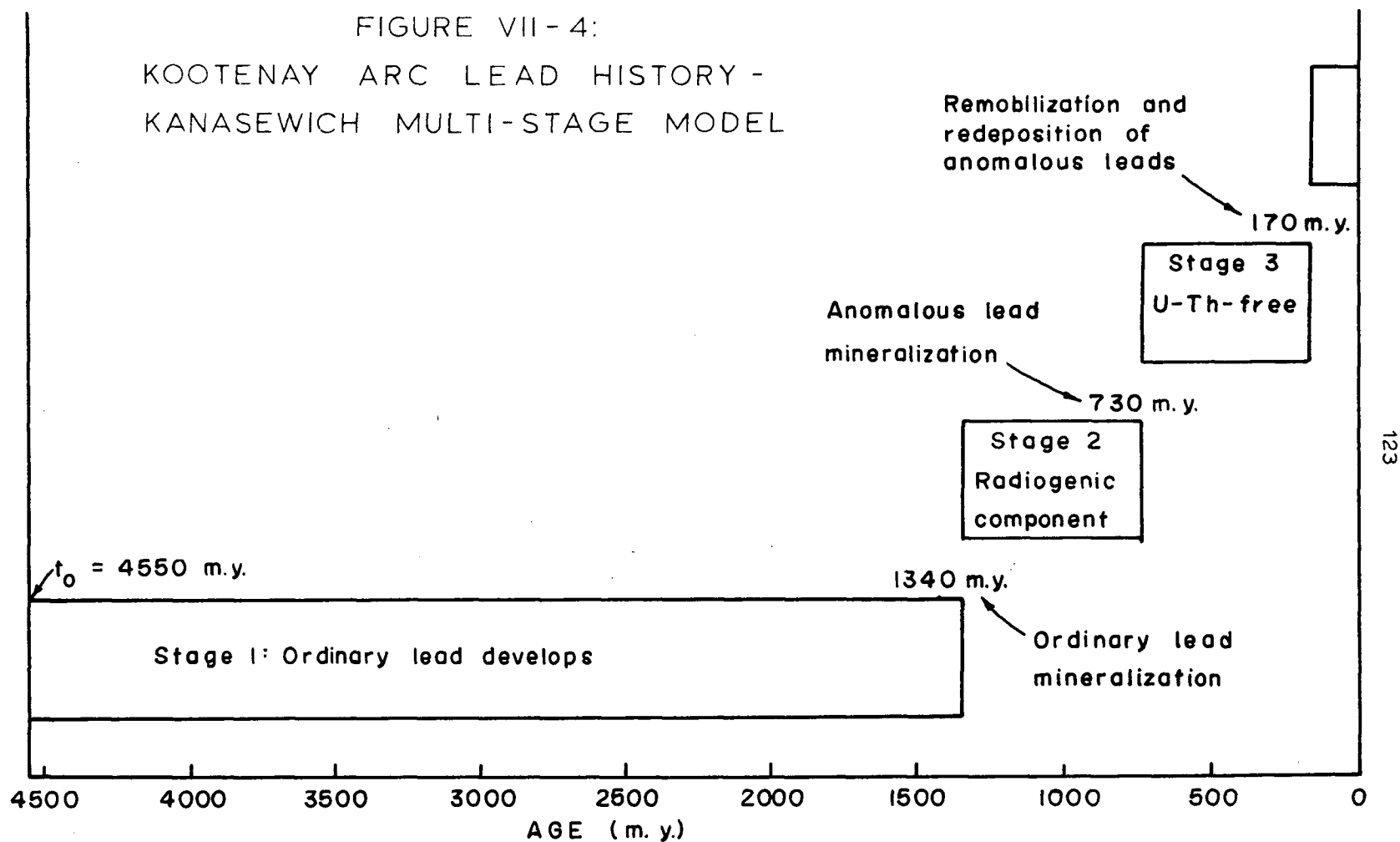
1. Ordinary lead, uranium and thorium mineralization 1340 m.y. ago.

2. Anomalous lead mineralization 730 $\pm$ 75 m.y. ago in a uranium-thorium-free environment.

3. Remobilization and redeposition of lead during Mesozoic Era without addition of lead of a different composition.

There are several problems with this interpretation. There is no evidence to support the assumption that ordinary lead, uranium and thorium were emplaced contemporaneously. The third stage of the model requires a uranium-thorium-free environment, present along the entire length of the arc, that contained anomalous leads for more than 500 m.y. Cambrian limestones could have been the uranium-thorium-free environment except that they seem too young. Furthermore, limestones normally contain appreciable uranium and thorium. Turekian and Wedepohl (1961) give mean U and Th contents of limestone of 2.2 and 1.7 ppm respectively. A discussion in Appendix VIII indicates that mean crustal abundances of uranium and thorium are sufficient to produce more than enough radiogenic lead to change appreciably in 500 m.y. the isotopic composition of common lead in sediments. If Cambrian limestones were free of uranium and thorium a difficulty arises in remobilizing their contained common lead without contamination by radiogenic lead in enclosing quartzites and phyllites. The writer concludes that the 3-stage lead model outlined above is not applicable to Kootenay arc leads.

RUSSELL-FARQUHAR ANOMALOUS LEAD INTERPRETATION

The Russell-Farquhar anomalous lead model provides a maximum possible age of anomalous lead mineralization, and information concerning source rocks of the radiogenic component of an anomalous lead suite. Using a slope of 0.1084 for Kootenay arc anomalous lead line the following results are calculated:

1. oldest possible age of anomalous lead mineralization is 1050 m.y.

2. maximum age of emplacement of uranium and thorium that produced the radiogenic component of Kootenay arc anomalous leads is 1800 ± 45 m.y.

The maximum possible age calculated for anomalous lead mineralization is not particularly useful because: (a) mineral deposits occur in Cambrian or younger rocks, and (b) geological information indicates that most sulfide deposits in the Kootenay arc formed during the Mesozoic Era. Maximum age of uranium emplacement is meaningful because small changes from zero age, of time of anomalous lead mineralization, will not greatly affect the calculated time of uranium emplacement.

The slope of a least squares line through Kootenay arc lead data plotted on a Pb^{208}/Pb^{204} versus Pb^{206}/Pb^{204} graph (Figure VII-6) is 1.287 ± 0.033 from which a Th^{232}/U^{238} ratio of 3.8 is calculated for the source rocks of the radiogenic component (Appendix I).

FIGURE VII - 5:

KOOTENAY ARC LEAD HISTORY -

RUSSELL - FARQUHAR ANOMALOUS LEAD MODEL

Maximum age of
U - Th emplacement

1800 m.y.

1050 m.y.

Maximum age of
anomalous lead
mineralization

t_0 = 4550 m.y.

1340 m.y.

Ordinary lead develops

Ordinary lead
mineralization

AGE (m.y.)

Anomalous Lead Line

Sullivan
Lead

KOOTENAY ARC LEAD DATA
Pb^{206}/Pb^{204} VS. Pb^{208}/Pb^{204} GRAPH

FIGURE VII - 6
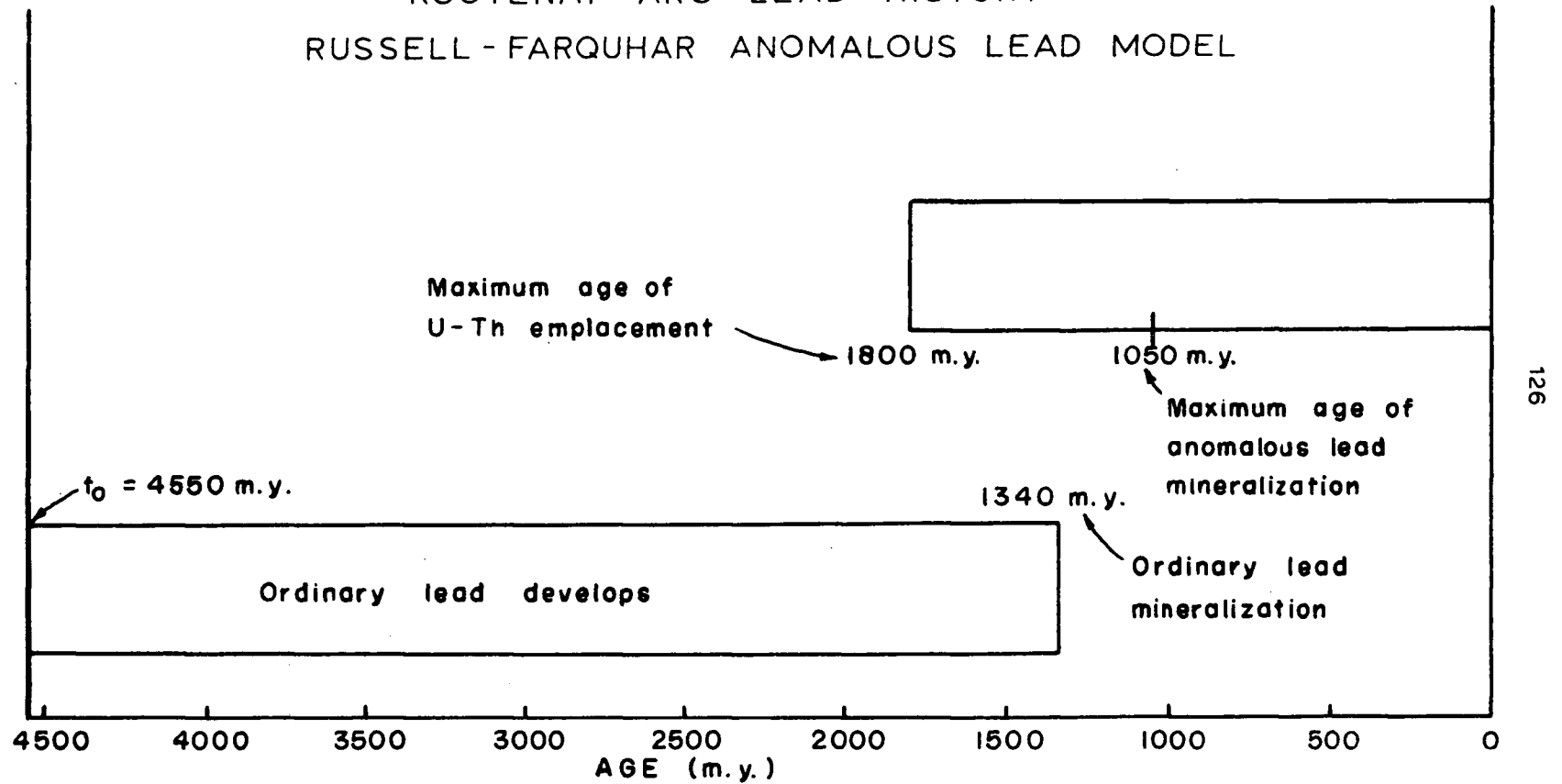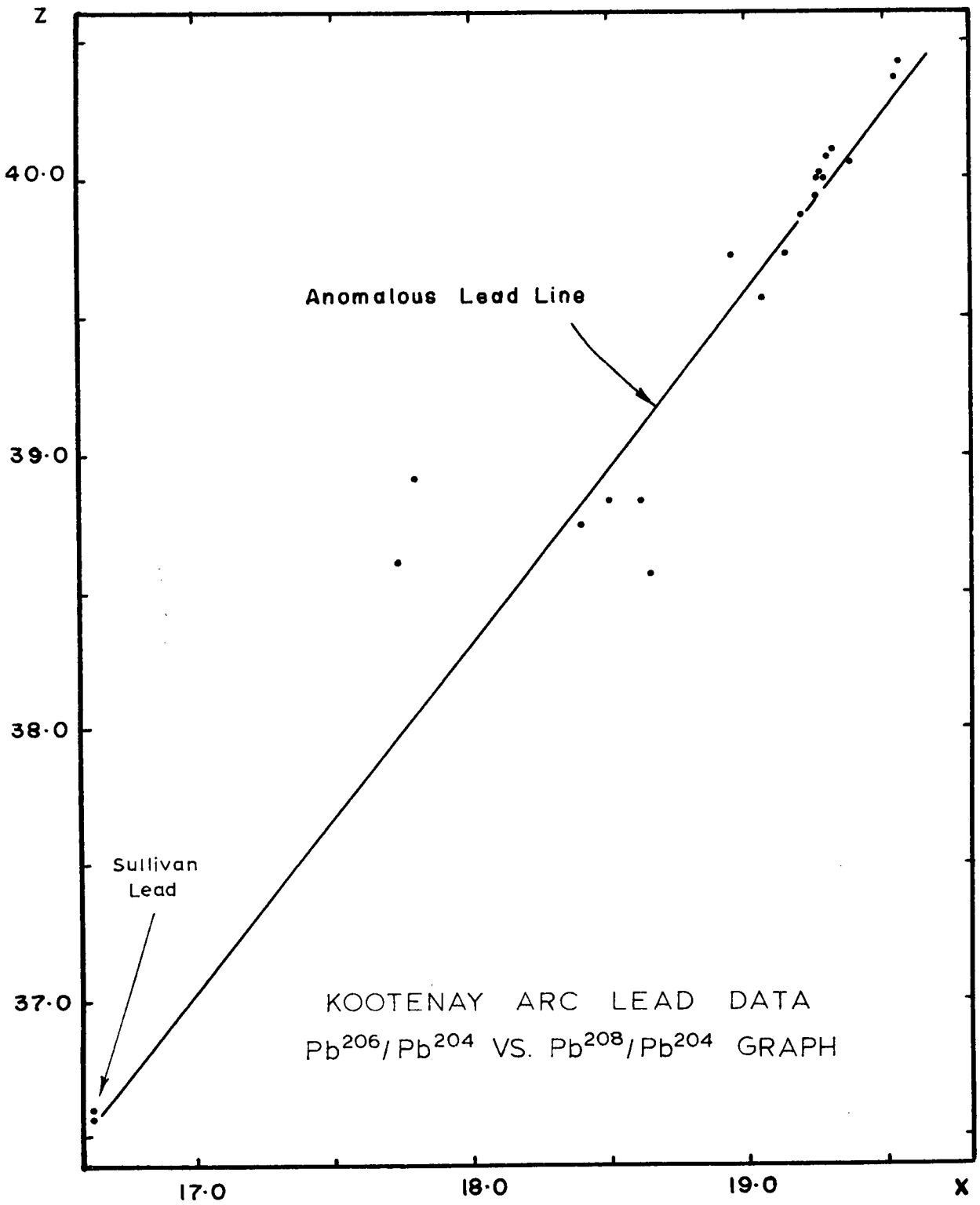
EXTENSION OF RUSSELL-FARQUHAR ANOMALOUS LEAD MODEL

Source of Radiogenic Component

Geological field evidence indicates that at least some mineral deposits in the Kootenay arc are post-Triassic. Assuming several times of mineralization in the range 0 m.y. to 200 m.y., corresponding times of uranium-thorium deposition can be calculated (Appendix I).

Assumed time of anomalous lead mineralization.	Calculated time of uranium and thorium deposition.
0 m.y.	1800 ± 45 m.y.
80 m.y.	1760 ± 45 m.y.
120 m.y.	1740 ± 45 m.y.
170 m.y.	1710 ± 45 m.y.
200 m.y.	1690 m.y.

Mineralization in Slocan camp is thought to have occurred shortly after emplacement of the Nelson batholith (Hedley, 1952) about 170 m.y. ago. Therefore a source approximately 1700 m.y. old containing uranium and thorium is required to explain Kootenay arc anomalous leads. Two potential sources are considered: (1) metamorphic rocks of the Churchill geological province, and (2) Lower Purcell rocks.

A frequency histogram of potassium-argon dates from the Churchill province indicates that major orogeny occurred 1800 to 2100 m.y. ago (Kanasewich, 1962a, p. 61). The Churchill province has been traced from the Canadian

Shield beneath Paleozoic strata in Saskatchewan and Alberta to the foothills of the Rocky Mountains. However, Churchill rocks seem too old to have supplied the radiogenic component of Kootenay arc anomalous leads, even if these rocks are assumed to extend beneath the Kootenay arc.

The Precambrian Lower Purcell series, more than 22,000 feet of predominantly fine-grained clastic sediments, borders the Kootenay arc on the east. Lower Purcell rocks are intruded by Moyie sills, dikes and stocks, one of which gives a potassium-argon date of 1580 ± 100 m.y. (Hunt, 1961). Hence, a minimum age for Lower Purcell strata is 1580 ± 100 m.y. If Lower Purcell strata were the source of the radiogenic component of Kootenay arc leads, two conditions must be fulfilled:

1. Lower Purcell rocks have an age of about 1700 m.y.

2. Lower Purcell rocks extend beneath the Kootenay arc.

The first assumption is justified as a working hypothesis on the basis of potassium-argon data presented by Hunt (1961). That Purcell strata, nine miles thick where exposed east of the arc, should thin abruptly to nothing seems unreasonable. A possibility that Monashee rocks of Shuswap terrane west of the arc, correlate with Purcell rocks is considered by Jones (1959, p. 132). Evidence for the suggested correlation is:

1. Both the Monashee group and Purcell system have minimum thicknesses of about 50,000 feet.

2. Both rock units had similar original lithologies.

3. Gabbro dykes that cut Monashee rocks might be correlatives of Moyie Intrusions in the Purcell system.

Available lead data support the contention made previously by

Billingsley and Locke (1956) that the source of lead-zinc-silver mineral
deposits in southeast British Columbia and northeast Washington was
Prichard (Aldridge) formation. They state:

> "We may suggest therefore that granitized lower Prichard
> was a lead-zinc-silver-enriched sediment, and has become the
> source from which these metals were expelled....... to be trapped
> in various specialized channelways of those (Lardeau, Slocan,
> Ainsworth, Salmo, Metaline, etc.) districts."

However, information is not sufficient to exclude completely rocks similar
to those of the Churchill geological province. Possibly the radiogenic
component of some deposits was derived in part from Lower Purcell strata
and in part from rocks of the Churchill province.

Ordinary Lead Component

Evidence has been given that Sullivan-type lead is a major component
of Kootenay arc anomalous leads. Therefore, the question of origin of the
Sullivan orebody and similar deposits is of interest in discussing the
history of lead mineralization in the Kootenay arc. Figure VII-7 is a plot
of available lead isotope analyses for the Sullivan mine. The distribution
of plotted compositions along an error line indicates that most of the ob-
served scatter is the result of error in measurement of Pb^{204}. Two inter-
comparison analyses of Sullivan lead by the writer are identical (within
limits of experimental precision).

The large size and "conformable" nature of Sullivan orebody, and appar-
ent uniform lead isotopic composition suggest that Sullivan lead is ordinary.
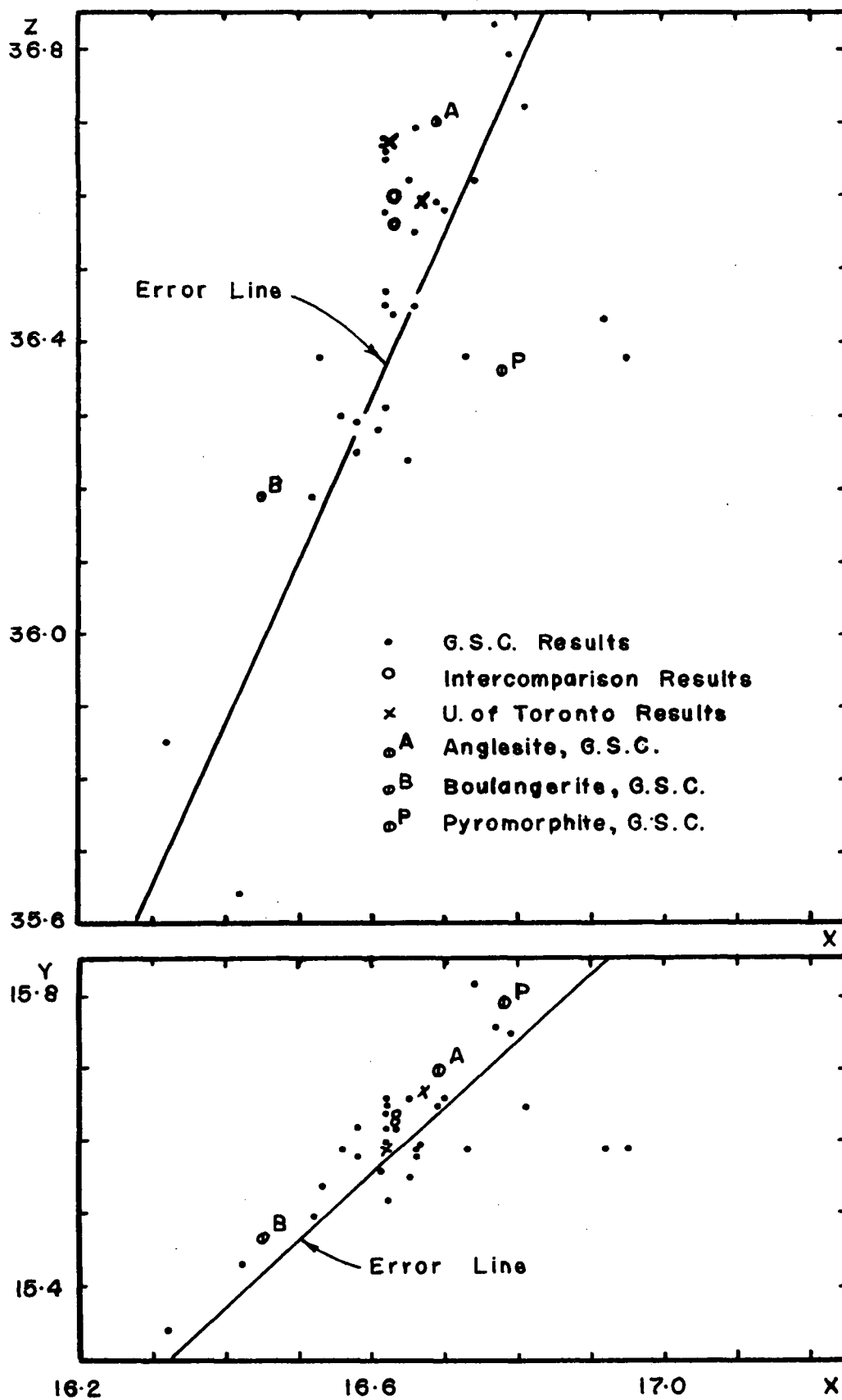
FIGURE VII-7: SULLIVAN MINE - LEAD ISOTOPE DATA

Using the mean composition of two intercomparison analyses the following

characteristics are calculated for source rocks of Sullivan lead:

$$U^{238}/Pb^{204} \qquad 9.02$$

$$Th^{232}/Pb^{204} \qquad 36.71$$

$$Th/U \qquad 4.07$$

These data agree well with criteria for ordinary leads (Chapter II). There-

fore, the Holmes-Houtermans model age of 1340 m.y. dates the time of extrac-

tion of lead from a uniform source, and may closely date time of Sullivan

mineralization. The model age is calculated assuming age of the earth,

decay constants of U^{235} and U^{238}, and composition of primeval lead are

perfectly known. In fact, these constants are known with varying degrees

of precision and the probable uncertainty attached to the model age is about

$\pm$ 100 m.y.

Several theories of origin have been proposed for the Sullivan ore

deposit:

1. Epigenetic ore genetically related to Mesozoic acid
   intrusions (Rice, 1941).

2. Syngenetic deposition more-or-less in the present
   configuration of the ore deposit (cf. Stanton and
   Russell, 1959).

3. Emanations from Moyie Intrusions precipitated metals
   at or near the sea floor (Leech and Wanless, 1962,
   p. 254).

4. Syngenetic deposition of metals followed by remobil-
   ization and redeposition during metamorphism
   (Sullivan, 1957).

5. Epigenetic ore genetically related to the source
   magma of Precambrian Moyie Intrusions (Swanson
   and Gunning, 1948).

Results of isotope studies can aid in evaluating some of the foregoing hypotheses.

(1) Epigenetic Ore Genetically Related
to Mesozoic "Acid" Intrusions

Leech and Wanless (1962) obtained potassium-argon dates of 765 m.y. and .580 m.y. for a lamprophyre dike in the Sullivan mine. This dike is interpreted as having been intruded either after or at the same time as ore deposition. Thus 765 m.y. is a minimum age of ore deposition, and Rice's (1941) contention that Sullivan ores are genetically related to Mesozoic intrusions is untenable.

A Precambrian age for Sullivan mineralization is further suggested by isotopic composition of Sullivan lead. The Holmes-Houtermans model age of 1340 m.y. is difficult to explain unless mineralization occurred during Precambrian time. Evidence has been presented that Sullivan lead is ordinary. Thus the model age implies that Sullivan lead was separated from its original source 1340 m.y. ago. A Mesozoic age for Sullivan ore deposition would necessitate Sullivan lead being emplaced in an environment, free of uranium and thorium, for more than 1000 m.y., after which remobilization and redeposition took place without contamination by any lead of different composition. A complex history such as described seems unreasonable to the writer.

(2) Syngenetic Deposition of Sulfides

Lower Purcell rocks were shown to have a minimum age of 1580 ± 100 m.y., and may be as old as 1700 m.y. If Sullivan model age (1340 m.y.) is correct, the possibility of a syngenetic origin for Sullivan sulfides is unlikely. Also, there seems to be no obvious source for abundant syngenetic metals. Syngenetic lead commonly is considered to be derived from volcanic emanations (Chapter II; Stanton, 1962a), but Leech and Wanless (1962) point out that the only volcanic rocks in the Purcell system are 22,000 feet stratigraphically above the Sullivan orebody.

(3) Syngenetic Deposition of Metals and Later Concentration During Metamorphism

Concentration of Sullivan lead from upper crustal rocks necessitates a multi-stage history for lead. Multi-stage leads are commonly characterized by non-uniform isotopic compositions, in contrast to the uniformity of isotopic composition of Sullivan lead.

Furthermore a huge volume of source rock would be needed to supply all the lead of the Sullivan mine. Assuming 40 ppm lead, 100 percent extraction of lead during concentration, and 7 million tons of lead in the Sullivan orebody, about 57 cubic kilometers of rock are required to supply lead in the Sullivan deposit. No evidence exists that low grade metamorphism such as affected Lower Purcell rocks, can remobilize and concentrate metals from such a large volume of rock to form orebodies the size of the Sullivan deposit.

(4) Metals Precipitated at or Near the Sea Floor From Emanations Related to Moyie Intrusions

Leech and Wanless (1962, p. 254) consider the possibility of a direct genetic relation between Moyie Intrusions and Sullivan ore. They suggest a variant of Stanton's volcanic-syngenetic theory (Chapter II), that Moyie Intrusions were emplaced near surface and emanations from them carried metals to sites of deposition at or near the sea floor, despite the fact that Moyie Intrusions metamorphose adjacent Aldridge strata. This hypothesis implies that:

1. Moyie Intrusions were emplaced intermittently while Lower Purcell strata were deposited, and

2. Time of metal deposition approximates time of sedimentation of enclosing rocks.

The first implication above contradicts a suggestion (Schofield, 1915, p. 69) that Moyie Intrusions are the same age as Purcell lavas. Two possible interpretations of potassium-argon ages of Moyie Intrusions have been put forward (Hunt, 1961, p. 123):

1. Two periods of intrusion about 1500 and 1100 m.y. ago; and

2. One period of intrusion about 1500 m.y. ago, with younger "ages" due to argon loss from dated minerals.

Sullivan model age (1340 m.y.) does not agree well with either postulated time of emplacement of Moyie Intrusions. The implication that Sullivan lead is approximately the same age as enclosing strata is unlikely because Sullivan model age is younger than the minimum age (1500 m.y.) of the enclosing Aldridge formation. Hence, isotope data does not support the hypothesis of precipitation of metals at or near the sea floor from emanations derived

from Moyie Intrusions.

(5) Epigenetic Ore Genetically Related to
Source Magma of Moyie Intrusions

A number of characteristics of Sullivan lead suggest that sulfides of

Sullivan orebody are related genetically to the source magma of Moyie Intru-

sions:

1. Sullivan ore is spatially related to Moyie Intrusions.

2. Vein deposits thought genetically related to Moyie
    Intrusions have lead isotopic compositions similar
    to that of Sullivan lead (Leech and Wanless, 1962).

3. Of dated geological events in East Kootenay district,
    intrusion of Moyie sills is closest in time to Sullivan
    lead model age.

Available evidence suggests that Sullivan lead is epigenetic and some-

how related to Moyie Intrusions. Uniformity of lead isotope composition and

calculated geochemical parameters of the source rocks of Sullivan lead imply

a deep uniform source (cf. Leech and Wanless, 1962, p. 271). Similarly,

Moyie Intrusions (basic to intermediate rocks) probably were derived from a

deep source. Therefore the writer concludes that isotopic evidence supports

an epigenetic replacement origin for Sullivan ore, with ore-bearing fluids

most probably derived from the source magma of Moyie Intrusions. However,

mineralization was not necessarily contemporaneous with emplacement of Moyie

Intrusions. Recent work by Freeze (1963) on metal distribution in Sullivan

mine, and by Jardine (1963) on pre-ore breccias beneath Sullivan orebody,

support an epigenetic origin.

FIGURE VII-8: PUBLISHED LEAD ISOTOPE DATA FOR
THE KOOTENAY DISTRICT
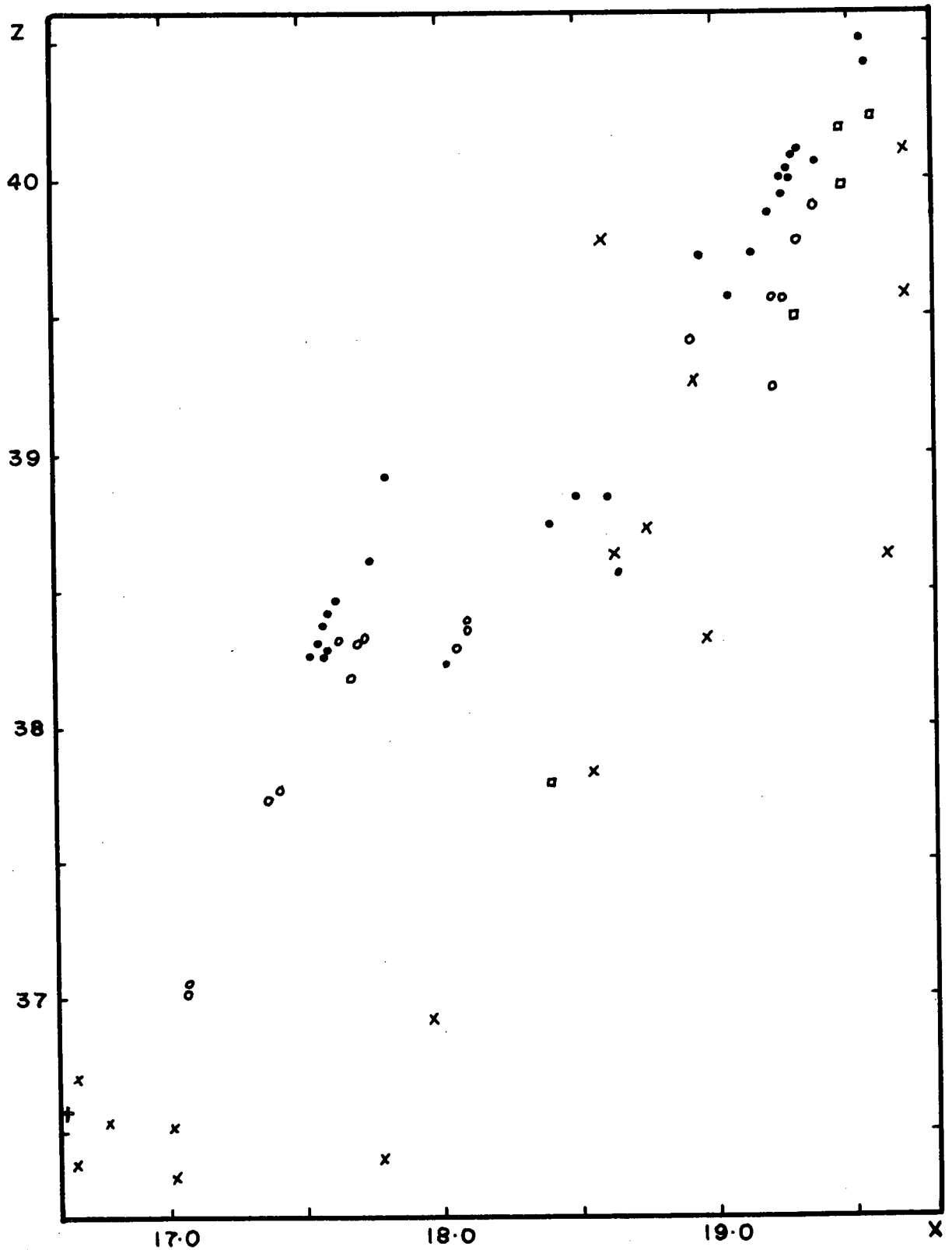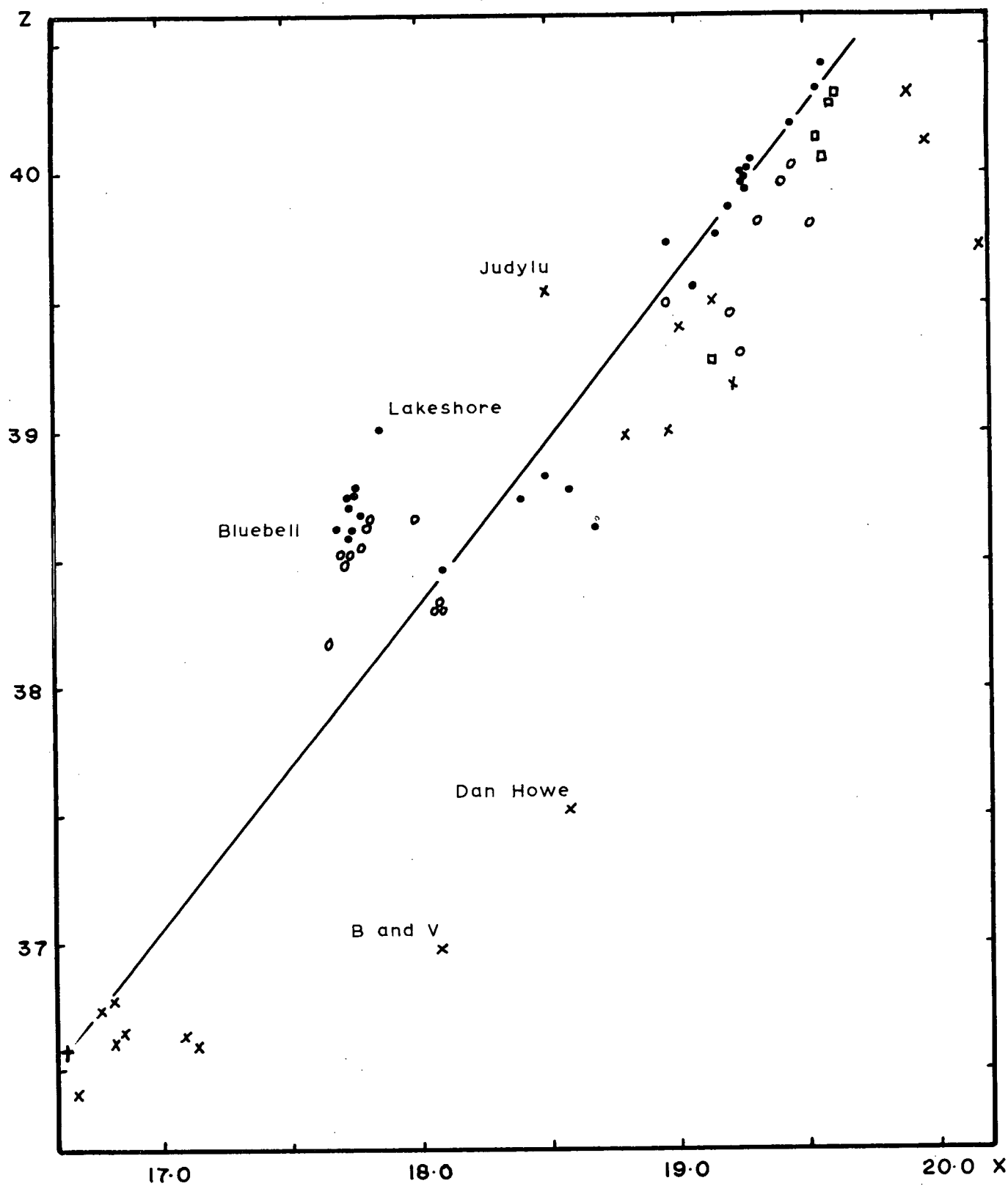
FIGURE VII-9: ADJUSTED LEAD ISOTOPE DATA FOR THE KOOTENAY DISTRICT (SEE TEXT)

Th/U Ratios of Anomalous Lead Source Rocks

Early Kootenay arc lead isotope analyses can be corrected for Pb^{204}

error by solving the equation of an error line through each analysis (on a

Pb^{206}/Pb^{204} versus Pb^{207}/Pb^{204} graph) with the equation of the Kootenay arc

anomalous lead line. Pb^{208}/Pb^{204} ratios can then be adjusted by multiplying

published values by the ratio

$$\frac{Pb^{206}/Pb^{204} \text{ (unpublished)}}{Pb^{206}/Pb^{204} \text{ (adjusted)}}$$

East Kootenay anomalous leads probably have the same history as Kootenay arc

leads. Thus both groups of leads can be corrected for Pb^{204} error in the

above way. Figure VII-8 is a Pb^{206}/Pb^{204} versus Pb^{208}/Pb^{204} graph of 61

published analyses of anomalous leads from the region here considered. These

61 analyses, adjusted as described above, are plotted in Figure VII-9. Ad-

justed compositions have much less scatter than published analyses, and have

a fairly definite pattern. A best fit diagonal regression line for U. B. C.

Kootenay arc analyses is plotted in Figure VII-9 for reference. Except for

a cluster of 16 Bluebell analyses plotting left of the reference line, most

adjusted compositions plot in a narrow band which, if projected, would in-

clude Sullivan lead.

Toronto Kootenay arc lead analyses have systematically higher Pb^{206}

values than U. B. C. analyses. This is shown by differences between U. B. C.

and Toronto Bluebell data. Geological Survey of Canada analyses are high in

Pb^{206} relative to both U. B. C. and Toronto analyses. Accurate corrections

Table VII-2: Calculated Th/U Ratios for Adjusted Anomalous
Lead Isotope Ratios

No.	Laboratory	Th/U	No.	Laboratory	Th/U
BLUEBELL DEPOSIT					
870	Toronto	5.96	226	U. B. C.	6.62
872	"	5.84	228	"	6.63
860	"	5.92	229	"	6.56
513	"	6.17	230	"	6.55
871	"	5.20	237	"	6.62
869	"	5.96	227	"	6.22
861	"	6.01	236	"	6.22
861	"	5.35	237	"	6.21
LAKESHORE SHOWING					
182	U. B. C.	6.78			
SALMO-TYPE DEPOSITS					
282	U. B. C.	4.44	300	U. B. C.	4.41
284	"	4.27	283	"	4.44
286	"	4.42	285	"	4.36
288	"	4.35	287	"	4.38
291	"	4.35	700	Toronto	4.06
293	"	4.33	163	U. S. G. S.	4.13
METALINE DEPOSITS					
9	Minnesota	4.00	162	U. S. G. S.	4.20
121N	Lamont	4.20	161	"	4.14
226	U. S. G. S.	3.66			
RIVER JORDAN DEPOSIT					
1129	Toronto	4.11	1131	Toronto	4.06
1130	"	4.10	326	U. B. C.	4.38
SLOCAN DEPOSITS					
294	U. B. C.	4.58	699	Toronto	4.24
295	"	4.15			

Table VII-2:   (continued)

No.	Laboratory	Th/U		No.	Laboratory	Th/U
EAST KOOTENAY DEPOSITS						
156	G. S. C.	4.15		289	G. S. C.	3.63
237	"	3.91		502	"	5.60
154	"	3.52		244	"	4.16
285	"	4.09		150	"	1.65
245	"	3.68		524	"	1.10
151	"	3.07		698	Toronto	3.96
MISCELLANEOUS DEPOSITS						
695	Toronto	4.15		317	U. B. C.	4.34
696	"	3.52		289	"	3.82
200	"	3.80		290	"	4.14
318	U. B. C.	4.10		292	"	3.39

(to face Figure VII-10)

Figure VII-10:   Frequency distribution of Th/U ratios for
                  source regions of the radiogenic component
                  of anomalous leads from the East Kootenay,
                  West Kootenay, and Metaline Districts.
                  Ratios calculated from "adjusted" isotope
                  compositions as explained in text.

        (a)   Frequency distribution of Th/U ratios
              for 12 East Kootenay analyses.

        (b)   Frequency distribution of Th/U ratios
              for 5 Metaline and 12 Salmo-type anal-
              yses.

        (c)   Frequency distribution of Th/U ratios
              for 8 U. B. C., and 8 Toronto analyses
              of Bluebell Mine lead; and one U. B. C.
              Lakeshore analysis.

        (d)   Frequency distribution of Th/U ratios
              for 61 isotopic analyses of lead from
              the East and West Kootenay district
              and the Metaline District.
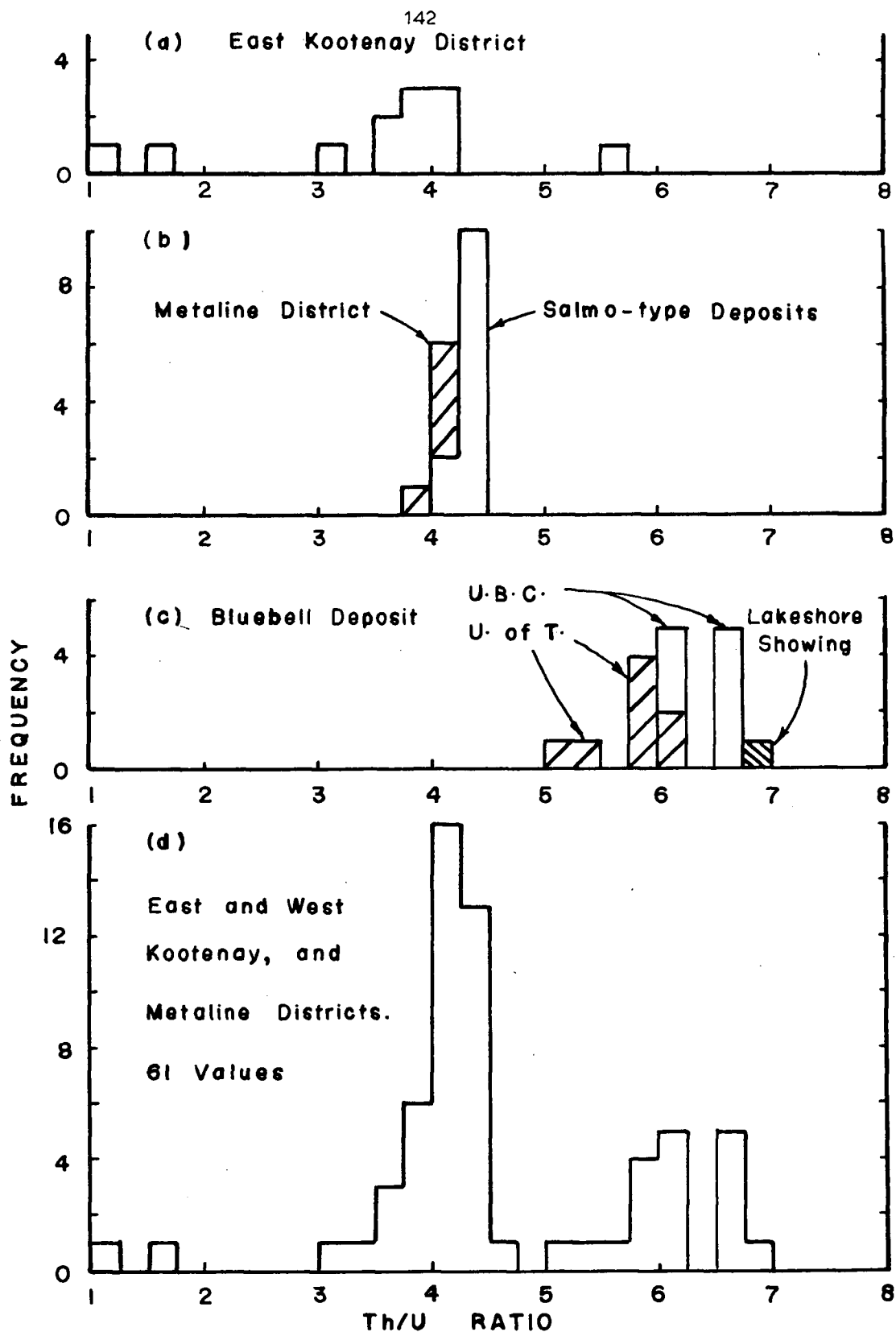
FIGURE VII-10

for interlaboratory variations in Pb^{206} measurement cannot be made because magnitude of corrections varies from one sample to another. If a "Pb^{206} correction" could be made, Toronto and Geological Survey of Canada analyses would plot even closer to the U. B. C. "best fit" line.

Th/U ratios of source rocks of each anomalous lead can be calculated using multi-stage lead equations and adjusted lead isotope compositions. Results are tabulated in Table VII-2 and are shown diagrammatically in Figure VII-10. Figure VII-10(d) has two major concentrations of Th/U ratios centered at 4 and 6 approximately. A comparison of Figures VII-10(c) and VII-10(d) shows that the maximum of Th/U ratios at 6 is due entirely to the large number of determinations from Bluebell mine. A total of 16 Th/U ratios were calculated from Bluebell lead analyses, whereas only 1 or 2 analyses are available for most other deposits.

Histograms in Figure VII-10 show that most deposits were derived from sources with Th/U ratios between 3.5 and 4.5. A previous discussion of systematic differences among laboratories in measurement of Pb^{206} peaks indicates that the range of Th/U values is probably less than that given. The isotope data are a close approximation to the Russell-Farquhar anomalous lead model involving mixing of two components, each of uniform composition.

Leads from 5 deposits depart significantly from this "mixing model": Bluebell and Lakeshore in the Kootenay arc, Judylu, B and V, and Dan Howe in the East Kootenay district. Lead in these 5 deposits apparently developed in Th/U environments considerably different to those of most lead deposits in the region. Real variations in Th/U ratios of source rocks of anomalous leads

144
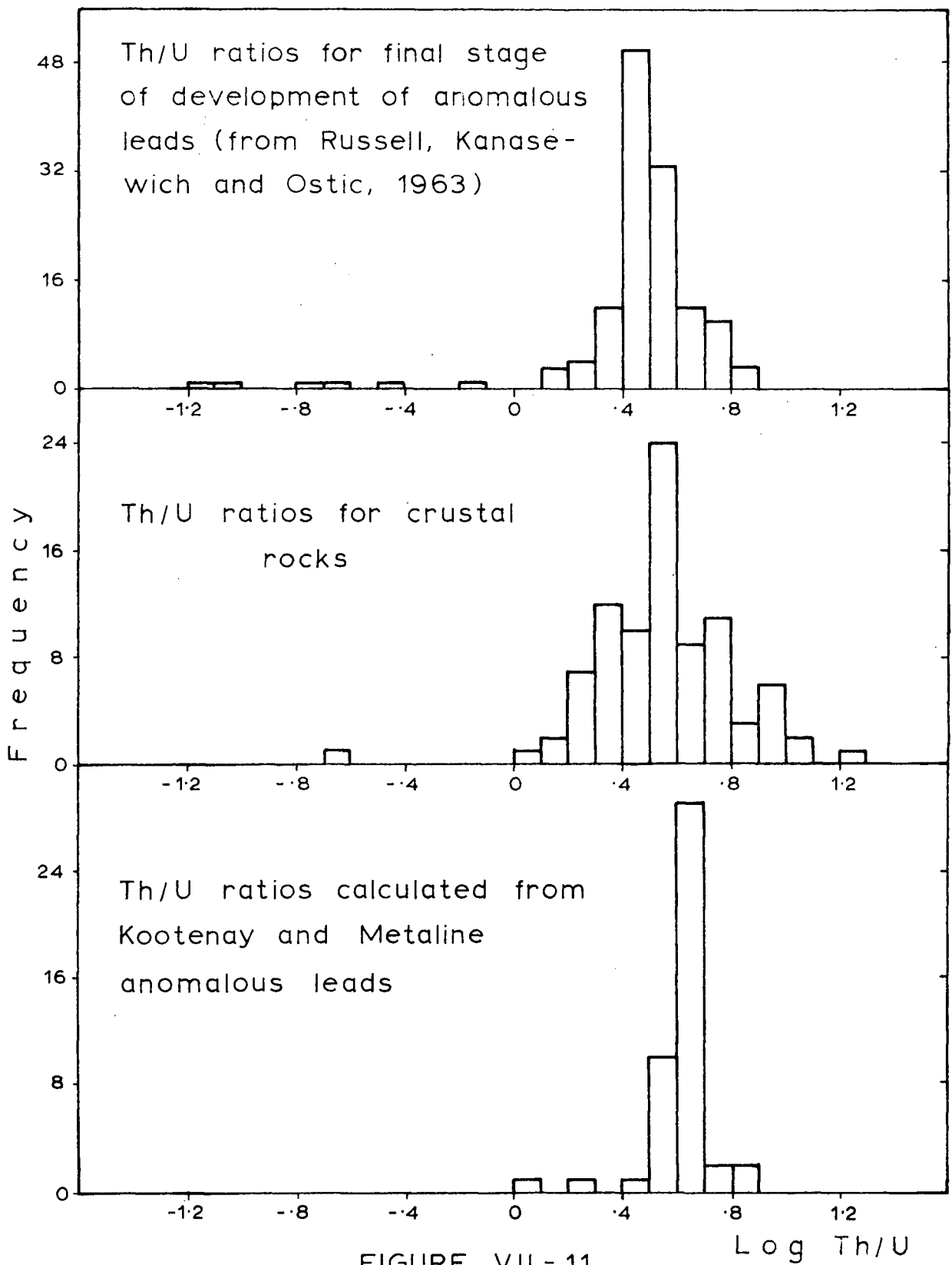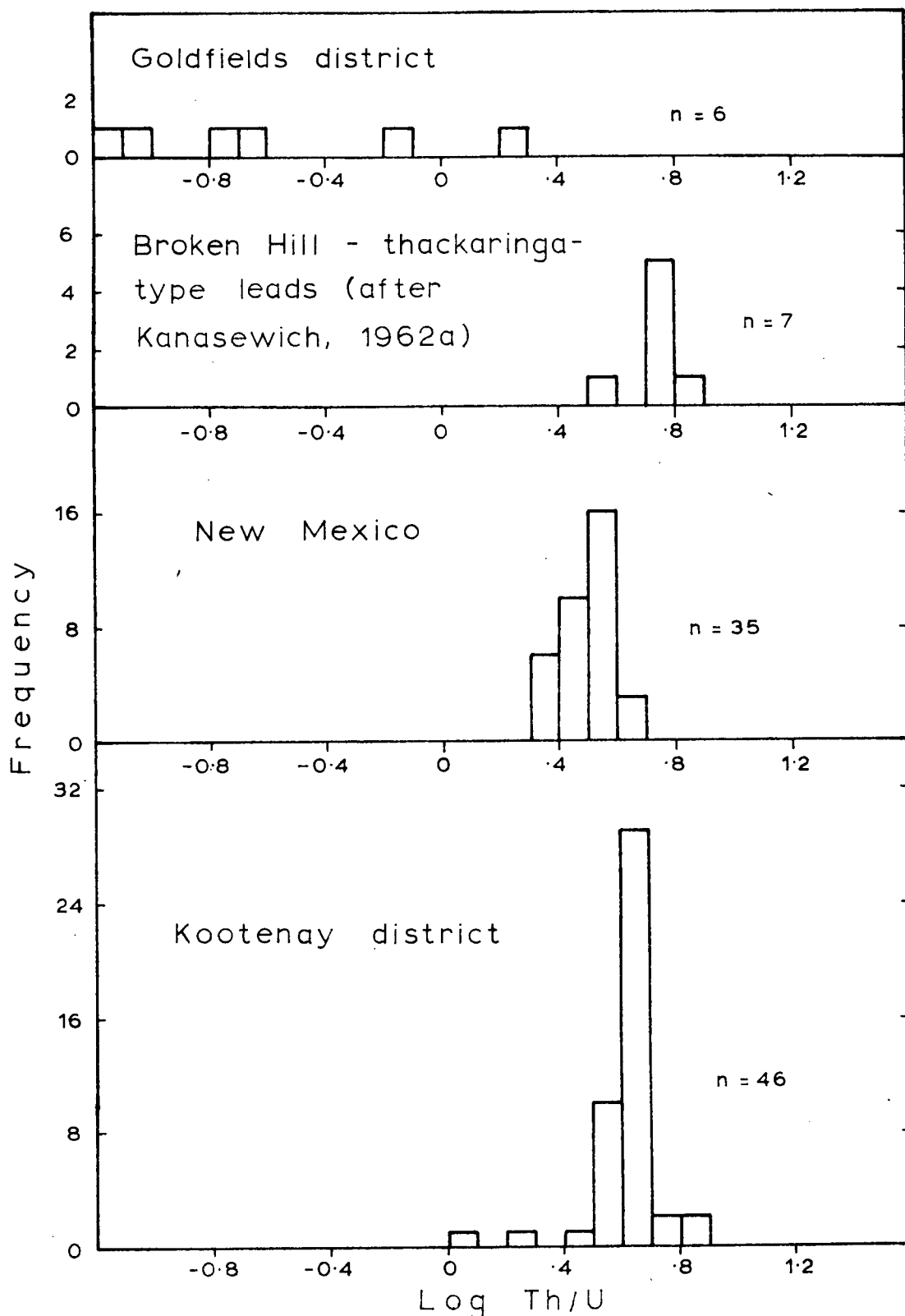
FIGURE VII - 11

FIGURE VII-12: COMPARISON OF CALCULATED Th/U RATIOS
OF SOURCE REGIONS OF ANOMALOUS LEADS FROM
SEVERAL DISTRICTS

indicate a crustal source for the leads. The fact that more than 85 percent

of deposits studied isotopically, were derived from rocks with similar, fair-

ly uniform Th/U ratios suggests that most deposits may have been derived from

a common source. Figure VII-11 compares calculated Th/U ratios for source

rocks of Kootenay arc anomalous leads with Th/U ratios in

1. crustal rocks, and,

2. a composite histogram of Th/U ratios calculated from
   a group of definitely established anomalous leads.

In Figure VII-12 Th/U ratios calculated from Kootenay arc anomalous leads

are compared with Th/U ratios calculated from other suites of anomalous

leads. An extreme maximum in the histogram for Kootenay district leads

shows that most of these leads were derived from a source unusually uniform

in Th/U ratio. Uniformity of Th/U ratios may reflect lithologic uniformity

of the source of Kootenay district anomalous leads. Hence the narrow range

of most calculated Th/U values may indicate the Lower Purcell strata were

the source rocks of many anomalous lead deposits.

Discussion of the Origin of Salmo-type Replacement Deposits

Kootenay arc lead isotope data can aid in determining genesis of Salmo-

type replacement deposits. Theories of origin that have been proposed, both

in the literature and verbally, include;

1. syngenesis,

2. derivation of metals from Ordovician slates by meteoric
   waters (Whishaw, 1954),

3. teleternal mineralization of unknown source, prior to
   structural deformation (Richardson, 1961), and,

4. epigenetic replacement deposits formed near the close
   of Phase II deformation.

Oldest probable date of mineralization in the Kootenay arc was shown

to be ~~350~~ 320 m.y. or Mississippian (see previous section in this Chapter).

However, Salmo-type deposits are in Lower Cambrian limestone that must be

nearly 600 m.y. old. Thus, a syngenetic origin is unlikely.

Whishaw (1954) suggests that lead and zinc in the Jersey mine may have

been derived from argillaceous rocks of the Ordovician Active formation

"...by meteoric or other waters" after folding. If the premise that Jersey

lead is a mixture of Sullivan-type and radiogenic components is true,

Whishaw's suggestion would necessitate the following lead history:

1. isolation of uranium and thorium in a closed system
   about 1700 m.y. ago;

2. introduction of Sullivan-type lead into the uranium-
   thorium system about 1340 m.y. ago, with different
   parts of the system having different U/Pb and Th/Pb
   ratios;

3. erosion and redeposition of the uranium-thorium-lead
   system during Ordovician period, with no change in U/Pb
   and Th/Pb ratios between original subsystems and Ord-
   ovician sediments;

4. extraction of lead from Ordovician rocks and deposition
   during Mesozoic Era.

Item (3) above seems unlikely because variations in U/Pb and Th/Pb ratios

appear to be characteristic of the crust. If random differences in $U^{238}/$

Pb^{204} and Th^{232}/Pb^{204} ratios existed between pre-Ordovician and Ordovician

systems in which the leads existed, a recognizable scatter of points about

an anomalous lead line would be expected (cf. frequently mixed source model,

Chapter II). The absence of such a scatter in Kootenay arc leads thus argues

against derivation of Salmo-type lead from Ordovician rocks.

Richardson (1961) suggests that Duncan Lake and possibly Salmo ores

formed prior to Phase II folding and were subsequently deformed. Lead iso-

tope data provides evidence that mineral deposition did not occur earlier

than $\overset{320}{350}$ m.y. ago. Consequently, if mineralization were pre-Phase II folding

the deposits probably formed between Mississippian and Triassic periods. A

possible variation of this idea is that sulfides could have been fixed as

disseminated replacements in Reeves-Badshot limestone in Phase I structures

during Paleozoic time. Leads could have remained fixed in this environment

relatively free of uranium and thorium until mid-Mesozoic orogeny occurred

when they were remobilized and redeposited in Phase II structures. Such a

history seems probable to the writer only if the time interval between init-

ial deposition and remobilization were short, or, if no contamination by

lead from other rock units occurred during remobilization. A short resi-

dence period of lead (say 100-200 m.y.) in a carbonate unit low in uranium

and thorium might not permit enough radiogenic lead to form to affect notice-

ably the isotopic composition of lead present. This idea cannot be invest-

igated quantitatively because of lack of information on concentrations of

uranium, thorium and introduced lead in Reeves-Badshot limestone. Remobil-

ization of lead in Phase I folds in Reeves-Badshot limestone during Mesozoic

orogeny without contamination by lead from adjacent rocks seems unlikely.

If remobilization were attributed to orogeny then high temperatures and

pressures probably prevailed. Under such conditions it seem improbable to

the writer that lead would be extracted solely from a 100 to 300-foot thick

carbonate unit. Lead in rock units adjacent to Reeves-Badshot limestone is

multi-stage, and probably of variable composition from one unit to another.

Incorporation of such lead in Salmo-type replacement deposits only coincid-

entally would result in an anomalous lead line without scatter. Consequent-

ly, a history of formation of Salmo-type deposits involving primary mineral-

ization in Phase I structures during mid-Paleozoic time followed by remobil-

ization accompanying Mesozoic orogeny appears unlikely to the writer.

A simple and possible genesis of Salmo-type deposits that fits the

lead isotope data is that leads were extracted from source rocks after or

during late stages of Phase II deformation and sulfide deposition was con-

trolled by Phase II structures. Such an origin has been implied by Fyles

(1962a) and Fyles and Hewlett (1959).

No mention has been made of the manner by which anomalous leads were

concentrated and transported prior to deposition. In Chapter III it was

suggested that uniformity of anomalous lead isotope ratios from a single

deposit supports but does not prove a hydrothermal origin. More than one

galena sample have been analysed isotopically for only a few deposits in

the arc. Kanasewich (1962a, p. 119) reports 7 Bluebell galenas with lead

isotopic compositions that vary by less than 0.5 percent. Farquhar (person-

al communications, 1960) found 3 River Jordan galenas to have identical lead

isotope compositions. The author analysed 4 galenas from Jersey mine, three

by an intercomparison method, and found uniform lead isotopic composition.

Available data suggest that each deposit contains lead of fairly uniform

isotopic composition and that significant differences in isotopic composit-
ion can exist among deposits. The writer suggests that source rocks of
Kootenay arc leads were melted to produce magmas in the crust. Lead was
homogenized locally and extracted in hydrothermal solutions during a late
phase of magma consolidation.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The intercomparison technique for analysing a suite of anomalous leads with a wide range of compositions is an important method of studying histories of leads prior to their final deposition as lead minerals. In fact, results of this study emphasize the _necessity_ of precise analyses of lead isotopes if meaningful quantitative treatment of data is to be made. Isotope studies such as that done on Kootenay arc leads provides information concerning:

1. source of lead, crust or mantle,

2. age of lead mineralization, and

3. certain geochemical information about source rocks of lead.

There appears to be no correlation between isotopic composition of lead in Kootenay arc deposits and,

1. minor element content of galena,

2. age of wallrock, and

3. geological type of deposit, fissure vein or replacement.

Thermal metamorphism of Salmo-type deposits by granite and lamprophyre dikes has not changed lead isotope abundances measureably. Even where metamorphism and hydrothermal alteration have greatly changed minor element content of galena the lead isotope composition does not seem to have been affected.

Sullivan deposit in the East Kootenay district appears to contain single-

FIGURE VIII - 1
PROPOSED HISTORY OF DEVELOP-
MENT OF KOOTENAY ARC LEAD

Anomalous lead
mineralization

1760 m.y.   80 m.y.

Uranium - thorium   Anomalous leads develop
emplacement

1700 m. y.   190 m.y.

t_0 = 4550 m.y.   1340 m. y.

Ordinary lead develops   Ordinary lead
mineralization

4500   4000   3500   3000   2500   2000   1500   1000   500   0

AGE (m.y.)

152
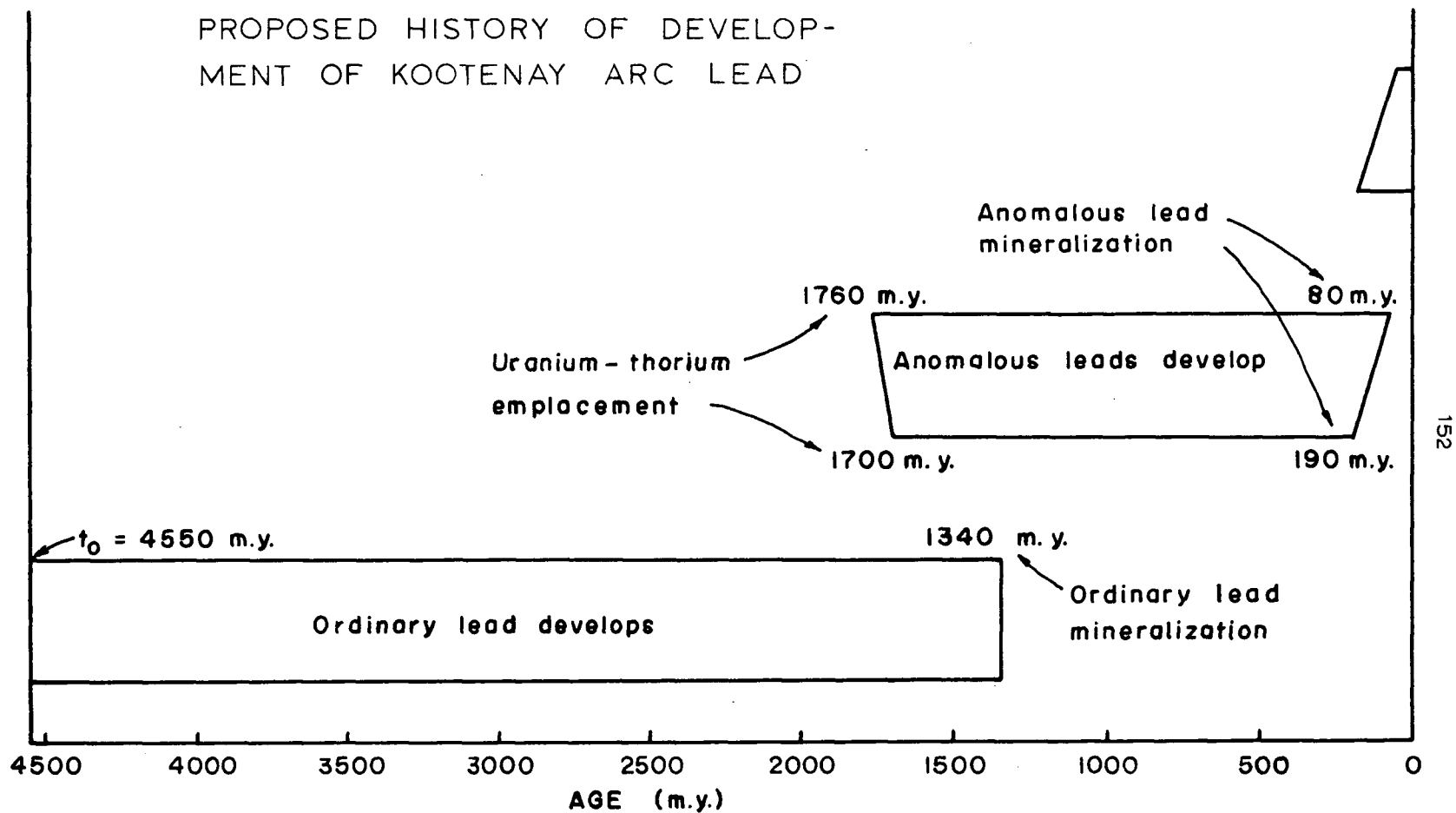
stage lead. The deposit can be interpreted best as an epigenetic replacement genetically related to the source magma of Moyie Intrusions. Mineralization probably occurred 1340 ± 100 m.y. ago.

Kootenay arc leads plot on an anomalous lead line that passes through Sullivan lead. These anomalous leads can be interpreted consistently with the geology of the region by assuming they are mixtures of different proportions of a radiogenic lead and lead similar in composition to Sullivan lead. A postulated history of Kootenay arc leads (Figure VIII-1) is as follows:

1. Introduction of uranium and thorium into a closed system approximately 1700 m.y. ago. This closed system is the source of Kootenay arc anomalous leads, and may have been Lower Purcell strata or metamorphic rocks similar to those of the Churchill geological province of the Canadian Shield.

2. About 1340 m.y. ago Sullivan-type lead was introduced into anomalous lead source rocks. The system then apparently remained closed for more than 1000 m.y.

3. Radiogenic lead began forming in the closed system about 1700 m.y. ago by the decay of uranium and thorium.

4. During the Mesozoic Era radiogenic and Sullivan-type leads were extracted from source rocks, mixed in different proportions and deposited as anomalous leads.

This history requires that the ultimate source of most Kootenay arc lead and probably other base metals is the mantle. Mantle lead at a late stage in its history mixed with crustal lead to form the mineral deposits we now find. Evidence of the crustal phase of Kootenay arc lead development is given by the existence of an anomalous lead line, and variations in Th/U ratios of source rocks of Kootenay arc leads. Shuswap, East Kootenay and Metaline anomalous leads appear to have undergone histories similar to Kootenay arc

leads, but present data are either insufficient or lack precision necessary to prove this possibility.

Kootenay arc lead data indicate that all leads analysed were deposited during a time interval that did not exceed 150 m.y. Hence, Salmo-type deposits could not be syngenetic. Furthermore, it is improbable that metals in Salmo-type deposits were derived from any Lower Paleozoic strata, because this would involve a much more complex history than that suggested. Such a complex history probably would have resulted in an anomalous lead line with much more scatter than was found. Salmo-type leads most likely had a simple history with extraction of lead from source rocks and mineralization accompanying mid-Mesozoic orogeny. A late Paleozoic mineralization cannot be ruled out completely but extensive remobilization of Paleozoic sulfides during a later orogeny is improbable.

Extraction of Kootenay arc anomalous leads from their source rocks most probably occurred by partial melting of source rocks and subsequent release of hydrothermal solutions as melted rocks solidified. Local homogenization of lead in source rocks accompanied melting. However, neighbouring volumes of source rocks may have had very different overall lead isotope compositions at the time of anomalous lead mineralization as indicated by the variation of lead isotope abundances among deposits.

Minor element contents of Kootenay arc galenas indicate the presence of two populations that correspond to two geologically distinct types of deposits — fissure veins and replacement bodies. Galenas from fissure deposits have higher silver, antimony, tin and copper contents than do galenas from

Salmo-type replacement deposits. Thallium is generally present only in galena from replacement deposits. Low silver, antimony, bismuth, tin, and high thallium contents of galena in Salmo-type replacement deposits suggests but does not prove that these deposits formed at low temperatures. Thermal metamorphism and hydrothermal alteration in places seem to have changed the minor element content of galena from replacement deposits by the addition of significant quantities of silver, antimony and tin to galenas.

Examination of more than 100 polished sections shows that Salmo-type replacement deposits are characterized by similar mineralogy, textures and paragenesis. Principal minerals from oldest to youngest are: pyrite, sphalerite and galena. Pyrrhotite is abundant locally and in places is a product of thermal metamorphism of pyrite. Chalcopyrite is present in very minor amounts in some polished sections and generally is associated with sphalerite or pyrrhotite. In places textures indicate extensive deformation of sulfides. Some pyrite is fractured and fragments are drawn into contorted patterns reminiscent of mylonites. In places slickensided surfaces are present on sulfides. Age or ages of deformation of sulfides is not known precisely. Textural relations indicate that much of the dolomite associated with the ores is later than pyrite.

Economic Implications

Leech and Wanless (1962, p. 269) find that virtually all base metal production in the East Kootenay district has come from deposits containing lead of Sullivan-type. They state (p. 270):

"In the search for new lead deposits, the presence of lead of
Sullivan isotopic type in a prospect is apparently a statistically
favorable indication of the presence of an ore body, except in de-
posits genetically related to Moyie Intrusions."

All lead from the Kootenay arc thus far analysed contains much more radio-

genic lead than does lead in the Sullivan mine. The generalization that re-

latively "non-radiogenic" lead is "a statistically favorable indication of

the presence of an ore body" does not apply in the Kootenay arc. In fact,

the largest sulfide deposits in the arc, replacement bodies of Salmo-type,

are among those whose galena contains the highest proportions of radiogenic

component of any common lead yet found in the area. Another large deposit,

Bluebell mine, contains the lowest proportion of radiogenic component of any

common lead known in the arc. There seems to be no correlation between lead

isotopic composition and economic potential of Kootenay arc deposits.

The interpretation suggested for Kootenay arc leads implies that Sulli-

van-type lead was deposited over a large area. Thus, the possibility exists

that economic deposits containing Sullivan-type lead also might be found over

a large area. The writer previously indicated the possibility that Monashee

group of the Shuswap terrane might correlate with Purcell rocks. Should

such a correlation be correct, Monashee rocks would be a logical place to

prospect for metamorphosed deposits containing Sullivan-type lead.

Some veins in the East Kootenay district contain lead of the same iso-

topic composition as Sullivan lead. Although a few of these veins may be

genetically related to Moyie Intrusions and are, therefore, of Precambrian

age, some are related to Mesozoic structures. Thus, Sullivan-type lead, in

veins of Mesozoic age, was concentrated and transported in such a way that

a radiogenic component was not included in ore-bearing solutions. Processes of base metal concentration, transport, and deposition are not well understood. However, lack of "contamination" of Mesozoic veins containing Sullivan-type lead by a radiogenic lead component suggests that metals were transported only short distances. Hence, the presence of Mesozoic veins containing Sullivan-type lead implies the possible presence of Sullivan-type mineral deposits near such veins.

Suggestions for Future Work

This study has placed certain restrictions on the history of Kootenay arc lead deposits. Available information indicates lead isotope studies might lead to solutions of some of the remaining problems.

More lead isotope data are desirable to support the conclusion that all leads in the Kootenay arc have had similar histories. These additional analyses might be done fruitfully in two ways:

1. the area studied might be extended by examining deposits from Metaline district south of the area studied, and from as far north as the Caribou district.

2. detailed lead isotope study of mineral deposits in specific mining camps in the arc could be undertaken.

The Metaline district is a natural southern extension of the region studied. Intercomparison analyses of Metaline lead could be very important in evaluating origin of Salmo-type replacement deposits. Caribou district and the Kootenay arc appear to have undergone similar geological histories. Whether or not lead histories in the two districts are similar is not known.

Detailed isotope studies in specific mining camps could add important

information to our interpretation of lead histories. For example, published

lead isotope analyses from Slocan camp are very different from those from

the neighbouring Ainsworth camp and Bluebell mine. Defining regions charact-

erized by "Bluebell-type" and "Slocan-type" leads might be important in eval-

uating size of blocks of source rock that can be homogenized, amount of mixing

of solutions from adjacent sources, possible evidence of more than one period

of mineralization, and possible relationship of a particular type of lead to

a particular type or age of structure. In connection with a detailed study

such as suggested, it would be of considerable interest to analyse trace

leads in rocks that might have been sources of metals.

The degree to which mixing of ordinary and radiogenic components takes

place may be important in evaluating the origin of anomalous lead deposits.

Thus a study of possible variations or uniformity of lead isotopic composit-

ions in individual deposits is warranted.

Published analyses of East Kootenay anomalous leads have a wide range

of isotopic compositions but there appears to be considerable Pb^{204} error.

Probably 5 or 6 intercomparison analyses of leads representative of the

entire range of compositions would be sufficient to determine whether or not

these leads had undergone histories similar to Kootenay arc leads.

Leads analysed from Shuswap terrane plot on the Kootenay arc anomalous

lead line. Further study of Shuswap leads is warranted but probably should

await a better understanding of the geology of Shuswap terrane.

An important factor in determining the origin of Sullivan deposit is

the composition of syngenetic lead in the Aldridge formation. Therefore, a

study of abundances of lead, uranium and thorium, and isotopic compositions

of lead in the Aldridge formation could be important. Such a study would

also provide information on the distribution of Th/U ratios in the Aldridge

formation for comparison with calculated Th/U ratios of source rocks of

Kootenay arc and East Kootenay leads.

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APPENDIX I

EQUATIONS FOR THE RUSSELL-FARQUHAR

ANOMALOUS LEAD MODEL

The slope R of an anomalous lead line is determined by linear regression of anomalous lead isotope ratios relative to Pb^{204}, minimizing diagonally because errors exist in values of all coordinates of the two plots used (Farquhar and Russell, 1963).

A general equation for the slope of an anomalous lead line is

$$R = \frac{e^{\lambda t_2} - e^{\lambda t_m}}{(e^{\lambda t_2} - e^{\lambda t_m})} \qquad (AI-1)$$

where t_2 is the time of uranium emplacement and t_m is the time of anomalous lead mineralization.

The maximum age, t_r, of anomalous lead mineralization is determined by the expression

$$t_r = 1,223 \log_e 21.79 \, R \qquad (AI-2)$$

If $t_m = 0$ m.y. equation (AI-1) reduces to

$$R = \frac{e^{\lambda t_u} - 1}{(e^{\lambda t_u} - 1)} \qquad (AI-3)$$

and, t_u, the maximum age of uranium emplacement in the crust can be calculated.

The Th^{232}/U^{238} ratio of the source region of an anomalous lead suite

formed by mixing two components can be calculated from the equation

$$R' = \frac{Th^{232}}{U^{238}} \quad \frac{\lambda''}{\lambda} \quad \exp(\lambda - \lambda'')t \qquad (AI-4)$$

The equation is relatively insensitive to t, the age of mineralization, and

t_r from equation (AI-2) can be used.

APPENDIX II

EQUATIONS FOR KANASEWICH MULTI-STAGE LEAD MODEL

(after Kanasewich, 1962a)

The equation for radioactive decay, written in terms of the number of lead atoms being generated relative to Pb^{204}, is:

$$x = a_o + \int_t^{t_o} \lambda \left[137.8V(t)\exp(\lambda t) \right] dt$$

Symbols used here are defined in Table I-1. The quantity in brackets is the U^{238}/Pb^{204} ratio at any time t. V is a function of time and many investigators have tried various functions for this quantity. In general this is a different function for each deposit and a statistical treatment of measurements from many widely spaced localities will obscure these differences. The function used here is one in which V is taken to be a constant for discrete intervals of time so that the integral reduces to

$$x = a_o + 137.8V_o(e^{\lambda t_o} - e^{\lambda t_1}) + 137.8V_1(e^{\lambda t_1} - e^{\lambda t_2}) \ldots$$

Similar treatment gives equations for y and z:

$$y = b_o + V_o(e^{\lambda' t_o} - e^{\lambda' t_1}) + V_1(e^{\lambda' t_1} - e^{\lambda' t_2}) + \ldots\ldots\ldots$$

$$z = c_o + W_o(e^{\lambda'' t_o} - e^{\lambda'' t_1}) + W_1(e^{\lambda'' t_1} - e^{\lambda'' t_2}) + \ldots\ldots\ldots$$

APPENDIX III

MINOR ELEMENT STUDY OF KOOTENAY ARC GALENAS

Introduction

Study of minor element contents of Kootenay arc galenas might aid in interpreting lead isotope abundances. Few minor element studies have been done in connection with lead isotope research. However, some investigators (Russell, Farquhar and Hawley, 1957; Vaäsjoki and Kouvo, 1959) found that geologically distinct types of sulfide deposits could be distinguished on the basis of both lead isotope compositions and trace element contents of galenas.

Cahen and others (1958) who studied trace element and lead isotopic compositions of galenas from the Alps and North Africa, state:

> "Practically all galenas we have investigated that have model ages comparable to the age of the host formation are found in veins, often with more or less obvious magmatic connexions and they are silver rich. On the other hand the leads of those occurrences, located in sedimentary rocks and apparently independent of igneous activity, are poor in silver and have model ages which are older than the host formation."

Silver-poor deposits, with ages older than enclosing strata are interpreted as rejuvenated deposits (B-type leads), presumably having lost silver during migration. Only slight changes in values of parameters used in calculations are required to give model ages for silver-poor deposits equal to ages of wallrocks. Hence, Russell and Farquhar (1960) suggest that silver-poor ores contain ordinary lead. They propose that vein deposits formed by remobiliz-

ation of ordinary leads, and that during mobilization ordinary lead was "contaminated" with radiogenic lead and possibly silver.

Hawley (Russell, Farquhar and Hawley, 1957) who did qualitative spectrographic studies of galenas containing anomalous and ordinary lead from Broken Hill district, Australia, found:

> "A very distinct difference between the two groups, however, is the presence in the first (ordinary) of bismuth and tin and the absence in the second (anomalous) of detectable amounts of these elements."

Vaasjoki and Kouvo (1959) studied lead isotopic composition and minor base metal content of 9 galenas from 9 Finnish mineral deposits. Two distinct groups of galenas with characteristic minor element assemblages correspond to a division into ordinary and anomalous leads.

Russell and Farquhar (1960) emphasize the possibility that minor element contents of galenas may prove an important method of distinguishing ordinary and anomalous leads because these two types of lead have undergone different histories.

Previous Minor Element Studies in the Kootenay Arc

Warren and Thompson (1945) studied minor element content of 52 sphalerites from the Kootenay arc by a semi-quantitative spectrographic technique. Specimens were analysed from deposits in Revelstoke, Lardeau, Slocan, Ainsworth and Nelson mining camps. A particularly significant result is recognition of high tin content of sphalerites in Kootenay district, commonly in the range 0.05 to 0.20 percent Sn. Silver is present in all 52 analyses

and generally ranges from a trace to 0.10 percent, with 9 specimens containing somewhat more. Antimony was detected in 23 sphalerites.

Dr. W. H. Mathews of the Department of Geology, University of British Columbia, did an extensive minor element study of sulfides from Slocan City, and Slocan and Ainsworth camps during the early 1940's while employed by the British Columbia Department of Mines. His quantitative spectrographic data were not published, but were made available to the writer by Dr. Mathews. Mathews analysed sphalerites, pyrites and galenas from the three camps for minor element contents. Only galena results (159 analyses representing 126 mines or showings) are pertinent to this study. For purposes of presenting Mathews' data, frequency histograms were constructed using logarithms of minor element abundances (ppm). In some cases ideal lognormal distribution curves are also shown. Data for silver, antimony, copper and tin are presented for comparison with the author's results.

In general, frequency distributions of an element in each of the three camps are similar (Figures A-III-1 to A-III-4). Two possible exceptions are:

1. Ainsworth galenas seem to be characterized by slightly lower antimony contents than Slocan and Slocan City camps.

2. Galena in Slocan City camp contains little tin relative to the other two camps.

Ainsworth deposits commonly contain less silver than ores from the Slocan where argentiferous tetrahedrite is a common ore mineral. Thus, differences in antimony content of galena from the two camps might be the result of differences in amounts of tetrahedrite included in galena. If this were so, differences in silver content of galena from the two camps might also be expected, and some suggestion of this can be seen in Figure A-III-1 (a) and (b).
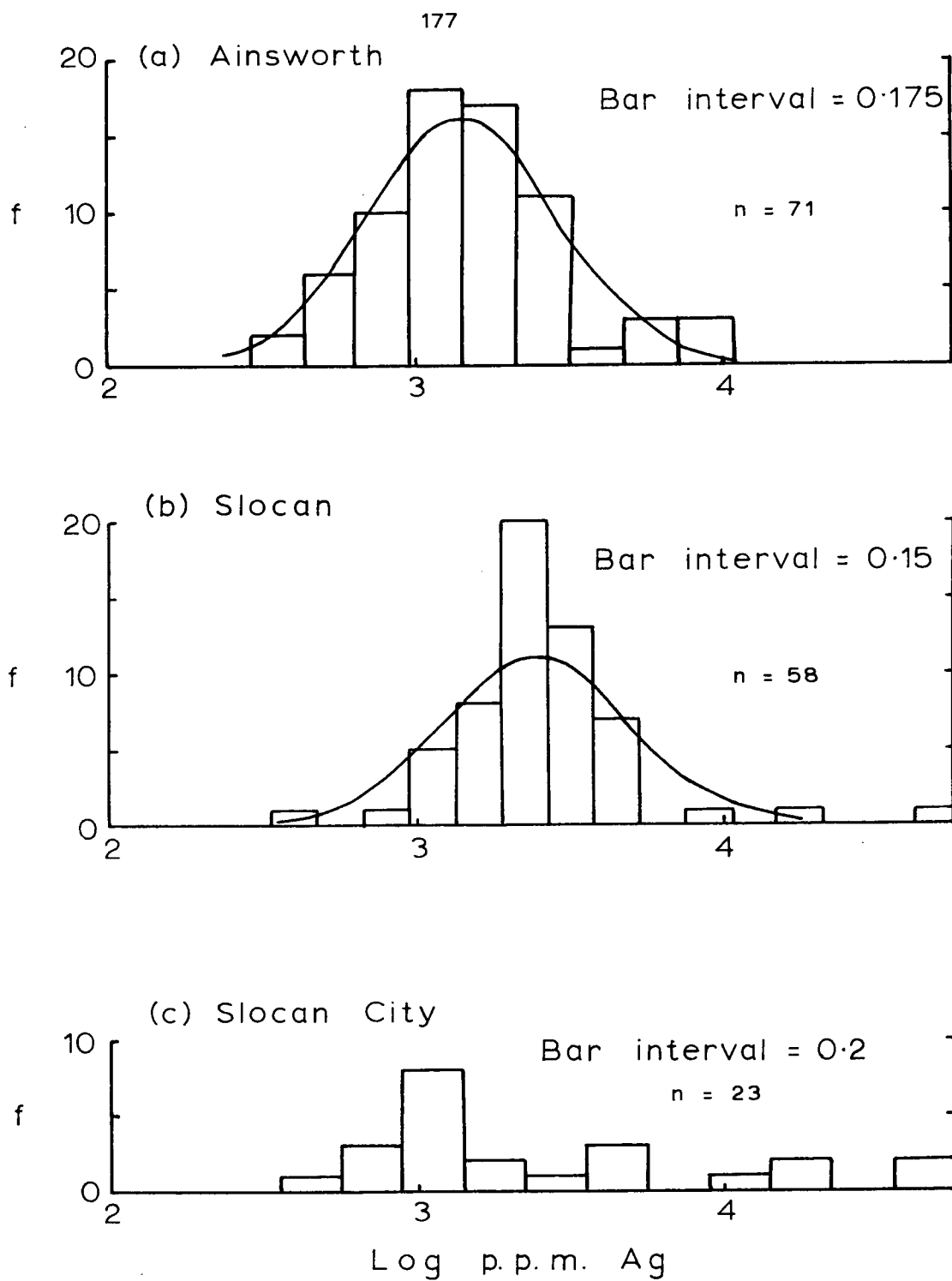
FIGURE A-III-1: SILVER CONTENT OF GALENAS
(data from W. H. Mathews)
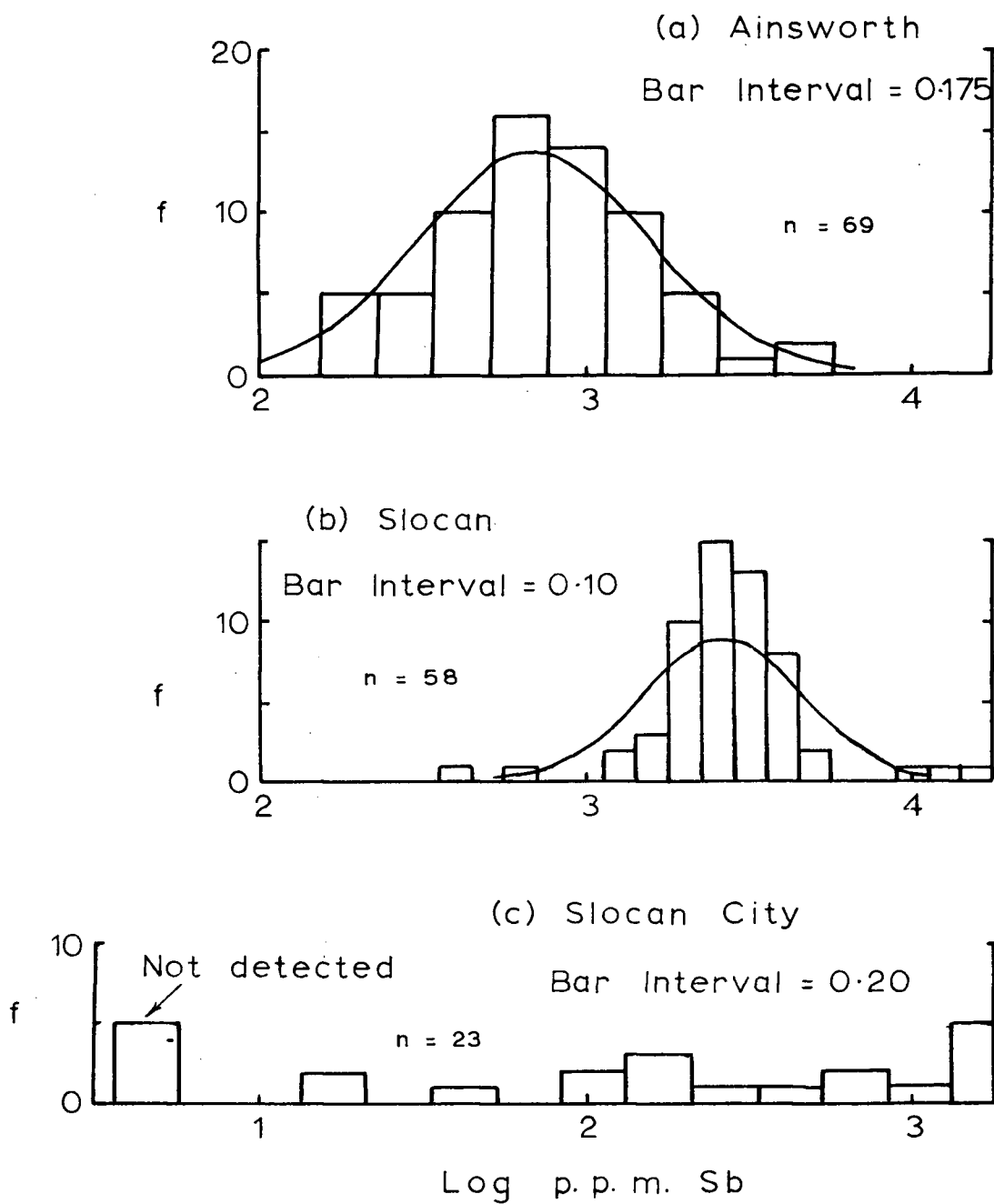
FIGURE A - III - 2: ANTIMONY CONTENT OF
GALENAS (data from W. H. Mathews)
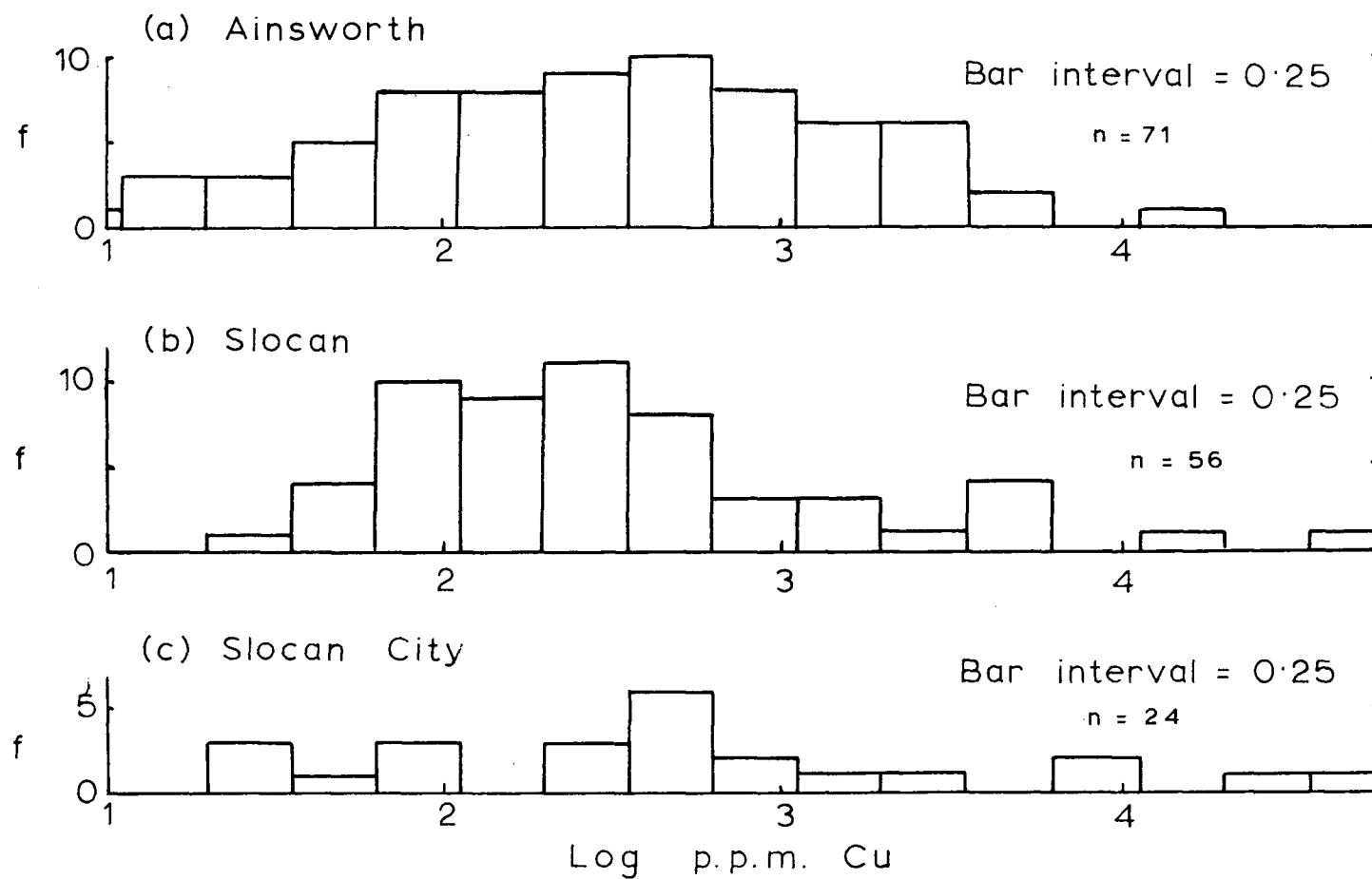
FIGURE A-III-3: COPPER CONTENT OF GALENAS (data from W. H. Mathews)

(a) Ainsworth

Not detected in 19
Bar interval = 0·15

f

10

0

n = 71

1   2   3

Log p.p.m. Sn

(b) Slocan

Not detected in 9
Bar interval = 0·20

f

10

0

n = 58

1   2   3

Log p.p.m. Sn

(c) Slocan City

Not detected in 18
Bar interval = 0·20

f

10

0

n = 23

1   2   3

Log p.p.m. Sn
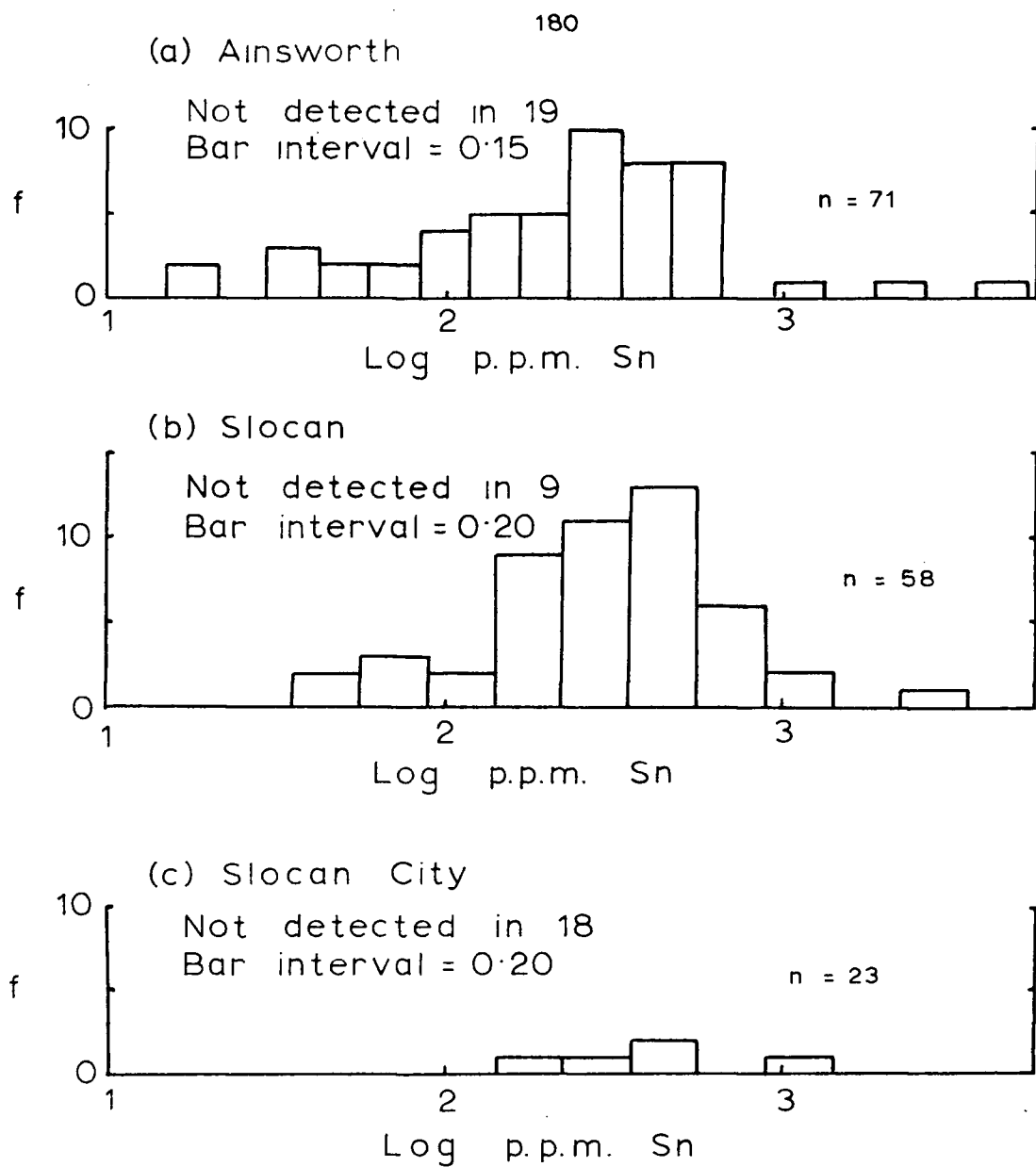
FIGURE A - III - 4: TIN CONTENT OF
GALENAS (data from
W. H. Mathews)

No explanation can be offered for the apparently low tin content of galena
from Slocan City camp.

Preparation of Galena Specimens for Analysis

Minor element analyses were restricted to those specimens containing
galena of sufficient grain size that sorting of cleavage fragments under a
binocular microscope was a feasible purification method. Specimens were
chosen from deposits along the entire arc to represent two geologically
distinct types of deposits:

1. those of replacement origin with negligible evidence
   of open space filling, and

2. those characterized by evidence of open space filling
   with different degrees of wallrock replacement.

Sulfide specimens were crushed to less than 1 mm. grain size and individual
grains were inspected microscopically. Cleavage fragments were inspected
and collected under a binocular microscope.

Analytical Technique

Purified galena specimens were submitted to the British Columbia Depart-
ment of Mines and Petroleum Resources for quantitative spectrographic anal-
yses. Analyst R. Hibberson kindly supplied the following account of prepar-
ation of standards and analytical procedure.

Spectrograph - The Spectrograph used for analyses was an A.R.L. (Applied

Research Laboratories) #2100 - two meter spectrograph equipped with a 24,400

line per inch original grating mounted to produce a spectrum covering the

range from 1850 - 9200 Å at a linear dispersion of 5.2 Angstroms in the first

order with 2500 Å coverage by 20" camera, and from 1850 - 4600 Å at a dis-

persion of 2.6 Å in the second order with 1250 Å coverage.

Standard Samples - Standard samples were prepared, using a base of lead

oxide, a specially prepared "spec-pure" compound synthesized by Johnson,

Mattey and Co. Ltd., containing none of the minor and trace elements ident-

ified and determined in suites of galena specimens. To the base was added

Spex Mix #1000 - a mixture of pure compounds containing 43 elements each at

a concentration of 1.34%. The resulting mixture was ground thoroughly in a

diamonite mortar, followed by further mixing in a Spex Mixer Mill to ensure

an even distribution of minor elements in the base. A suite of standards

was then prepared by diluting the above standard with the lead oxide, mixing

as above.

Unknowns - Galena specimens were crushed to a fine powder and thoroughly

mixed in the Mixer Mill, prior to analysis.

Arcing Conditions - Part (A) - Duplicate 20 mgms portions of galena powder

were weighed and transferred to "super-pure" 101-L pre-formed carbon elect-

rode cups. The samples were arced with an A.R.L. Multi-source unit, using

220 V.D.C., adjusted to a current of 10 amperes. The lower electrode con-

taining the sample was made positive, while the upper electrode which con-

sisted of a 1/8" diameter carbon rod of "super-pure" grade, was negative.
Samples were arced to completion, using a setting of 3% Transmission on the
A.R.L. Intensity Control Stand.

Arc gap was set at 40 mm. and primary slit at 20 microns. Standard samples
were then arced using the same conditions as for unknowns.

Part (B) - To obtain maximum sensitivity for certain minor elements at very
low concentrations, it was necessary to use a 50 mgm portion of galena
sample. All unknowns and standard samples were re-run in duplicate using
the same electrodes and conditions as in Part (A) with the exception that
the Intensity Control Stand was set for 8% Transmission.

Film and Development - The resulting spectra were photographed with Eastman
Kodak 35 mm. Spectrum Analysis No. 2 film. It was developed for 3 minutes in
Eastman Kodak D-19 developer at 68°F in the regular A.R.L. developing machine.
The film was rinsed in an acetic acid short stop, then "fixed" in Kodak Rapid-
Fixer for 5 minutes.

Film Calibration - By use of two-step focal plane filters in the 2 meter
filter assembly, iron spectrograms were obtained in the wave-length regions
of interest. Each step of several iron lines was read with an A.R.L. densit-
ometer and from these readings film calibration curves were drawn.

Densitometry - All spectral lines were read on the A.R.L. densitometer.
Transmittancies were converted to light intensities by using the previously
described calibration curves. Linearity of the densitometer had been con-
firmed previously. With light intensity data obtained on standard samples,

working curves for various minor elements were drawn - a plot of light intensity vs % metal present.

Reproducibility - Precision for duplicate determinations was approximately ± 9%. Results submitted represent average of duplicates analysed.

Results

Results of minor element analyses of Kootenay arc galenas are presented in two tables: Table A-III-1 - galenas from replacement deposits (18 analyses), and Table A-III-2 - galenas from deposits with evidence of open space filling (23 analyses). Besides those elements listed, galenas were analysed for Ga, Ge, In, Te, Au and As. These elements were detected in only a few or none of the 41 galenas analysed.

Means and standard deviations were calculated for logarithms of element abundances (cf. Shaw, 1961). Where an element was detected in most galena specimens frequency histograms were constructed (Figures A-III-5 and A-III-6). Linear correlation coefficients were calculated for each pair of the following elements: Ag, Sb, Bi, Tl, Sn, Cu, Zn and Cd. Good correlations were not found, suggesting that abundances of a single element may be due to several modes of occurrence in galena. For example, Ag might be present only in matildite ($AgBiS_2$) in which case a 1:1 ratio of Ag/Bi would be expected. On the other hand, if Ag were present in included tetrahedrite as well as matildite no simple relation need exist between Ag and Bi.

TABLE A-III-1 : Quantitative trace element results for galenas from Salmo-type deposits in the
Kootenay area. Analyses by optical emission spectrography. Analyst: R. Hibberson,
B. C. Department of Mines and Petroleum Resources

B.C.Dept. Mines No.	U.B.C. No.	Bi	Sn	Cu	Tl	Ag	Sb	Cd	Zn	Mo	Co
8445M	CX-1	N.D.<1	N.D.<1	1	N.D.<5	5	N.D.<5	210	24,000	N.D.<0.1	0.5
8447M	RM-1	"	"	0.3	140	270	312	272	110	"	N.D.<0.5
8503M	Sal-A	12	22	17	19	300	750	56	N.D.<5	"	"
8504M	J-2	10	22	2	12	900	1,250	65	35,000	1	1
8696M	J-1	10	10	24	N.D.<1	515	725	153	80,000	0.75	N.D.<0.5
8697M	CX-3	15	3	13	9	40	87	320	50,000	N.D.<0.1	"
8699M	HB-18	N.D.<1	5	2	N.D.<1	87	125	490	60,000	"	"
8507M	DL-18	1	4	T.<1	35	200	400	50	700	0.4	"
8508M	DL-23	350	15	"	21	750	575	36	27,000	N.D.<0.1	10
8509M	DL-30	1.2	4	1	4.5	35	10	25	13,000	0.4	1
8510M	DL-33	N.D.<1	5	T.<1	50	20	65	72	20,000	N.D.<1	N.D.<0.5
8511M	DL-41	T.<1	6	"	80	14	74	34	4,300	"	"

Table A-III-1: cont'd

B.C. Dept. Mines No.	U.B.C. No.	Bi	Sn	Cu	Tl	Ag	Sb	Cd	Zn	Mo	Co
8512M	CX-11	25	5	1.5	N.D.< 1	65	102	297	50,000	N.D.< 1	N.D.<0.5
8513M	CX-42	1,400	200	500	7	3,000	36	93	600	250	0.7
8487M	HB-22	N.D.< 1	18	3	13	700	780	93	1,000	N.D.<0.1	N.D.< 5
8488M	W-6	T.< 1	5	9	29	120	460	75	11,500	"	"
8489M	C-3	15	15	0.6	N.D.< 1	570	240	67	80	"	"
8490	JP-7	60	60	217	150	340	3,230	87	N.D.< 5	"	"

Symbols:

CX – Jersey mine   RM – Reeves Macdonald mine   Sal A – Sal showing   J – River Jordan
HB – H. B. mine   DL – Duncan Lake   W   – Wigwam   C – Cotton Belt
JP – Jackpot

N.D.   –   not detected (detection limit indicated)

T   –   trace (detection limit indicated)

Table A-III-2: Quantitative trace element data for galenas from fissure and fissure-replacement deposits in the Kootenay arc. Analyses by optical emission spectrography. Analyst: R. Hibberson.

B.C.Dept. Mines No.	U.B.C. No.	Bi	Sn	Cu	Tl	Ag	Sb	Cd	Zn	Mo	Co
8436M	BB-2	T.<1	322	16	N.D.<5	600	625	16	535	0.5	N.D.<0.5
8437M	BB-10	T.<1	615	145	N.D.<5	450	550	55	12,000	0.1	"
8438M	BB-15	15	760	13	"	750	500	20	5	N.D. 0.1	"
8439M	BB-24	700	500	160	"	680	250	160	48,000	0.5	6
8440M	Yale	T.<1	280	690	"	2,500	1,750	25	5,100	0.2	0.5
8441M	St. Pat.	6	200	3	"	5,000	3,900	19	N.D.<5	N.D.<0.1	N.D.<0.5
8442M	Triumph	T.<1	480	193	"	2,700	3,600	8	15	0.1	"
8443M	MS	50	N.D.<1	2	"	3,000	3,400	23	N.D.<5	N.D.<0.1	"
8444M	Nicolet	N.D.<1	665	45	"	2,000	1,200	15	210	"	"
8446M	BB-12	3	800	135	"	1,000	650	13	220	"	"
8491M	VM-4	N.D.<1	130	410	1	5,000	4,800	30	N.D.<5	"	"

Table A-III-2: cont'd

B.C.Dept. Mines No.	U.B.C. No.	Bi	Sn	Cu	Tl	Ag	Sb	Cd	Zn	Mo	Co
8492M	VM-7	N.D. < 1	170	12	N.D. 1	3,000	2,700	30	N.D. < 5	N.D. < 0.1	N.D. < 0.5
8493M	VM-9	"	100	530	"	5,500	4,300	59	2,200	"	"
8494M	VM-13	"	90	315	3	4,000	5,300	21	N.D. < 5	"	"
8495M	VM-16	4	465	130	N.D. < 1	5,000	5,650	29	500	"	"
8496M	VM-20	22	45	65	"	3,500	4,900	26	N.D. < 5	"	"
8497M	NL-4-2	100	192	2,500	"	2,500	6,000	60	400	"	"
8498M	Scran-10	9	28	100	"	3,500	4,100	120	15	"	"
8499M	B.F.	20	11	662	"	1,000	1,300	90	8,900	"	4
8500M	Empire	5	T. < 1	3	"	3,500	3,300	18	T. < 5	"	N.D. < 0.5
8510M	MM-3	N.D. < 1	5	22	"	400	720	8	175	"	"
8502M	CP	T. < 1	175	0.5	T. < 1	4,000	3,400	70	3,400	"	"
8698M	NL-1-2	N.D. < 1	30	1	N.D. < 1	1,000	2,600	21	N.D. < 5	"	"

Table A-III-2: cont'd

<u>Symbols</u>:

BB – Bluebell   Yale – Highland Banker   St. Pat. – St. Patricks   Triumph – Triumph
MS – Moonshine   Nicolet – Nicolet   VM   – Victor mine   NL   – Nettie L
B.F. – Black Fox   Empire – Empire   MM   – Mollie Mac   Scran – Scranton
CP – Cork Province

Discussion of Results

A: Galena from Replacement Deposits (18 Specimens)

Bismuth

Fifteen of the galenas contain less than 25 ppm Bi. Two specimens, CX-42

and JP-7 (Appendix IV) probably "contaminated" during metamorphism and/or hydro-

thermal activity, have Bi abundances of 1,400 and 60 ppm respectively.

A wide variation in Bi content of galenas from a single deposit is shown

by 5 analyses from Duncan Lake mine (DL-18, -23, -30, -33, -41) whose bismuth

contents range from "not detected" (less than 1 ppm) to 350 ppm. Specimen

DL-23 contains the abnormally high abundance of 350 ppm Bi and has, further-

more, an usually high Ag/Sb ratio. Thus, in this specimen (DL-23) some Ag and

Bi may be combined as the mineral matildite ($AgBiS_2$).

Generally, Bi (ionic radius $0.96A^{\circ}$) substitutes for Pb (ionic radius $1.20A^{\circ}$)

in the galena lattice.

Low bismuth content of galena is thought to indicate low temperature of

mineral deposition (cf. Fleischer, 1955, p. 980). However, an equally plausible

explanation could be that the ore fluids were low in bismuth.

Tin

Sixteen galenas contain less than 22 ppm Sn. Abundances of 60 and 200 ppm

were found for specimens JP-7 and CX-42 respectively. Both of these specimens

have probably been "contaminated" (Appendix IV). Nature of occurrence of tin is

not known. Goldschmidt (1958) thinks that small amounts of tin can substitute

for lead. Generally, when tin is abundant in common sulfides, stannite or

cassiterite are present as small inclusions (cf. Warren and Thompson, 1945).

Goldschmidt (1958, p. 395) states that when both sphalerite and galena are present in the same ore deposits, tin in high temperature deposits preferentially enters lead sulfide whereas in low temperature deposits preferentially or exclusively enters zinc sulfide. Hence, a low tin content of galena in a tin metallogenetic province implies a low temperature of deposition.

Copper

Copper was detected in each of the 18 galenas analysed. Sixteen of the determinations are in the range trace (less than 1 ppm) to 24 ppm. Two high values of 500 ppm and 217 ppm were obtained for thermally metamorphosed galenas, CX-42 and JP-7 respectively.

Nature of occurrence of Cu in galena is not known from observation. However, chalcopyrite is the only copper mineral recognized in Salmo-type deposits and it is inferred that Cu occurs as inclusions of chalcopyrite in the galena specimens because substitution of copper for lead seems unlikely.

Thallium

Thallium is present in 13 of 18 analysed galenas in the range 7-150 ppm. Monovalent thallium has an ionic radius of $1.47A^{\circ}$ and it may substitute for Pb $(1.20A^{\circ})$ in galena. Goldschmidt (1958, p. 338) states that a Tl atom and a Bi atom may substitute for two Pb atoms. Such is not generally the case for galenas here considered because Tl may be present to the exclusion of Bi and vice versa.

Moderately high Tl abundances recorded here may indicatea fairly low

temperature of deposition. Thallium, as a chalcophile element, concentrates in low temperature deposits (Kayaga, 1963), and has been found by several workers in Mississippi Valley type deposits (Evrard, 1945; Stoiber, 1940).

Silver

Silver is present in all 18 galena specimens analysed in the range 5-900 ppm, except for CX-42. This metamorphosed galena contains 3000 ppm Ag. Variations in silver content of galena within one deposit are shown by 5 Duncan Lake mine specimens that have a range of 14-750 ppm Ag.

The manner in which Ag occurs in galena is not known by observation. No silver minerals are known in Salmo-type deposits, although in an earlier discussion of bismuth the author suggested that high Ag and Bi contents of one Duncan Lake galena specimen might indicate the presence of matildite. Wide variation of Ag/Sb ratios indicates that these two elements probably are not combined in a compound common to each specimen analysed. For example, if Ag and Sb were present in a 1:1 atomic ratio (as in miargyrite-$AgSbS_2$) calculated atomic ratios (Table A-III-3) should be in the range 0.82-1.22 (allowing for 10 percent precision). Only 4 calculated ratios are within this range. In general, as the silver contents of galena from replacement deposits are low, silver probably occurs in the galena lattice with no particular relationship to other minor elements. Goldschmidt (1958, p. 408) attributes the "universal occurrence of silver in galena" to the capture of silver in tetrahedral interstices between 4 nearest sulfur atoms.

Table A-III-3:   Weight ratios and atomic ratios of
Ag/Sb in galenas from replacement
deposits in the Kootenay arc.

Sample	Weight Ratio Ag/Sb	Atomic Ratio Ag/Sb
CX-1	-	-
RM-1	0.866	0.977
Sal-A	0.400	0.452
J-2	0.720	0.813
J-1	0.711	0.803
CX-3	0.460	0.508
HB-18	0.696	0.786
DL-18	0.500	0.564
DL-23	1.304	1.472
DL-30	3.500	3.950
DL-33	0.308	0.348
DL-41	0.190	0.214
CX-11	0.644	0.727
CX-42	83.4	94.1
HB-22	0.898	1.012
W-6	0.261	0.294
C-3	2.375	2.680
JP-7	0.105	0.119

Antimony

Antimony was detected in 16 galenas in the range 10-1250 ppm. In one specimen (CX-1) Sb was not detected and another (JP-7) contained 3,230 ppm Sb.

Amount of solid solution of Sb in galena is unknown. No evidence of an exsolved or included mineral phase containing Sb has been found. Tetrahedrite is a common mineral in the Kootenay arc, but because of low copper abundances in galena only a small proportion of the antimony present can occur as tetrahedrite.

With few exceptions antimony is more abundant than silver. This may reflect (1) a consistent difference in abundances of the two elements in ore-forming solutions of Kootenay arc deposits, or

   (2) combinations of the two elements in unidentified compounds with Sb/Ag ratios greater than 1, present in solid solution in galena.

Zinc

Zinc detected in all but two of the 18 galenas analysed probably represents inclusions of sphalerite (cf. Fleischer, 1955, p. 982). Zinc analyses were made specifically to give a measure of purity of galena specimens. Ten of the galenas contain more than 1 percent Zn, to a maximum of 8 percent in J-1. In general, it is thought that the amount of sphalerite contained in galena specimens is sufficiently low that trace element abundances, except for cadmium, are representative of galena.

Tin is commonly present in the range 0.1-0.2 percent in Kootenay arc sphalerites (Warren and Thompson, 1945). However, Sn reported in Kootenay arc galenas is not present entirely in included sphalerite because

   1. the highest concentrations of tin recorded (Sal-A and JP-7

with 60 and 22 ppm respectively) were for specimens containing no detectable zinc, and

2.   a single sample in which Sn was not detected contained 2.4 percent zinc.

Cadmium

Cadmium occurs in all galenas in the range 34-490 ppm, probably in sphalerite inclusions. However, two specimens that did not contain detectable Zn contained 56 and 87 ppm Cd, and a third specimen contains more Cd than Zn. Thus all Cd abundances cannot be explained by the presence of sphalerite. Fleischer (1955, p. 980) states "that cadmium may be present in solid solution in galena".

Molybdenum

Molybdenum was detected in 7 of 18 galenas. Six of these 7 specimens contain Mo in the range 0.1-1.0 ppm. Specimen CX-42 contains 250 ppm Mo probably due to "contamination" by late mineralizing solutions that altered wallrock near the specimen. The penetrating ability of these late solutions is shown in a polished surface of hand specimen CX-42 where thin carbonate-quartz veinlets less than 1/8" thick are bordered by irregular bleached zones up to 3/4" wide. Ball (1954) records abundant molybdenite-quartz veins associated with scheelite deposits in Jersey mine and the writer has identified molybdenite in the quartz-rich interiors of two granitic dikes that cut sulfide ore at the Jersey mine. Thus, the high Mo content of CX-42 is probably due to presence of molybdenite, deposited during a later period of mineralization than was galena.

Other Elements

Cobalt was detected in 5 of 18 galenas in abundances from 0.7 to 10 ppm, and probably occurs in solid solution in pyrite inadvertently included in purified galena specimens.

Tellurium (detection limit 100 ppm), gold (detection limit 10 ppm), arsenic (detection limit 10 ppm), and germanium (detection limit 1 ppm) were not found in any specimens analysed.

Indium (detection limit 1 ppm) was found only in J-1 (11 ppm).

Gallium (detection limit 1 ppm) was also found only in J-1 (5 ppm).

Summary

Galenas from Salmo-type deposits have a characteristic minor element assemblage, and characteristic ranges of values for certain minor elements. Silver and antimony are consistently present generally in the ranges 14-750 ppm Ag and 10-1250 ppm Sb. Antimony commonly is more abundant than silver. Bismuth is generally present (less than 25 ppm) as are tin (less than 22 ppm) and copper (less than 24 ppm). Thallium is commonly present, in places in abnormally high concentrations (up to 150 ppm).

Minor elements probably occur largely in solid solution in galena. In some specimens certain minor elements are too abundant to be present entirely in solid solution. Low copper abundances show that tetrahedrite cannot occur in the galena specimens in appreciable quantities. Copper probably occurs primarily as chalcopyrite inclusions, this being the only copper mineral found in many of these replacement deposits. Tin may be present in solid solution.

Cassiterite and stannite have not been recognized in replacement deposits. Thallium most likely substitutes for lead in the galena structure. Silver probably occurs in interstitial solid solution in galena. Presence of antimony has not been explained. Zinc and most of the cadmium occur in sphalerite inclusions in galena. Some cadmium is probably in solid solution in galena. Cobalt may be present in pyrite impurities in galena. Molybdenum is rarely present, probably in the form of molybdenite.

Galena specimens that have been affected by thermal metamorphism and/or fluids related to granitic intrusions (JP-7 and CX-42) have minor element abundances markedly different from those of galenas unaffected by metamorphism or hydrothermal fluids. Apparently post-depositional processes have changed extensively the minor element contents of these galenas. However, no measurable changes in lead isotopic composition occurred.

Minor element contents of galena cannot be used for quantitative determinations of temperature of sulfide deposition. However, many previous workers (see Fleischer, 1955) have shown that consistent differences in minor element contents occur among 3 broad classes of deposits — high, medium, and low temperature groups. Available minor element data suggest that Salmo-type deposits formed under fairly low temperature conditions. Low silver, antimony, tin and bismuth, and high thallium, all features of galena in Salmo-type replacement deposits, are characteristic of galena in low temperature deposits. Such a consistent indication of low temperature of deposition could only coincidentally be attributed to availability of metals in medium or high temperature ore solutions.

B: Galena From Fissure Deposits (23 specimens)

Bismuth

Bismuth was found in 16 specimens in the range trace (less than 1 ppm) to 700 ppm but only 3 specimens (NL-4-2, BB-24 and MS) contain more than 22 ppm Bi. The high bismuth content of BB-24 (700 ppm) may indicate the presence of matildite. Other galena specimens may contain Bi in solid solution.

Tin

Tin was detected in 22 galenas in the range trace (less than 1 ppm) to 800 ppm. Only 4 galenas contain less than 28 ppm Sn, and most contain more than 100 ppm Sn. Warren and Thompson (1945) state that sphalerites of Western Canada "....tend to carry slightly higher and more uniform amounts of tin than does galena". A comparison of the author's data with that of Warren and Thompson supports this quotation. Warren and Thompson found that most sphalerites from fissure deposits in the Kootenay arc contain 100 to 1500 ppm tin in the form of cassiterite and stannite. Tin probably occurs as inclusions of such minerals in galena.

Ideal weight ratio of Cu/Sn in stannite is 1.16. Cu/Sn weight ratios for galenas from Kootenay arc fissure deposits are commonly much less than 0.5. Hence, if all the copper were in the form of stannite, this would account for only a small percentage of tin. Thus, cassiterite must be by far the most abundant tin mineral included in galena. Also, some tin could be present in solid solution in galena, and in inclusions of tetrahedrite.

Table A-III-4: Weight ratios and atomic ratios of Ag/Sb and Cu/Sb in galenas from fissure deposits in the Kootenay arc.

Sample	Weight Ratio Ag/Sb	Atomic Ratio Ag/Sb	Weight Ratio Cu/Sb	Atomic Ratio Cu/Sb
BB-2	0.961	1.084	0.0256	0.049
BB-10	0.819	0.923	0.264	0.505
BB-15	1.500	1.692	0.026	0.050
BB-24	2.720	3.068	0.640	1.225
Yale	1.430	1.613	0.394	0.755
St. Pat	1.282	1.448	0.0008	0.002
Triumph	0.750	0.846	0.054	0.103
MS	0.883	0.996	0.0006	0.001
Nicolet	1.667	1.890	0.038	0.072
BB-12	1.538	1.734	0.028	0.054
VM-4	1.042	1.176	0.086	0.164
VM-7	1.112	1.255	0.0044	0.008
VM-9	1.279	1.441	0.123	0.236
VM-13	0.755	0.851	0.059	0.114
VM-16	0.886	1.000	0.023	0.044
VM-20	0.715	0.806	0.013	0.025
NL-4-2	0.417	0.470	0.417	0.799
Scran-10	0.853	0.963	0.024	0.047
BF	0.769	0.868	0.510	0.976
Empire	1.060	1.195	0.0009	0.002
MM-3	0.556	0.627	0.031	0.059
CP-	1.177	1.326	0.0001	0.0003
NL-1-2	0.384	0.433	0.001	0.002

Copper

Copper is present in all galenas in the range 0.5 to 2,500 ppm. Most deposits contain visible chalcopyrite and/or tetrahedrite, and inclusions of these minerals and stannite probably account for copper content of galenas.

Thallium

Thallium was detected in 3 of 23 galenas. Two specimens from Victor mine, Vm-4 and Vm-13 contain 1 and 4 ppm respectively. A galena from Cork Province mine contains only a trace (less than 1 ppm) of thallium. In general, galena in fissure deposits within the Kootenay arc is characterized by absence of thallium.

Silver

Silver is present in all galenas examined in the range 400 to 5,500 ppm (i.e. 0.04 - 0.55%). The maximum amount of silver that can be in solid solut- ion in galena is about 1000 ppm (approximately 30 oz/ton) according to Edwards (1954). Hence, in at least 65 percent of galenas analysed, silver must occur in a separate phase included in galena (Table A-III-2). Microscopic examin- ation indicates that tetrahedrite is a common mineral in deposits in the Koot- enay arc closely associated with galena. If tetrahedrite accounts for most Ag and Sb, the tetrahedrite must be an almost pure antimony variety because of the negligible arsenic content in the galenas (Table A-III-2). A single pub- lished analysis of West Kootenay tetrahedrite (Table A-III-5) is arsenic- deficient. This analysis shows that West Kootenay tetrahedrite is rich in silver -- the Ag/Sb weight ratio of the analysis in Table A-III-5 being
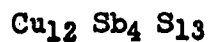
Table A-III-5: Argentian Tetrahedrite, West Kootenay
district, B. C., after Palache and
others (1944, p. 377).

	Percent cor- rected to total 100%	Atomic Proportions
Cu	22.14	0.348
Fe	0.93	0.017
Zn	6.22	0.095
Ag	11.20	0.104
Pb	9.38	0.045
Sb	28.22	0.232
As	0.23	0.003
S	21.68	0.678

Calculated Formula:

$$(CuAgZnPbFe)_{10.36} (SbAs)_4 S_{11.52}$$

Ideal Formula:

$$Cu_{12} Sb_4 S_{13}$$
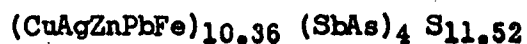
Metal/non-metal ratio in the calculated formula is

$10.36/11.52 = 11.7/13$ which is very close to the

same ratio in the ideal formula.

approximately 0.4. A comparison of this figure with Ag/Sb weight ratios in galenas from the Kootenay arc (Table A-III-4) shows that if all antimony were present in tetrahedrite, this would account for only about one-half of the silver. The highest percentage silver recorded in tetrahedrite is about 18 percent (Palache and others, 1944), which would give an Ag/Sb weight ratio of about 0.6. Hence, even assuming an extremely silver-rich tetrahedrite included in galena, much of the silver remains unexplained. Other common silver-rich minerals recognized in the Kootenay arc include argentite (Ag_2S), polybasite $(Ag,Cu)_{16} Sb_2 S_{11}$, and pyrargyrite ($Ag_3 Sb S_3$). Most galenas from fissure deposits probably contain some silver in solid solution, some silver in solid solution in tetrahedrite inclusions, and some silver in the form of one or more of the minerals argentite, polybasite or pyrargyrite.

Antimony

Antimony is present in all galenas analysed in the range 250 to 6,000 ppm (i.e. 0.025-0.6 percent). Although some antimony may be in solid solution in galena, it is probably combined with silver in included phases because:

1. range of Ag/Sb atomic ratios is narrow — 0.8 to 1.8, and

2. both silver and antimony are present in abundances one to three orders of magnitude greater than other minor elements (except zinc).

Zinc

Zinc was analysed to give some indication of amount of sphalerite present as an impurity in each speciment. In only two galenas was the amount of zinc more than 1 percent, whereas nine specimens contained less than 5 ppm zinc.

Sphalerite contamination was generally low and minor element abundances (except for cadmium) are thought representative of galena.

Cadmium

Cadmium is present in all specimens, in the range 8 - 160 ppm. In a general way high cadmium values correlate with high zinc values, but exceptions exist. For example, Scran-10 contains 120 ppm cadmium and only 15 ppm zinc. In 9 specimens containing less than 5 ppm zinc, cadmium abundances range from 18 to 30 ppm. Four of these specimens were taken from surface exposures or mine dumps and possibly galena was contaminated with cadmium released from sphalerite during weathering. However, the remaining 5 galenas come from fresh underground workings and probably indicate cadmium solid solution in galena.

Other Elements

Molybdenum (detection limit 0.1 ppm) detected in 5 of 23 specimens in amounts up to 0.5 ppm probably occurs as molybdenite.

Cobalt (detection limit 1 ppm) found in 3 specimens, Yale (0.5 ppm), BB-24 (6 ppm), and BF (4 ppm), probably occurs in pyrite inclusions.

Arsenic (detection limit 10 ppm) is present in 3 specimens: Nicolet (800 ppm), BB-12 (10 ppm), and NL-4-2 (100 ppm). Two of these hand specimens contained visible arsenopyrite.

Indium (detection limit 1 ppm) was found in 3 specimens in the range 1 - 12 ppm.

The following minerals (detection limits in brackets) were not detected:

tellurium (100 ppm), gallium (1 ppm), germanium (1 ppm), and gold (10 ppm).

Summary

Galenas from fissure deposits in the Kootenay arc generally contain 0.04-0.55 percent silver, 0.025-0.6 percent antimony, less than 22 ppm bismuth, more than 100 ppm tin, and copper in the range 0.5 to 2,500 ppm. Silver is commonly more abundant than antimony. Thallium, arsenic, cobalt and molybdenum are rarely present in detectable amounts.

Some elements may be in solid solution in galena and others must be present as separate mineral phases. Bismuth and some silver may substitute for lead in galena. Inclusions of cassiterite probably account for high tin content of galenas. Copper probably occurs as inclusions of tetrahedrite, chalcopyrite, and/or stannite. However, stannite cannot account for much of the tin content of galena. Silver and antimony are most likely combined in one or more mineral phases included in galena, but tetrahedrite, the most common sulfosalt in the Kootenay arc, cannot account for more than half the silver and antimony contained in many galenas. Zinc and cadmium are present largely as inclusions of sphalerite in galena, although there is evidence that up to 30 ppm cadmium is contained in solid solution in galena. Molybdenum, cobalt and arsenic probably occur in galena as inclusions of molybdenite, pyrite and arsenopyrite respectively.
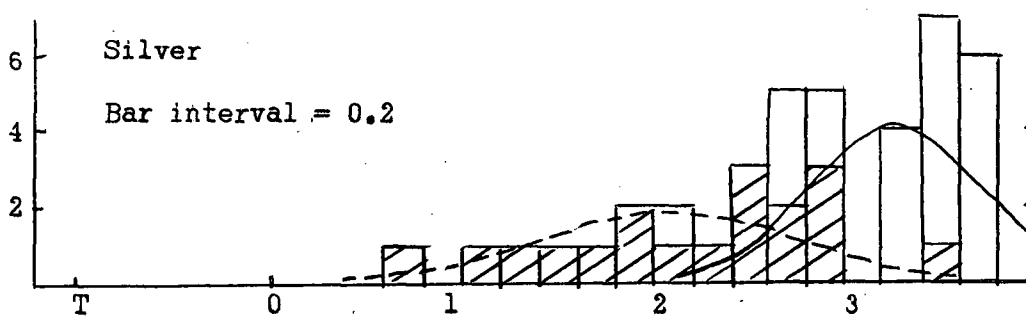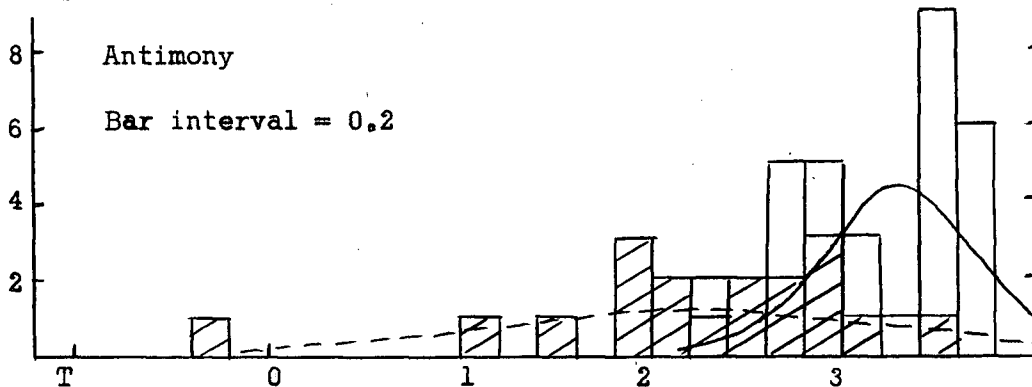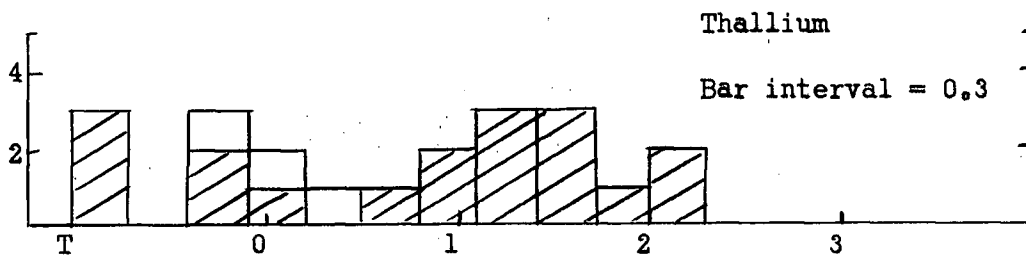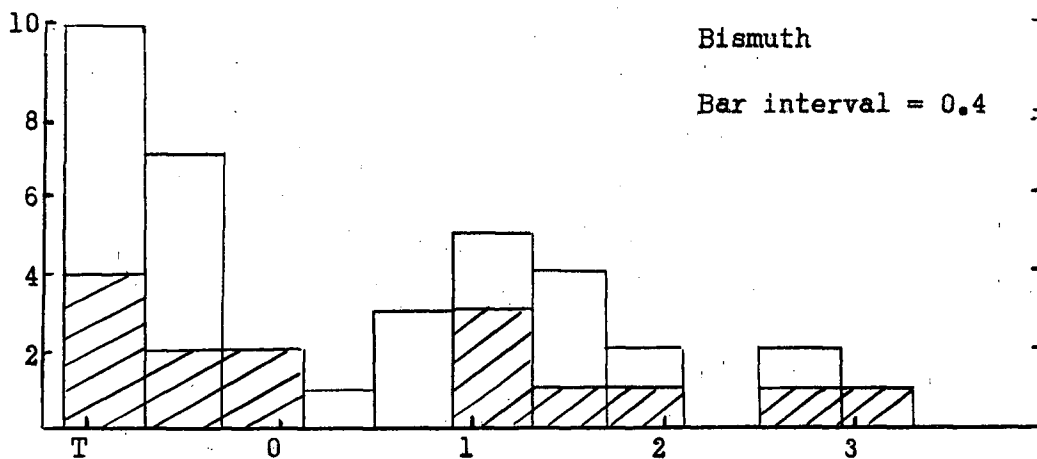
log ppm
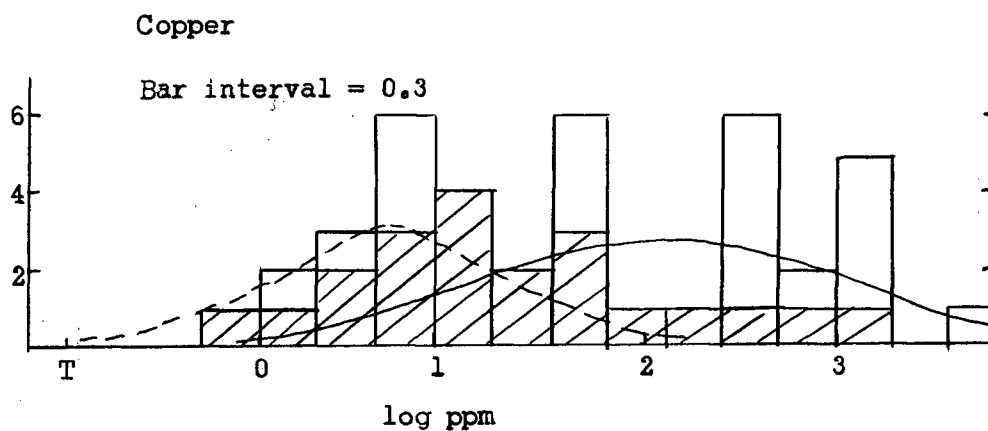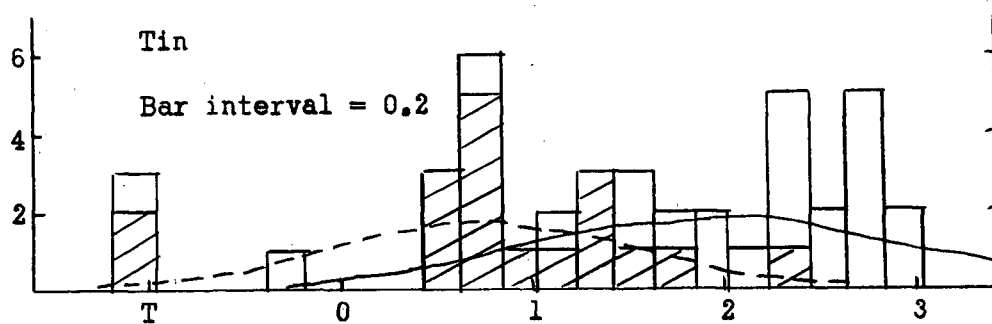
FIG. A-III-5: HISTOGRAMS OF QUANTITATIVE MINOR ELEMENT DATA FOR KOOTENAY ARC GALENAS (Analyst - R. Hibberson).

Comparison of Minor Element Abundances of Galena
From Fissure and Replacement Deposits

A summary of prominent features of minor element content of galenas from

fissure and replacement deposits in the Kootenay arc is given in Table A-III-6

and Figures A-III-5. ~~and A-III-6~~. Galena from fissure deposits generally con-

tains more antimony, silver, tin and copper than does galena from replacement

deposits. Bismuth is about the same in both classes of deposits. Thallium

is commonly present in galenas from replacement deposits, and rarely in gal-

enas from fissure deposits. Distinct differences in minor element contents

of galenas from the two groups of deposits is apparent. Some possible expl-

anations of the two different minor element populations are:

1. different sources for the two classes of deposits, with
   the implication that different amounts of minor elements
   would be present in ore-bearing solutions, and

2. different physical conditions during deposition of the
   two groups of deposits.

The fact that the same minor elements are present in both classes of

galena suggests that minerals in both classes of deposits were derived from

similar sources. This supports lead isotope data (Chapter VII). However,

the two groups of deposits could well have formed at different times and

under different physical conditions. No information is known about a poss-

ible time interval between deposition of replacement and fissure deposits

except that it probably could not have been greater than 150 m.y. but could

have been much less (Chapter VII). However, there is some evidence that re-

placement deposits formed at fairly low temperatures (cf. Whishaw, 1954;

Richardson, 1961).

Table A-III-6: Comparison of certain minor element data for galenas from replacement and fissure deposits in the Kootenay arc.

	Range of values in galena from:	
	Replacement deposits	Fissure deposits
Bismuth	25 ppm	22 ppm
Tin	25 ppm	100 ppm
Copper	24 ppm	0.5 - 2,500 ppm
Thallium	Generally present up to 150 ppm	Not detected (less than 1 ppm)
Silver	14 - 750 ppm	400 - 5,500 ppm
Antimony	10 - 1,250 ppm	250 - 6,000 ppm
Ag/Sb (atomic)	1.0	0.8 - 1.8

Galena in replacement deposits contains low Sn, Ag, Sb, and high Tl rel-
ative to galena in fissure deposits. As noted, these are all features of low
temperature deposits (cf. Fleischer, 1955; Kagaya, 1963). Sphalerite in re-
placement deposits ordinarily contains a few percent iron or less except in
places where late dikes have thermally metamorphosed sulfides. On the other
hand, fissure deposits in the arc are generally characteristic of Lindgren's
class of mesothermal sulfide deposits (Lindgren, 1933, p. 569). One except-
ion is Bluebell mine where geothermometry studies indicate a minimum temper-
ature of deposition of sphalerite and pyrrhotite of about 470°C (Arnold, 1961).
The fact that abundances of 5 minor elements indicate lower temperatures of
deposition for replacement deposits than for fissure deposits provides a
reasonable argument for low to moderate temperature of deposition of Salmo-
type replacement deposits. Whishaw (1954) and Richardson (1961) compare
Jersey mine and Duncan Lake mine respectively, with Mississippi Valley-type
deposits and thereby imply low temperatures of sulfide deposition.

Conclusions

No obvious relationship exists between minor element content and lead
isotopic composition of galena from the Kootenay arc. However, deposits in
the arc can be grouped into two general subdivisions, replacement and fissure
deposits; and galenas from each group have distinctive minor element contents.
Similar minor elements in galenas from replacement and fissure deposits sugg-
ests that all sulfides were derived from similar sources. Lead isotope data

implies that these sources were in the crust.

Tin is consistently present in galenas in the Kootenay arc, supporting the conclusion of Warren and Thompson (1945) and Lang (1961) that this region is a tin metallogenetic province. Several lines of evidence suggest that the area is deficient in arsenic. In general, sulfosalts containing appreciable arsenic are not found. Arsenopyrite is present in some deposits but is generally rare. Arsenic was found in only 3 of 41 galenas analysed, despite the fact that arsenic is a common trace element in galena (Fleischer, 1955). Warren and Thompson (1945) found a trace of arsenic in only 6 of 52 sphalerites from the region.

Minor element abundances have been used to determine if spatially related deposits were derived from one or more sources (cf. Warren and Thompson, 1945, p. 330). Results described here show a wide range of abundances of an element where several galena specimens from a single deposit were analysed. Thus, conclusions as to common or different sources for deposits require detailed study of the deposits in question. Regional data reported here are inadequate for such work.

Minor element data reported here suggest, but do not prove, that replacement deposits formed at lower temperature than fissure deposits.

APPENDIX IV

MINERALOGRAPHY OF SALMO-TYPE ORES

Introduction

The term "Salmo-type deposit" refers to lead-zinc replacement bodies in

dolomitic parts of the Reeves limestone, and includes Jersey, H. B. and

Reeves Macdonald mines and Jackpot showing. General characteristics of these

deposits are outlined in Chapter V. Although many geological accounts of

Salmo-type deposits have appeared in the literature (e.g. Fyles and Hewlett,

1959) no descriptive mineralography has been published. This study is based

on specimens collected by the author in the fall of 1960. Jersey mine is

discussed in some detail because of the large suite of ore specimens avail-

able for study. Only brief reference is made to the other deposits to illus-

trate the general similarity of textures, mineralogy and paragenesis among

Salmo-type deposits.

Jersey Mine

At least two periods of mineralization occurred at the Jersey mine. A

major lead-zinc mineralizing episode that formed replacement ore deposits

was followed by a period of open space filling spatially related to post-ore

granitic intrusions.

The early period of lead-zinc ore mineralization resulted in deposition

of pyrite, sphalerite, galena, and minor amounts of chalcopyrite in a gangue
mainly of dolomite. In places gangue is skarn or more rarely, quartz. A
small amount of pyrrhotite is present, but as shown later, most of this
appears to be a product of thermal metamorphism of pyrite and not a primary
constituent of the lead-zinc ore. The megascopic structure of the ore diff-
ers from place to place in the mine. Generally, sulfides have a layered
aspect that may be either a primary or secondary feature. Primary layered
structure is of two main types; one in which nearly monominerallic contin-
uous layers of different sulfides are intercalated with layers of dolomite
(Figure A-IV-1); and a second in which discontinuous elongate blebs or agg-
regates of dolomite or a particular sulfide are strung out in a matrix of
mixed sulfides or gangue (Figure A-IV-2). Secondary foliation in the ore is
the result of deformation of pre-existing sulfides by shearing, still main-
taining coherence of the ore (Figure A-IV-3). Megascopic evidence of deform-
ation includes:

1. Porphyroclasts of pyrite with "trails" of broken fragments
   strung out parallel to the foliation.

2. Gneissic structure in sulfides reflected in a variation in
   grain size of sulfides from one layer to another.

3. Elongate blebs of galena that parallel gneissic structure.

4. Foliation in sulfides commonly at an angle to foliation
   in included fragments of dolomite.

Time of deformation of sulfides is not known but shearing probably occurred
during or after emplacement of the Emerald stock and related granitic intrus-
ions.

A second episode of mineralization resulted in the formation of small
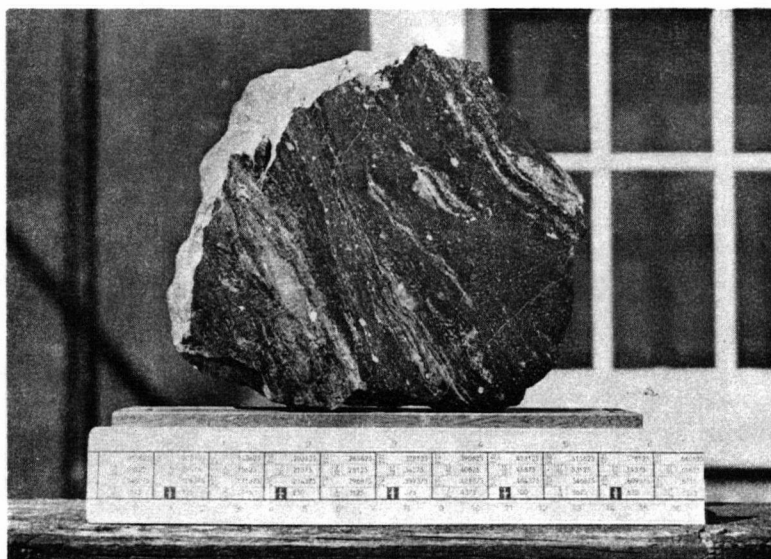
FIG. A-IV-1: Polished surface of deformed sulfides - Jersey
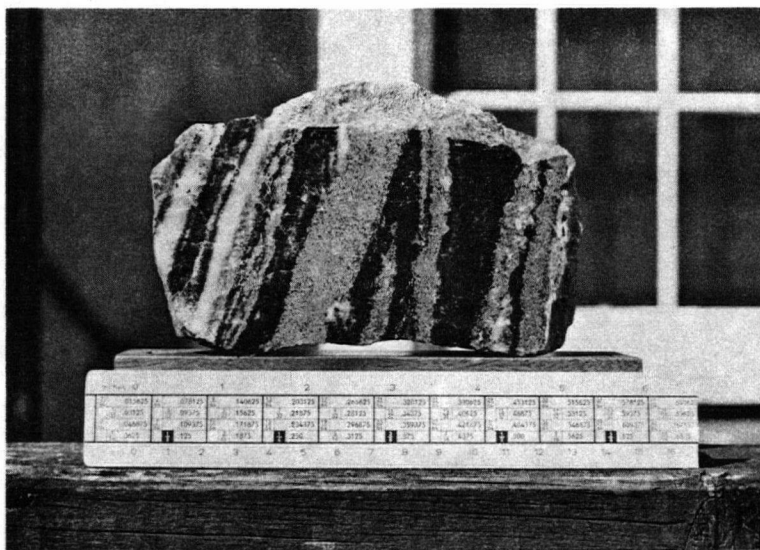   mine, B zone.

FIG. A-IV-2: Polished surface of ore with monomineralic layers
of pyrite, sphalerite and dolomite, Jersey mine,
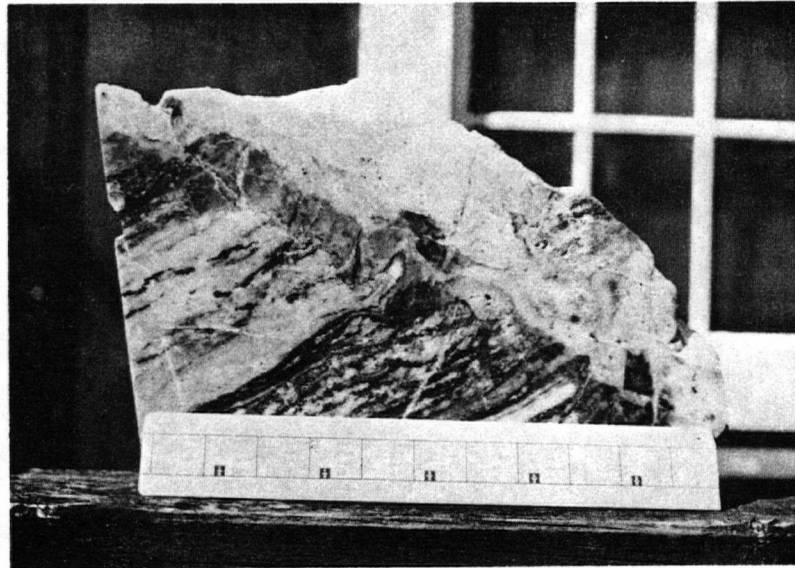85-G-1 subdrift north.

FIG. A-IV-3: Polished surface of discontinuous layers of
sphalerite in dolomite. Ore is cut by a
granite dike that has a thermal aureole about
one inch wide evident in the figure. Specimen
courtesy of J. Bristow.

veinlets some of which crosscut lead-zinc ore. Although there is no evidence

as to whether or not these veinlets formed contemporaneously, they probably

are related genetically to granitic intrusions and thus may be related to

scheelite-mineralized skarns. Veins commonly are about one-eighth inch wide

or less and only rarely have widths exceeding one-half inch. Vein minerals

include calcite, quartz, arsenopyrite, pyrite, pyrrhotite and chalcopyrite

although in no case investigated by the writer were all minerals found in a

single vein. A few examples will illustrate variations in vein mineralogy.

Where a post-ore fault, the F-8, cuts 52E drift north a fault breccia zone

2 feet wide made up of angular fragments of dolomite is cemented by coarse-

grained calcite. In 58H crosscut east a vein rich in arsenopyrite with

minor amounts of pyrite, quartz and calcite cuts layered dolomite. Small

veinlets of pyrrhotite, calcite and chalcopyrite are common in skarns.

Mineralography of Lead-Zinc Ores

Pyrite has several distinct textural variations. Where pyrite is the

most abundant mineral present it occurs generally as a compact mass of even-

grained subhedral crystals. Cubes and pyritohedrons are the common forms.

If dolomite and abundant pyrite are the only minerals present pyrite commonly

exhibits some crystal faces but other crystals appear to be relicts and to

have been replaced in part by dolomite. In a few cases replacement veinlets

of dolomite, continuous with interstitial dolomite, crosscut pyrite. These

relations indicate that at least some of the dolomite in the vicinity of the

lead-zinc ore was deposited later than pyrite.

Where isolated crystals of pyrite occur in a groundmass of dolomite and/or other sulfides, pyrite has one of two forms. It may occur as small blebs with rounded corners and some embayments of matrix material, or, as large relict crystals of pyrite, in part fractured, and excessively and intricately embayed at their margins. In deformed ore, large masses of pyrite have been broken and fragments somewhat rounded and strung out in planar orientation.

Sphalerite does not have good crystal form. Galena and sphalerite normally have mutual boundary relations, although in places galena embays and crosscuts sphalerite. When completely enclosed in galena, sphalerite commonly occurs as rounded blebs. In a dolomite matrix sphalerite occurs as irregular shaped grains generally with rounded edges and more rarely with small offshoots extending between dolomite grains. Sphalerite is embayed in some pyrite crystals. Most sphalerite grains are twinned.

Chalcopyrite is a minor but widely dispersed constituent of Jersey ore, invariably associated with sphalerite or pyrrhotite. Mutual boundary relations exist between chalcopyrite and sphalerite, and chalcopyrite and pyrrhotite, suggesting contempraneous crystallization of these two mineral pairs. This does not imply contemporaneous crystallization of sphalerite and pyrrhotite unless ores have been thermally metamorphosed. Two grains of sphalerite were observed that contained evenly distributed minute blebs of chalcopyrite that resembled exsolution texture. Both grains, however, occurred in speciments that had been thermally metamorphosed and the exsolution texture cannot

FIG. A-IV-4(a): Massive pyrite, Jersey mine (X40). Small
amounts of interstitial quartz.
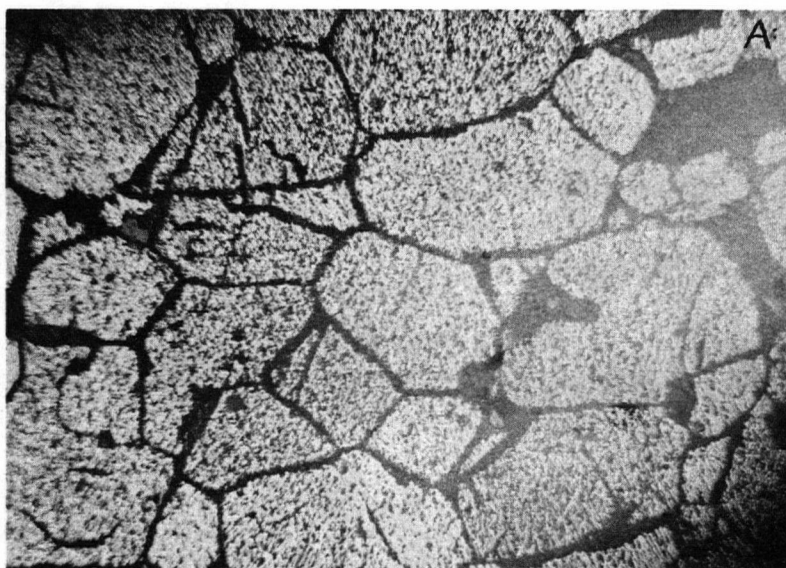
FIG. A-IV-4(b): Irregular grain of pyrite in dolomite
gangue, Jersey mine (X40).
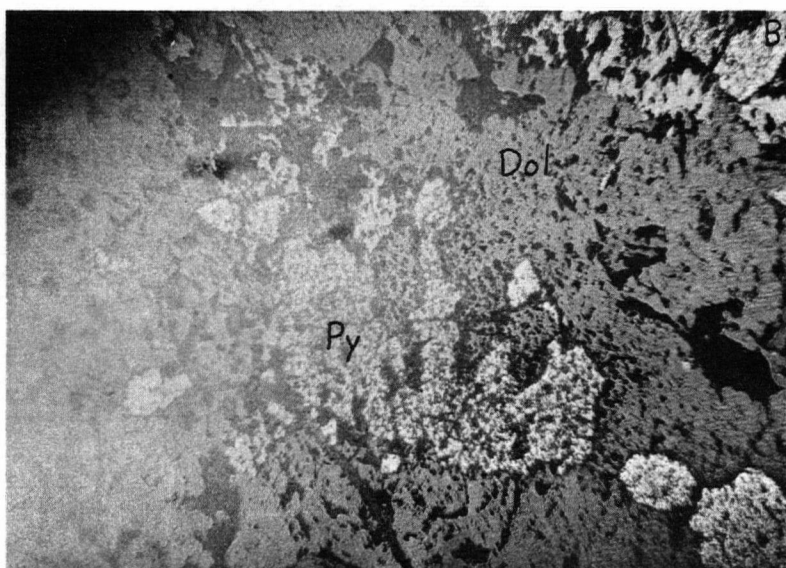
FIG. A-IV-4(c): Relict grain of pyrite in large mass of
pyrrhotite, Jersey A zone (X40).
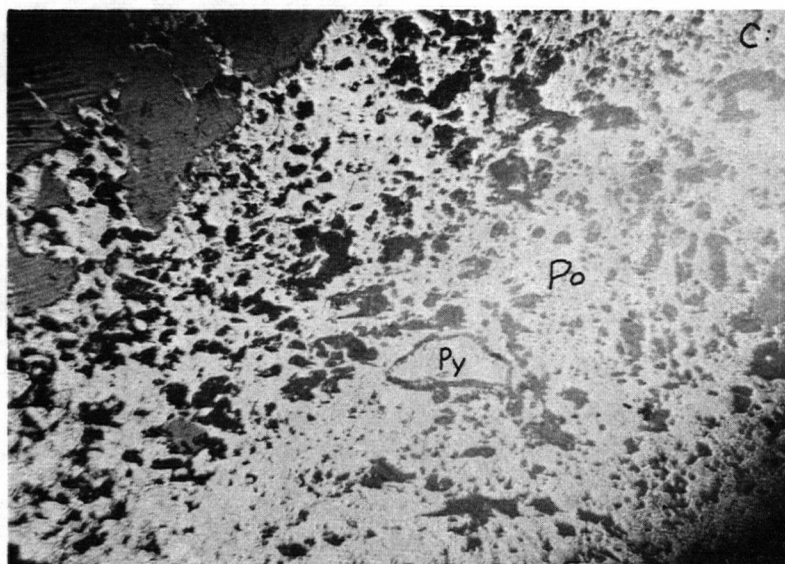
FIG. A-IV-4(d): Vein of dolomite crosscutting sphalerite
grain, Jersey mine (X40). Dolomite vein
is continuous with large masses of dolomite
gangue.
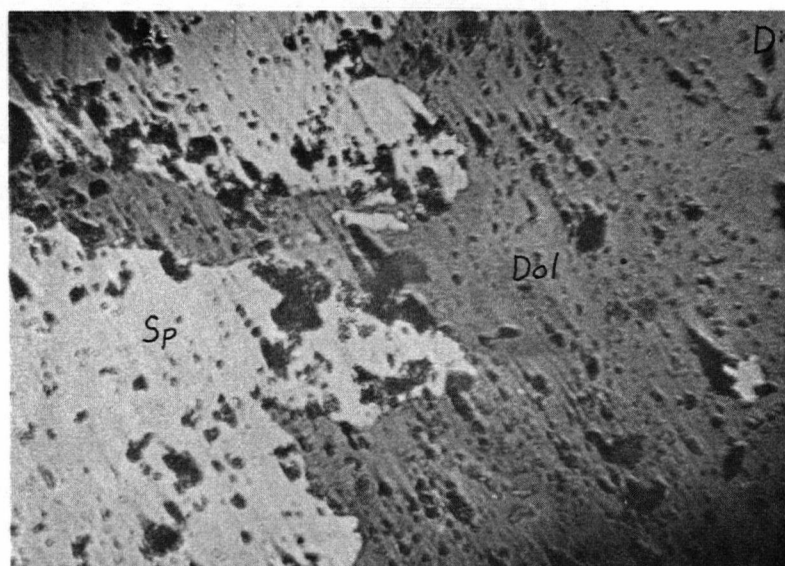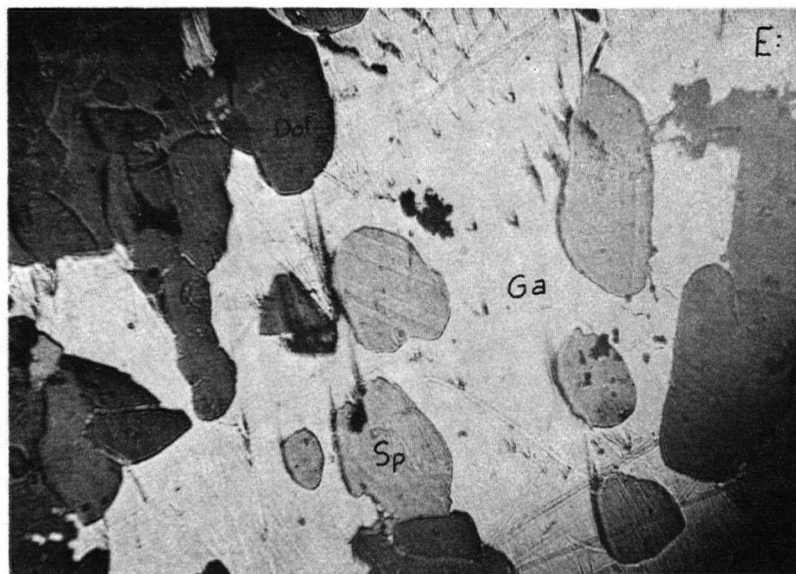
FIG. A-IV-4(e): Sphalerite grains wish rounded edges in galena (X40).
Note twinning in sphalerite. Typical texture in
Jersey A zone.

be used to place limits on the temperature of deposition of the replacement ore.

Galena invariably occurs interstitially to other constituents of the ore in highly irregular blebs. Where a large galena bleb is surrounded by dolomite small blebs of galena in dolomite form a ring around the larger galena mass (Figure A-IV-4). These small blebs occur both along boundaries of, and within, dolomite grains. Galena generally has mutual boundary relations with sphalerite but commonly penetrates and replaces sphalerite. In several specimens triangular cleavage pits in galena were curved indicating deformation by translation gliding.

A paragenetic sequence of primary ore minerals is outlined in Figure A-IV-5. Age relations indicated are based on veining relations and extensive penetration of one mineral by another. Contemporaneous deposition shown in the diagram is based on the prevalence of mutual boundary relations.

Pyrrhotite is present in minor amounts in all Salmo-type replacement deposits and occurs in several different geological environments. Fyles and Hewlett (1959, p. 83) report that at the Reeves Macdonald mine pyrrhotite "is found only within and at the margins of certain lamprophyre dykes which cut the ore." At the Jersey mine pyrrhotite is found:

1. in small quartz and calcite veinlets that crosscut replacement ore near the border of the Emerald stock;

2. at the border of granite dikes that crosscut replacement ore;

3. in skarn as irregular blebs and in small calcite veins; and

4. at north and south ends of the A zone orebody.

Dolomite ——————————— — — — — — ——————— — — — —

Pyrite   ————————————

Pyrrhotite   — — —

Sphalerite   ———————————

Chalcopyrite   ——

Galena   ——————————————

(a) Primary Replacement Ore

Quartz   — — — ——————— — — — — — — — — — — — — —

Arsenopyrite   ————

Pyrite   ————

Pyrrhotite   ————————

Chalcopyrite   ——

Calcite   —————————

(b) Post-Ore Veins

FIG. A-IV-5: Paragenesis — Jersey mine.

The first three associations above suggest that much pyrrhotite is a
product of thermal metamorphism of pyrite in replacement ore, although some
pyrrhotite in veins may have been introduced during a mineralizing episode
related to emplacement of the Emerald stock. However, there are no field
data to suggest whether or not pyrrhotite in the A zone is the result of
metamorphism or was an original constituent of the replacement ore. Two
large specimens of sulfide ore containing abundant pyrrhotite from the north
end of Jersey A zone were examined in polished surfaces to determine whether
a distinct paragenetic sequence existed or whether sulfides had crystallized
contemporaneously.

Pyrrhotite occurs in large irregular blebs, elongate in the plane of
foliation of the dolomite host. Small stringers extend between grains of
dolomite from large pyrrhotite masses. No crosscutting relations between
pyrrhotite and dolomite were observed. Dolomite is a compact mass of fine,
even-grained particles. Similarly, large masses of pyrrhotite are made up
of a compact mass of grains of more-or-less uniform size except for some
small particles that occur along grain boundaries of dolomite. A few small
relicts of pyrite with irregular boundaries occur in some of the large
pyrrhotite blebs. Other sulfides present in very minor amounts are sphaler-
ite, chalcopyrite and galena. These minerals generally have mutual boundary
relations with pyrrhotite. No diagnostic criteria were observed that indic-
ated an orderly sequence of deposition except for relict grains of early
pyrite. Textural relations thus do not indicate a sequence of deposition
among pyrrhotite, sphalerite, chalcopyrite and galena, but are compatible
with the suggestion that these minerals crystallized in their present forms

at the same time, probably as a result of metamorphism.

Mineralography of Post-Ore Veins

An extensive investigation of post-ore veins was not undertaken. However, some conclusions can be drawn on the basis of observation of numerous veins in the field and examination of several of these in polished sections. Minerals identified by the writer include quartz, arsenopyrite, pyrite, pyrrhotite, chalcopyrite and calcite, in that order of deposition (Figure A-IV-5). Paragenetic relations are based entirely on crosscutting relations and the presence of relicts of euhedral crystals that have been partly replaced. Some overlap of deposition of certain minerals is assumed on the basis of mutual boundary relations.

It is worthwhile to note certain contrasting features of lead-zinc ores and post-ore veinlets. The ore apparently was formed entirely by replacement processes whereas post-ore veins are open space fillings. Also, mineral assemblages characteristic of the two periods of mineralization are different.

H. B. Mine

Ore bodies at the H. B. mine are of two types: flat-lying, tabular, mineralized breccias and steeply dipping "stringer lodes" (Warning, 1960). Tabular ore bodies are thought to have formed by replacement of fault

breccias. "Stringer lodes" consist of numerous replacement stringers of sulfides that more-or-less parallel steeply dipping cleavage in wallrock. Stringer ore bodies are much larger than breccia ore bodies. Gangue is mainly dolomite but, in places, tremolite and talc are common. According to Warning (1960) talc and tremolite are pre-ore. Paragenetic relations of ore minerals in both types of ore bodies appear to be the same.

Mineralography of Lead-Zinc Ores

Dolomite and pyrite are the most abundant minerals in ores at the H. B. mine. Only rarely does pyrite exhibit crystal faces in contact with dolomite. Normally pyrite occurs as irregular blebs or masses of numerous anhedral to subhedral crystals of a wide range of sizes. In a few places cubic cross-sections of pyrite contain abundant irregular embayments of dolomite. Several examples of replacement veins of dolomite in pyrite were observed. These dolomite veins are continuous with dolomite matrix.

Generally dolomite patches consist of masses of very fine-grained, an-hedral, twinned crystals. These patches occur as irregular masses of a wide range of sizes or as discontinuous layers with irregular borders.

Sphalerite occurs as irregular blebs of different sizes, made up of numerous small, twinned, anhedral crystals. Embayments of sphalerite in pyrite are common and, in places, very small irregular blebs of sphalerite are strung out along grain boundaries in dolomite.

Galena is a minor constituent of the specimens examined, and charact-

eristically occurs as very small blebs along grain boundaries of dolomite

crystals. A few large irregular galena blebs were observed with thin irreg-

ular protrusions extending between grains of surrounding minerals.

Textural relations indicate a paragenesis similar to that at the Jersey

mine (Figure A-IV-5) except that the position of pyrrhotite in the sequence

is uncertain. Warning (1960) states:

> "Pyrrhotite is present sparingly in No. 1 zone and in somewhat
> larger quantity in X-1 zone, in association with galena."

A single specimen of pyrrhotite from X-1 zone studied by the writer indicated

that pyrrhotite was later than dolomite and probably earlier than galena.

Relations of pyrrhotite with pyrite and sphalerite could not be determined.

There is neither field nor microscopic evidence to indicate that this pyrr-

hotite is a product of metamorphism as seems to be the case at the Jersey

mine. Thus pyrrhotite may be a primary constituent of H. B. ore.

A single specimen of a "late vein" younger than the period of ore min-

eralization and containing abundant arsenopyrite was supplied by Dr. W. H.

White. Examination of this specimen in polished section indicated two dist-

inct phases of mineralization. An early phase resulted in the deposition of

arsenopyrite, pyrite and quartz. Arsenopyrite and pyrite appear to have

formed euhedral crystals contemporaneously. Interstitial quartz is in part

younger than these sulfides. A second phase of mineralization evident in the

same specimen resulted in deposition of calcite and small amounts of galena

and sphalerite. Both galena and sphalerite occur as small irregular blebs

at grain boundaries of calcite. Minerals of the second phase of deposition,

vein and replace minerals of the first phase of deposition.

The presence of rare post-ore veins rich in arsenopyrite compares with similar veins at the Jersey mine.

Reeves Macdonald Mine

Sulfides at the Reeves Macdonald mine occur in the trough of a phase II syncline on the south limb of the Salmo River (Phase I) anticline. Ore bodies have the form of a syncline as do the surrounding "envelopes" of dolomite. Primary ore minerals are pyrite, sphalerite and galena in a gangue mainly of dolomite and some quartz. Pollock (1960) states:

> "The ore has a banded appearance and may be partially brecciated. A band of breccia ore extends along the footwall branch. This breccia ore has a matrix of massive sulphides (mainly pyrite) with angular fragments of both limestone and dolomite scattered throughout."

Specimens collected and examined by the writer are mainly from pyrite-rich parts of mineralized dolomite and are not representative of the entire ore body. However, there is some evidence that extensive deformation followed deposition of at least some of the sulfides.

In one hand specimen sharply folded pyrite layers less than 1/8 inch thick had slickensided surfaces developed parallel to layering on pyrite on limbs of small folds indicating intense deformation after deposition of pyrite. In some places large blebs of pyrite had "trails" of smaller grains strung along a secondary foliation and may represent pyrite porphyroclasts.

Crosscutting the ore and dolomite are small vertical dilation veins containing coarse-grained quartz, dolomite, calcite and sulfides. Polished sections of these veins were not examined by the writer.

Mineralography of Reeves Macdonald Ores

Textural evidence suggests that some pyrite has been deformed extensively. Only a few of the specimens examined contained pyrite in contact with dolomite, but here pyrite occurred as angular fragments with a wide range of sizes. Commonly these fragments were strung out parallel to a secondary foliation. Pyrite was observed most commonly in contact with calcite and quartz, and occurred as subhedral crystals and completely irregular blebs containing embayments of both calcite and quartz. Crystal faces of pyrite are rare and where subhedral crystals occur, corners normally are rounded. In a few places small cubes of pyrite with sharp corners are present.

In two specimens large round fragments of pyrite with more-or-less concentric layering were observed. For the most part these round masses are made up of elongate blebs of pyrite that parallel concentric layering and have irregular edges. A few of the small blebs in the larger masses, however, have square cross-sections. These large round blebs may represent primary iron sulfide that has in part recrystallized. In addition to being deformed, pyrite may also have been slightly metamorphosed.

Where enclosed in galena and/or sphalerite, pyrite blebs are generally well rounded.

Only a small amount of galena and sphalerite were observed. These minerals appear to be in part contemporaneous. However, much of the galena present occurs along contacts of sphalerite with other minerals suggesting that galena is in part younger than sphalerite. Both these sulfides appear younger than calcite and quartz.

Relative ages of calcite and quartz could not be determined. Both minerals commonly occur together as irregular masses of fine-grained, anhedral crystals, and both replace pyrite. Large irregular masses of quartz and calcite containing sphalerite and galena but devoid of pyrite are common.

Paragenetic relations are summarized as follows: pyrite and dolomite formed first but relative ages of these two minerals are unknown. In places, these minerals were deformed and possibly recrystallized. Following deformation calcite and quartz were deposited perhaps contemporaneously, followed by sphalerite and galena in that order. Sphalerite and galena may be in part contemporaneous.

Mineralogy and paragenetic sequence reported here refer to fringes of ore zones at the Reeves Macdonald mine and may not be completely representative of ores themselves. Some apparent differences of Reeves Macdonald ores compared with Jersey and H. B. ores are:

1. Absence of pyrrhotite except at contacts of lamprophyre dikes.

2. Evidence of deformation of pyrite prior to deposition of galena and sphalerite.

3. Evidence of two distinct phases of ore mineral deposition separated by deposition of gangue minerals calcite and quartz.

4. Abundant calcite and quartz.

5. Complete absence of copper minerals in all polished sections examined.

Jackpot Showing

Several ore mineral specimens from Jackpot showing were collected mainly from "muck piles" near adits and trenches. Hence, precise locations and field relations of these specimens are not known. White (1960) states that some sulfide masses have been thermally metamorphosed. Consequently, it is difficult to compare mineralographic results from Jackpot specimens with those from other Salmo-type deposits.

However, examination of polished sections did reveal differences in mineralogy between some of the Jackpot showings and other Salmo-type deposits. Calcite is a common gangue mineral and one of the showings, on the Jackpot property, the Hunter V open pit, occurs in limestone rather than dolomite. Both tetrahedrite and chalcopyrite were also found and both these minerals are closely associated with galena. Mutual boundary relations exist among these three minerals.

Although some veining relations among ore minerals can be seen in polished sections, it is difficult to evaluate sulfide paragenesis because of the lack of knowledge of field relations of specimens investigated.

APPENDIX V

DESCRIPTION OF SPECIMENS ANALYSED ISOTOPICALLY

182 (LS-4): Lakeshore showing, Ainsworth, B. C. Located 20 feet above 2552

    crosscut east in E raise. Collected by A. J. Sinclair. Specimen is a

    small replacement pod of coarse-grained galena and a little pyrrhotite.

    Wallrock is crystalline limestone with alternating white and grey lay-

    ers. Sulfides cut across layering in limestone.

237: Bluebell mine, Riondel, B. C. Located in Kootenay Chief ore zone, 414

    raise. Specimen originally analysed at the University of Toronto

    (Toronto specimen no. 870; see also Kanasewich, 1962a). Specimen des-

    cription not available.

282 (DL-18): Duncan Lake showing on a peninsula on the east shore of Duncan

    Lake, B. C. Located in No. 7 zone, diamond drill hole C-9, 331 foot-

    age. Collected by A. J. Sinclair. Specimen consists of small irreg-

    ular masses of coarse-grained galena and a small amount of pyrite in a

    gangue of dolomite and quartz. In polished section pyrite is seen to

    occur as anhedral blebs of different sizes. Galena occurs as large

    irregular masses containing a few small rounded blebs of sphalerite,

    and as extremely small blebs interstitial to grains of gangue minerals.

283 (CS-3): Jersey mine, near Salmo, B. C. Specimen taken from north end of

    A zone. Approximate coordinates on mine grid system are 9500N and

7550E. Collected by A. J. Sinclair. Specimen is a 3 inch wide, mass-
ive galena layer in pyrrhotite-rich part of the ore zone. Pyrite is
a minor constituent. Sulfides are medium- to coarse-grained. Gangue
is mainly fine-grained, buff-coloured dolomite but numerous large
irregular blebs of coarse-grained white calcite are present in the
galena layer.

284 (JP-12): Jackpot showing, near Ymir, B. C. Specimen taken from mudk pile
near workings of main zone. Collected by A. J. Sinclair. Specimen
consists of coarse-grained massive galena with some pyrite and a small
amount of dolomite gangue.

285 (RM-1): Reeves Macdonald mine, Remac, B. C. Main zone, 1570 level, foot-
wall branch of ore near shaft. Collected by A. J. Sinclair. Specimen
is a vertical vein, one-quarter inch wide, that cuts layering in dolom-
ite. Vein minerals are pyrite, galena, calcite and honey-coloured
sphalerite -- all coarse-grained.

286 (HB-17): H. B. mine, near Salmo, B. C. X-2 zone, 87 stope, west wall.
Collected by A. J. Sinclair. Specimen is from a pyrite stringer 3
inches to 1 foot wide containing some medium-grained galena. The
stringer cuts across layering in dolomite and small protrusions from
the pyrite penetrate dolomite parallel to layering.

287 (CX-11): Jersey mine, near Salmo, B. C. 58A stope in central part of
A zone above Dodger 4200 portal. Approximate coordinates on mine grid

system are 6100N and 7270E. Collected by A. J. Sinclair. Fine-grained layered galena in dolomite is cut by a lamprophyre dike. An irregular thermal metamorphic aureole about 1 inch wide occurs at the contact of the dike. This aureole consists of anastomosing veinlets of coarse-grained galena. Galena from this thermal aureole was analysed isotopically. Outside the aureole macroscopic chalcopyrite is present, a rarity in Jersey ore.

288 (CX-42): Jersey mine, near Salmo, B. C. 53-H crosscut east at the south end of F zone. Collected by A. J. Sinclair. The specimen is a small pod of massive sulfides in pale green, fine-grained calc-silicate rock, that occurs less than 1 foot from the border of a granite dike 40 feet wide. Sulfides occur in three nearly monominerallic layers. Sulfide layers outline a sharp fold. Core of the fold is pyrrhotite surrounded by a galena-rich layer one-half to one inch thick. A thin layer rich in dark brown sphalerite occurs around the nose of the fold. Crosscutting sulfides and calc-silicate rock are thin veinlets of calcite with some quartz. Where these veinlets cross calc-silicate rock irregular bleached zones up to 1 inch wide are developed. Thin section study shows that bleaching is the effect of carbonatization of diopside.

289 (C-3): Cotton Belt showing, 18 miles north of Seymour Arm, B. C. Speciment from muck pile near portal of No. 2 tunnel. Collected by J. T. Fyles. Specimen is entirely coarse-grained massive sulfides, mainly galena with some dark brown sphalerite.

290 (W-6): Wigwam showing, 14 miles south of Revelstoke, B. C. Collected by
J. T. Fyles. Specimen is coarsely crystalline galena and subordinate
pyrite in folded white crystalline limestone. Elongate masses of sul-
fides with irregular borders both parallel and cut layering in lime-
stone.

291 (Sal-A): Sal showing, A zone. Located on Mt. Willet just east of the
north end of Kootenay Lake. Collected by J. T. Fyles. Specimen is
massive white quartz containing irregular blebs of coarse-grained
galena and some pyrite.

292 (V-2): Ruddock Creek showing on Gordon Horne peak, 60 miles northwest
of Revelstoke, B. C. Collected by J. T. Fyles. Specimen is a fine-
grained thinly layered rock consisting mainly of quartz and sphaler-
ite. Small amounts of galena occur interstitially to sphalerite.
Thin section study indicates that sulfides occur in a mylonite.

293 (RM-5): Reeves Macdonald mine, Remac, B. C. Main zone, 1460 east stope.
Collected by A. J. Sinclair. Specimen is a layer of massive pyrite
1 inch thick that parallels layering in wallrock. Main gangue miner-
al is calcite. A small amount of sphalerite is present and only
traces of galena.

294 (VM-16): Victor mine, near New Denver, B. C. No. 9 level at base of
959 raise. Collected by A. J. Sinclair. Massive coarse-grained gal-
ena with curved cleavage faces in a 1 inch wide part of a vein.

Nearby the vein contains some quartz.

295 (Scran-10): Scranton mine, about 10 miles southwest of Kaslo, B. C.
Collected by A. J. Sinclair. Specimen taken at portal where vein in
Nelson batholith is about 3 inches wide. Vein minerals in order of
deposition are quartz, pyrite and galena. Galena is coarse-grained
and occurs in the centre of the vein.

300 (CX-1): Jersey mine, near Salmo, B. C. South end of A zone. Coordin-
ates on mine grid are approximately 5050N and 7200E. Collected by
A. J. Sinclair. Well-layered, medium-grained, massive sulfides con-
sisting mainly of galena. Layering is apparent because of "streaks"
of pale brown sphalerite. Within galena-rich parts of the ore are
irregular masses of white, coarse-grained calcite.

317 (MS): Moonshine Right Bower showing, near Lardeau, B. C. Specimen
from surface exposure in vein where old workings broke through to
surface. Collected by A. J. Sinclair. Specimen consists entirely of
coarsely crystalline galena.

318 (MM-3): Mollie Mac showing, Ferguson district, B. C. Surface exposure
about 100 feet uphill from main adit. Collected by A. J. Sinclair.
Specimen is disseminated blebs of medium-grained galena in limestone.
Limonite is abundant.

321 (SK-3): Sullivan mine, Kimberley, B. C. Obtained from Cummings' coll-
ection of Sullivan ore at the Department of Geology, University of

British Columbia. Central ore zone — exact location unknown. Specimen consists of medium-grained galena with some sphalerite, pyrite and pyrrhotite. Pyrrhotite occurs in elongate discontinuous sheets that give the ore a layered appearance.

323 (SK-5): Sullivan mine, Kimberley, B. C. Obtained from Jewett's collection of Sullivan ore at the Department of Geology, University of British Columbia. H-12-6 stope, "I" ore zone adjacent to Burchell fault. Specimen consists of medium-grained sphalerite and galena.

APPENDIX VI

LEAD TETRAMETHYL PREPARATION

Sample preparation involves four stages: (1) handpicking and crushing of galena cleavage fragments, (2) lead iodide production, (3) production of a lead tetramethyl-ether solution, and (4) purification of lead tetramethyl by a gas chromatographic procedure. Normal laboratory procedure is to take a group of samples through one stage before proceeding with the next stage, thus allowing for semi-mass production of samples for mass spectrometric analysis.

Separation of Pure Galena

With the aid of a binocular microscope approximately 10 grams of hand-picked galena cleavage fragments are separated from a crushed mineral specimen and finely ground in an agate mortar. Where galena was intimately mixed with other sulfides the whole specimen was pulverized.
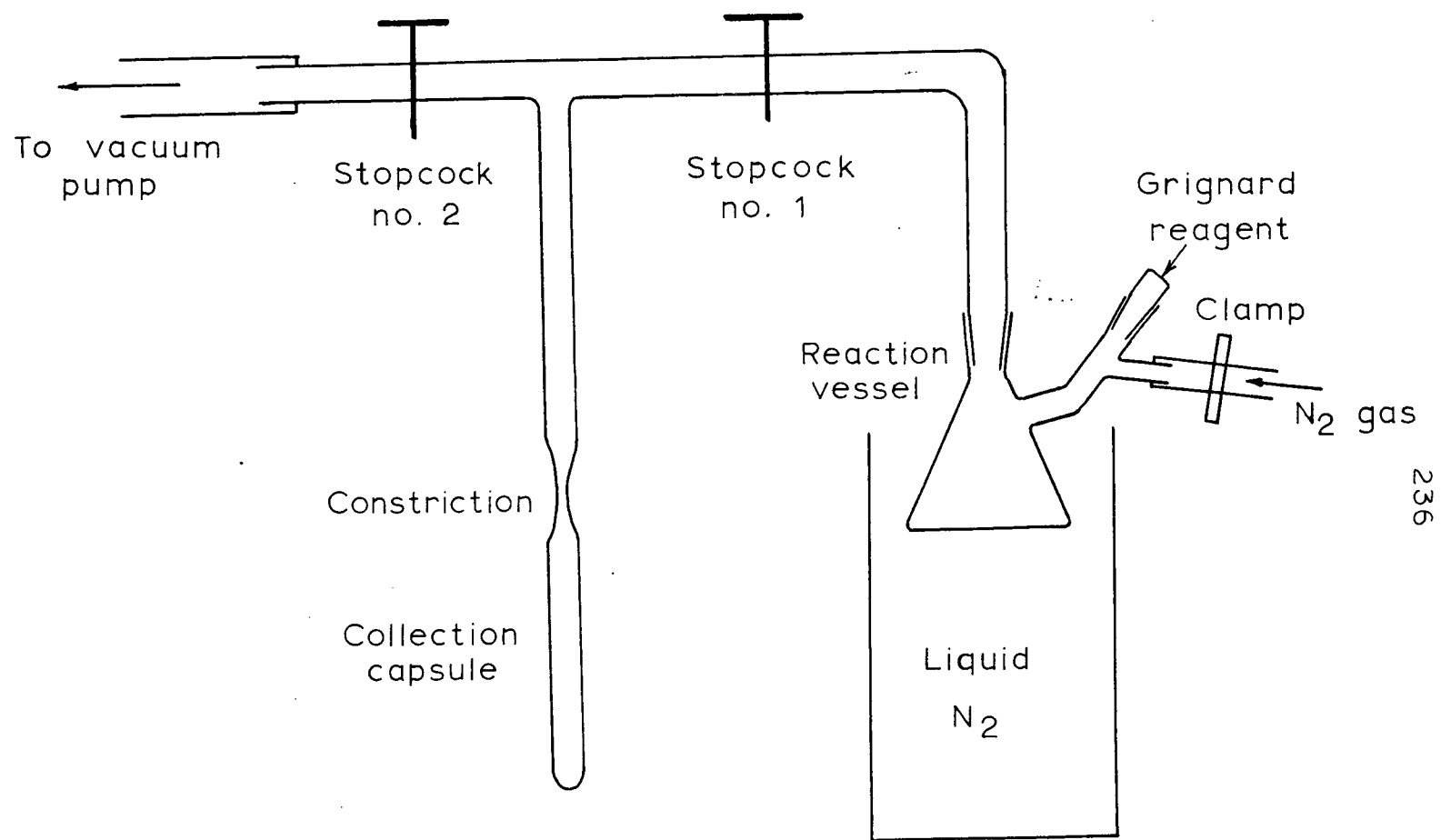

Lead Iodide Preparation

Crushed galena boiled in 100 ml. of 20 percent (by volume) HCl for one hour produces a saturated solution of lead chloride containing numerous white $PbCl_2$ crystals. The solution and precipitate are filtered hot to separate undissolved sulfides and gangue, and the crystals of $PbCl_2$ are re-

dissolved and carried through the filter paper with hot distilled water. The filtrate is cooled in ice water to allow precipitation of $PbCl_2$, and filtered. Lead chloride remaining in the filter paper as a residue is washed three times with cold distilled water, and then washed through the filter paper into a clean beaker with hot distilled water. This lead chloride filtrate is cooled and potassium iodide added to produce a bright yellow precipitate of lead iodide. Lead iodide is collected as a filtration residue, washed with cold distilled water, dried at room temperature, and stored in sealed glass vials.

Lead Tetramethyl Preparation

Equipment to prepare lead tetramethyl is illustrated in Figure A-VI-1. Approximately 500 mgm. of lead iodide is placed in a reaction vessel and the system evacuated. The reaction vessel is frozen down with liquid nitrogen, stopcock number 1 is closed, and the reaction vessel filled with nitrogen gas. Two milliliters of 3M grignard reagent (in ether solution) are pipetted into the reaction vessel. The reaction vessel is evacuated again, stopcock 1 closed, and the liquid nitrogen bath lowered. This allows grignard reagent to melt and react with lead iodide.

After allowing a reaction time of about one hour, the reaction is frozen with liquid nitrogen, the system evacuated, and stopcock 2 is closed. The liquid nitrogen trap is removed from the reaction vessel and placed about a collection capsule, permitting volatile reaction products to be

To vacuum pump

Stopcock no. 2

Stopcock no. 1

Grignard reagent

Clamp

Reaction vessel

N₂ gas

Constriction

Collection capsule

Liquid N₂

FIGURE A - VI - 1: APPARATUS FOR PREPARATION OF LEAD TETRA - METHYL (about one - half scale)

vacuum-distilled therein. After 20 minutes transfer by vacuum distillation

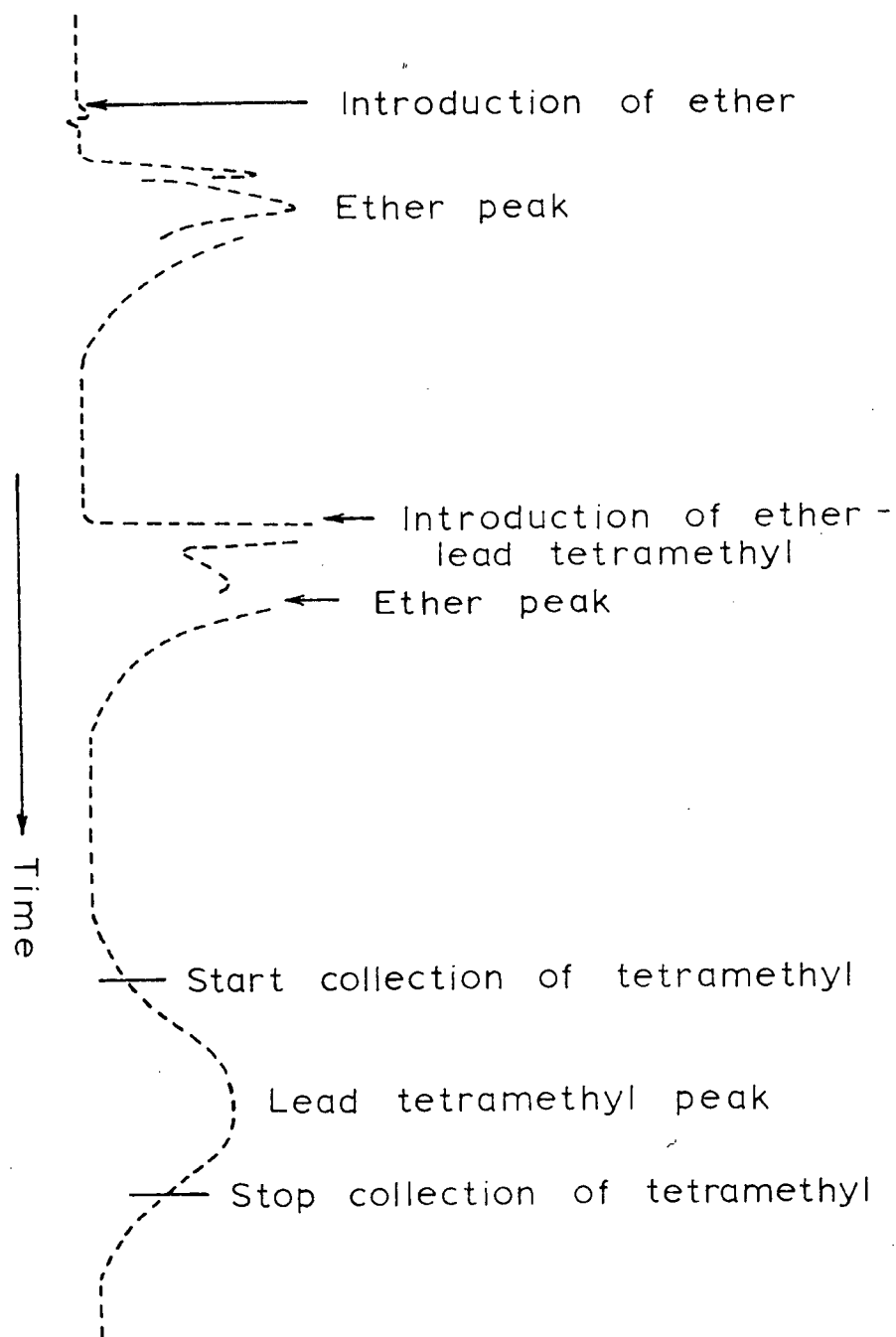at room temperature is complete and the collection capsule is sealed at a

constriction.

Several precautionary steps in the above procedure should be noted:

1. It is extremely important to ensure that glass apparatus
   illustrated in Figure A-VI-1 will hold a vacuum with
   pressures as low as 10^{-3} to 10^{-4} millimeters of mercury.
   Each time the system is closed and evacuated, it must be
   tested for leaks. Leakage of air and moisture into the
   system will destroy some of the grignard reagent and
   cause extremely slow vacuum distillation.

2. Lead tetramethyl is very poisonous and should be frozen
   in a liquid nitrogen bath at all times the system is
   open to air.

3. Lead tetramethyl-ether solution should be kept frozen in
   a liquid nitrogen bath for about 15 minutes after the
   collection capsule is sealed off, to allow the hot end
   of the collection capsule to cool.

4. Glassware must be cleaned prior to the next lead tetra-
   methyl preparation, and should be thoroughly washed in
   dilute nitric acid before extensive handling, so that
   any poisonous lead compounds are removed.

5. The entire lead tetramethyl preparation should be done
   in a fume cabinet.

Gas Chromatography

A diagram of gas chromatographic apparatus used in purifying lead

tetramethyl is shown in Figure A-VI-3. It is a coiled glass tube, 3/8"

inside diameter and about 3' long, filled with evenly packed, paraffin-coated

firebrick (60 gm. paraffin per 160 gm. of -45 to -62 mesh, acid-treated

firebrick). This column is in a constant temperature hot water bath (about

FIGURE A-VI-2: TYPICAL CHART RECORD OF GAS FLOW DURING CHROMATOGRAPHY

Introduction of ether

Ether peak

Introduction of ether - lead tetramethyl

Ether peak

Time

Start collection of tetramethyl

Lead tetramethyl peak

Stop collection of tetramethyl

75°C.). Anhydrous nitrogen gas is passed through the column and the left hand
side of the apparatus, into a beaker containing dilute nitric acid. Gas flow
is monitored by a chart recorder sensitive to changes in electrical conduct-
ivity of gases passing through a karthometer. When constant water bath temp-
erature and constant nitrogen flow (about 180 bubbles per minute in the nitric
acid trap) have been attained, the left side of the apparatus is evacuated,
a liquid nitrogen bath is placed around trap X, and the left side of the
apparatus is filled with nitrogen by switching the flow of nitrogen at stop-
cock A for a short time.

Before the lead tetramethyl-ether mixture is released into the system,
a test run is made with ether. About 3 to 5 ml. anhydrous ether are inserted
into the column through a rubber cap by means of a hypodermic needle, and the
flow of nitrogen and ether monitored on the chart recorder. A typical chart
record is shown in Figure A-IV-2. The capsule containing an ether-lead tetra-
methyl solution is broken with a pair of pliers and flow of gases through the
column and right side of the apparatus monitored on the chart recorder. Pass-
age of lead tetramethyl through the karthometer is indicated by a sudden div-
ergence of the chart record from baseline, at which time gas flow is diverted
through the left hand side of the apparatus by switching stopcock A. This
part of the apparatus had previously been evacuated and filled with nitrogen
gas. Stopcock B is immediately opened to the atmosphere, allowing nitrogen
to pass out of the system as lead tetramethyl is deposited in trap X. Sub-
sequently, the left side of the apparatus is evacuated and lead tetramethyl
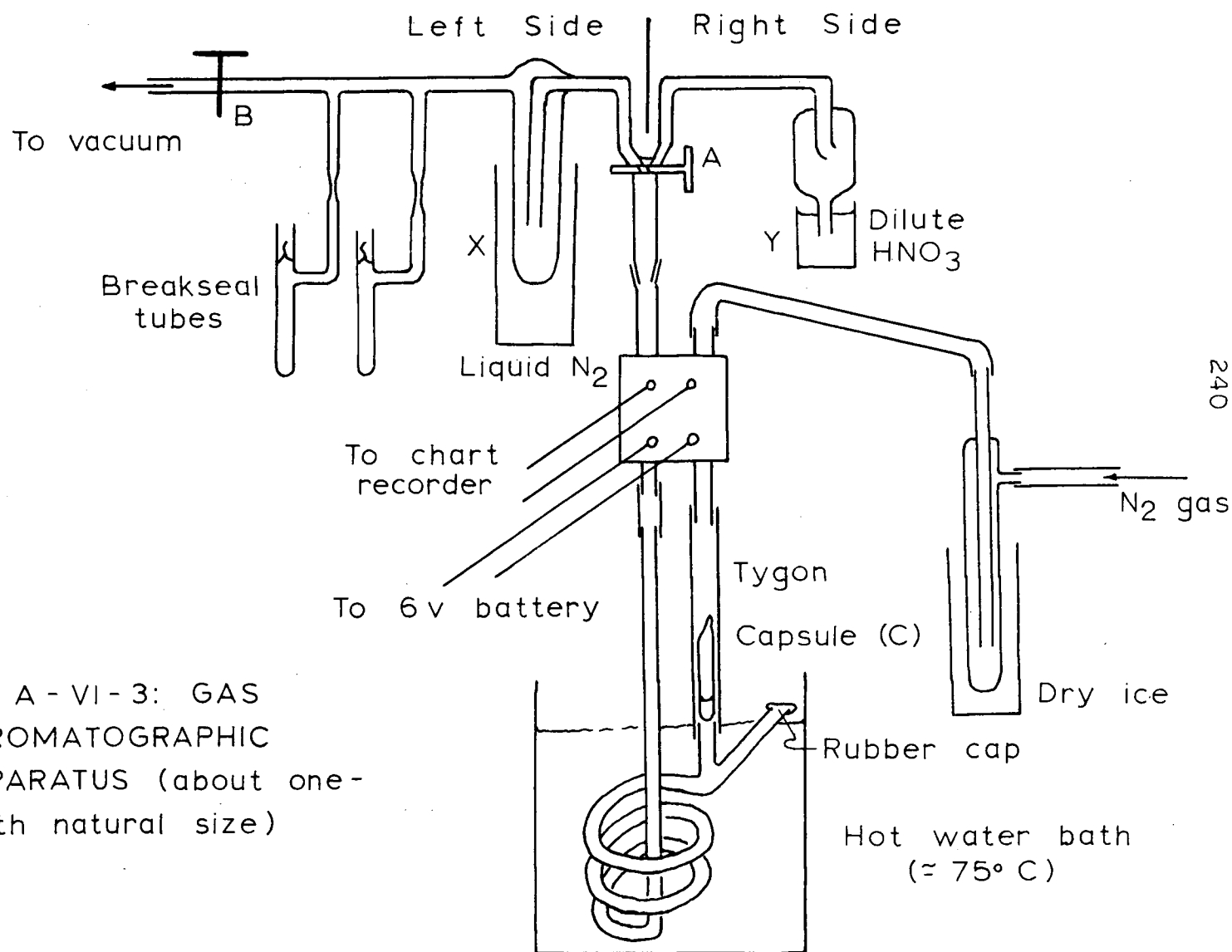vacuum-distilled from trap X to a breakseal tube.

FIGURE A-VI-3: GAS CHROMATOGRAPHIC APPARATUS (about one-tenth natural size)

APPENDIX VII

CALCULATIONS FOR INTERCOMPARISON METHOD

Samples are analysed according to the pattern given in Chapter VI. The first and third analyses each day are averaged and the mean isotope ratios are subtracted from the corresponding ratios of the second analysis of the day. This procedure assumes that short term instability of the mass spectrometer produces linear changes in measured lead isotope abundances. Differences obtained in the foregoing manner for any specific isotope ratio ideally would sum to zero for an intercomparison loop. In practice the differences do not sum to zero and a "loop closure error" is obtained that is distributed evenly among the three days analyses.

Ideally, $(S - A) + (B - S) + (A - B) = 0$

In practice, $(S - A) + (B - S) + (A - B) = \Delta$

where Δ is the loop closure error and capital letters stand for a particular isotope ratio.

Differences are corrected as follows:

$(S - A)_{corrected} = (S - A) + \Delta/3$

$(B - S)_{corrected} = (B - S) + \Delta/3$

$(A - B)_{corrected} = (A - B) + \Delta/3$

Corrected differences are then added to the standard sample (of stipulated composition) to obtain final intercomparison results.

APPENDIX VIII

VOLUME OF SOURCE ROCKS OF THE RADIOGENIC COMPONENT

OF ANOMALOUS LEADS

Kootenay arc anomalous leads are mixtures of an ordinary component and a radiogenic component. Knowing average compositions of ordinary and radiogenic components an estimate of volume of rock in which the radiogenic component was generated can be calculated. To do this the following assumptions must be made:

    1. Uranium content of source rocks:

        Uranium abundances for different kinds of igneous and sedimentary rocks range from 0.45 to 3.7 ppm (Turekian and Wedepohl, 1961). Common rock types including "granitic" rocks, syenites and shales have mean uranium contents of 3.0 to 3.7 ppm. The assumption made herein is that the source rocks of a suite of anomalous leads contains 3.0 ppm uranium.

    2. Time during which the radiogenic member developed:

        Specific or limiting values for time of anomalous lead mineralization, and age of source rocks of the radiogenic member are inherent in the interpretation of anomalous leads (Russell and others, 1954; Kanasewich, 1962b). Other dating techniques may aid in refining data obtained from anomalous lead lines. Calculations presented later include the assumption that the radiogenic component of Kootenay arc anomalous leads developed during the time interval 1760 m.y. ago to 80 m.y. ago.

3. Average isotopic composition of anomalous leads:

If measured isotopic compositions represent a random sample of a suite of anomalous leads, an approximation of the mean isotopic composition is given by averaging available analyses.

4. Average density of source rocks:

Upper crustal rocks have densities of the order of 2.7 to 2.8 grams per cubic centimeter. Calculations will be based on a density of 2.8 gm/c.c., but results are not changed significantly by assuming a slightly different value.

5. Total volume of anomalous lead:

An estimate of the minimum quantity of anomalous lead in a deposit can be made from production and ore reserve figures. This minimum value must be multiplied by an arbitrary factor to account for lead in submarginal sulfide bodies and in "undiscovered" ore, to give a crude estimate of total anomalous lead.

6. Percent radiogenic lead extracted from source rocks:

It is difficult to estimate the proportion of radiogenic lead in a source rock that would become incorporated in anomalous leads. Russell and Farquhar (1960, p. 109), discussing data of Tilton and others (1955), state:

"Within the rock, the uranium, thorium and lead were distributed in a heterogeneous manner, between one-third and one-half of these elements occurring in positions accessible to removal by laboratory acid washes."

Acid washes cannot be compared with ore-bearing fluids, but the experiments of Tilton and others, show that a significant amount of radiogenic lead, in such minerals as zircon, sphene and apatite is readily available for solution in a fluid of appropriate composition under favorable temperature-pressure conditions.

METHOD OF CALCULATION

Calculations are restricted to Pb^{206} and Pb^{207} because multi-stage lead lines involving Pb^{208} are less well defined than those of the two uranium-derived isotopes of lead. Let f_o be the number of atoms of lead-206 plus lead-207 in any unit quantity of ordinary lead with Pb^{207}/Pb^{206} ratio R_o. To f_o atoms of ordinary lead, are added f_r atoms of crustal-derived radiogenic lead with Pb^{207}/Pb^{206} ratio R_r (given by the slope of an anomalous lead line), to form $(f_o + f_r)$ atoms of anomalous lead with Pb^{207}/Pb^{206} ratio R_a.

There are $f_o/(1 + R_o)$ atoms of Pb^{206} in f_o atoms of ordinary lead, and $f_r/(1 + R_r)$ atoms of Pb in the radiogenic addition. Therefore total Pb^{206} atoms in $(f_o + f_r)$ atoms of anomalous lead is $f_o/(1 + R_o) + f_r/(1 + R_r)$, and the Pb^{207}/Pb^{206} ratio is given by the expression

$$R_a = \frac{(f_o + f_r) - f_o/(1 + R_o) + f_r/(1 + R_r)}{f_o/(1 + R_o) + f_r/(1 + R_r)} \quad \text{(VIII-1)}$$

By making the substitutions: $K = f_r/(f_o + f_r)$, and $(1 - K) = f_o/(f_o + f_r)$

where K is a fraction of the total ($Pb^{206} + Pb^{207}$) representing the radiogenic component of the anomalous lead, it is possible to solve for K in terms of ratios of Pb^{207}/Pb^{206} (Appendix IX).

$$K = \frac{(R_r + 1)\ (R_o - R_a)}{(R_a + 1)\ (R_o - R_r)} \qquad (VIII-2)$$

Total ($Pb^{206} + Pb^{207}$) in an anomalous lead is a fraction T of the anomalous lead:

$$T = \frac{(Pb^{207} + Pb^{206})}{(Pb^{204} + Pb^{206} + Pb^{207} + Pb^{208})} \qquad (VIII-3)$$

The fraction of the anomalous lead representing the radiogenic member is (K x T) atoms per atom. For present purposes it is unnecessary to transpose to mass units.

An estimate of the quantity of anomalous lead can be obtained by a procedure outlined previously. A quantity, Q, of radiogenic component is determined by the equation

$$Q(kgms) = \frac{total\ anomalous\ lead\ (lbs)\ x\ K\ x\ T}{2.205} \qquad (VIII-4)$$

Amount of radiogenic lead produced between t_1, time of uranium mineralization, and t_2, time of anomalous lead mineralization, from a specified

quantity of uranium, U(atoms), is determined as follows: atoms of Pb^{206} and Pb^{207} produced during the time interval t_1 to t_2, per U atoms of uranium at the present time, are given by

$$Pb^{206} = \frac{137.8}{138.8} \cdot U \cdot (e^{\lambda t_1} - e^{\lambda t_2})$$

(VIII-5)

$$Pb^{207} = \frac{1}{138.8} \cdot U \cdot (e^{\lambda t_1} - e^{\lambda t_2}$$

To obtain abundance figures in terms of mass, the above equations are re-written in the following manner:

$$Mass\ Pb^{206} = \frac{206}{238} : \frac{137.8}{138.8} \cdot P\ (e^{\lambda t_1} - e^{\lambda t_2})$$

$\because$ (VIII-6)

$$Mass\ Pb^{207} = \frac{207}{235} \cdot \frac{1}{138.8} \cdot P\ (e^{\lambda t_1} - e^{\lambda t_2})$$

where P is mass uranium.

The quantity of lead produced between times t_1 and t_2 from P mass units of uranium at the present time, is Q where

$$Q = Mass\ Pb^{206} + Mass\ Pb^{207}$$

or

$$Q = P\ 0.8593\ (e^{\lambda t_1} - e^{\lambda t_2}) + 0.0635\ (e^{\lambda t_1} - e^{\lambda t_2}) \qquad (VIII-7)$$

If t_1 and t_2 are known equation VIII-7 reduces to

$$Q = P \times C, \text{ where C is a constant.}$$

Equation VIII-7 is readily solved for P, the total uranium necessary to produce the radiogenic component during a given time interval. Volume of source rocks is then obtained from the expression

$$V = P/(2.8 \times D \times 10^6) \tag{VIII-8}$$

where V is volume in cubic kilometers and D is parts per million uranium in the source rocks.

APPLICATION OF VOLUME CALCULATIONS

Three deposits in the Kootenay arc — Jersey, Reeves Macdonald and Bluebell mines — have been selected to illustrate volume calculations outlined in the foregoing section. In each case the assumptions are made that

1. lead in each deposit is a mixture of a radiogenic component and Sullivan-type lead, and

2. the radiogenic component developed during the time interval 1760 m.y. ago to 80 m.y. ago.

Jersey Mine

Results and data used in calculations are listed in Table VIII-1. The mean isotopic composition of Jersey lead was obtained by averaging nearly identical analyses of four lead specimens from widely separated locations within the mine. Total lead originally present in Jersey mine is estimated

at 370 million pounds. This estimate is double the lead production from 1949 to 1962 inclusive of 185 million pounds. A multiplication factor of 2 seems adequate in this instance because the mine is presently operating on a salvage basis, and is expected to close in the near future.

K is determined by making the substitutions

$$R_o(\text{Sullivan mine}) = 0.9402$$

$$R_a(\text{Jersey mine}) = 0.8262$$

$$R_r(\text{slope of anomalous lead line}) = 0.1084$$

in equation VIII-2. T(Jersey)= 0.462 as determined from the average isotopic composition of Jersey lead.

An estimate of quantity of radiogenic component is obtained by multiplying (K x T) x (Total lead in the Jersey mine), and dividing by 2.205 to give an answer in kilograms. The radiogenic component is estimated as 6.44 x 10^6 Kgm.

Volume of source rocks of the radiogenic component can now be estimated from equation VIII-8 by assuming

1. a uranium content for the source rocks, and

2. percentage radiogenic lead extracted.

Assuming 100 percent extraction of radiogenic lead, the following volumes are calculated for different uranium concentrations of source rocks:

Table VIII-1: Source volume results, and data used in calcul-
ations.

| Mine	Sullivan	Reeves Macdonald	Jersey	Bluebell
No. of samples analysed	2	2	4	1
Pb^{206}/Pb^{204}	16.632	19.224	19.284	17.743
Pb^{207}/Pb^{204}	15.638	15.912	15.933	15.728
Pb^{208}/Pb^{204}	36.577	39.906	40.038	38.608
$(1 + x + y + z)$	69.847	76.042	76.255	73.079
Pb^{207}/Pb^{206}	0.9402	0.8277	0.8262	0.8864
Millions of lbs Lead pro-duced to end of 1962		80	185	310
Multiplication factor		3	2	3
Assumed total lead (millions of pounds)		160	370	930
K		0.0820	0.0832	0.0380
$T = (x + y)/(1 + x + y + z)$		0.462	0.462	0.458
K x T x (assumed total lead) i.e. amount of radiogenic component in Kgm. x 10^6		2.75	6.44	7.34
Volume of source region of radiogenic member, assuming 100% extraction (Km^3)				
1 ppm U		3.34	7.82	8.89
2 ppm U		1.67	3.91	4.45
3 ppm U		1.11	2.61	2.96
4 ppm U		0.83	1.96	2.22
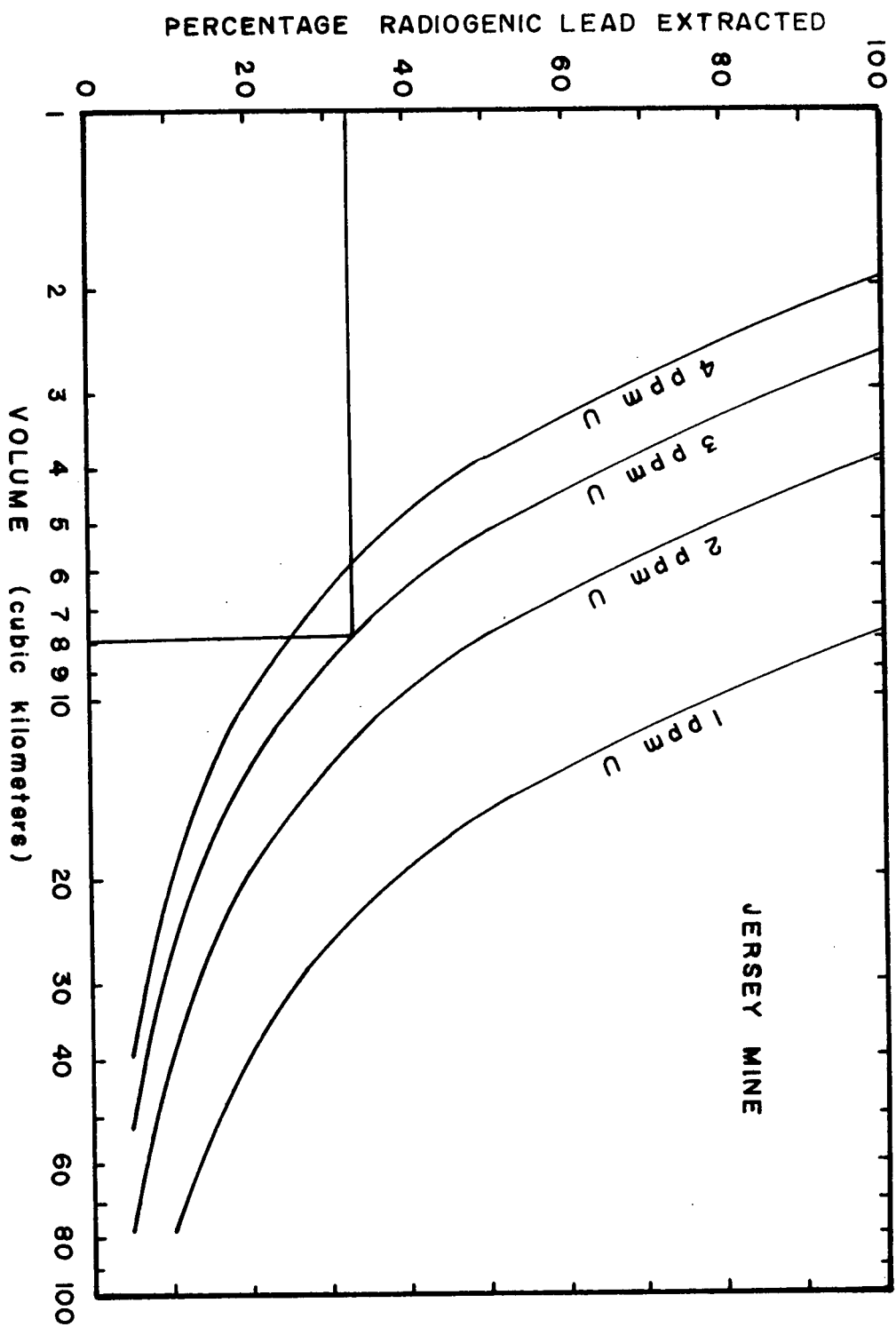
FIGURE A-VII-1: SOURCE VOLUME DATA FOR JERSEY MINE
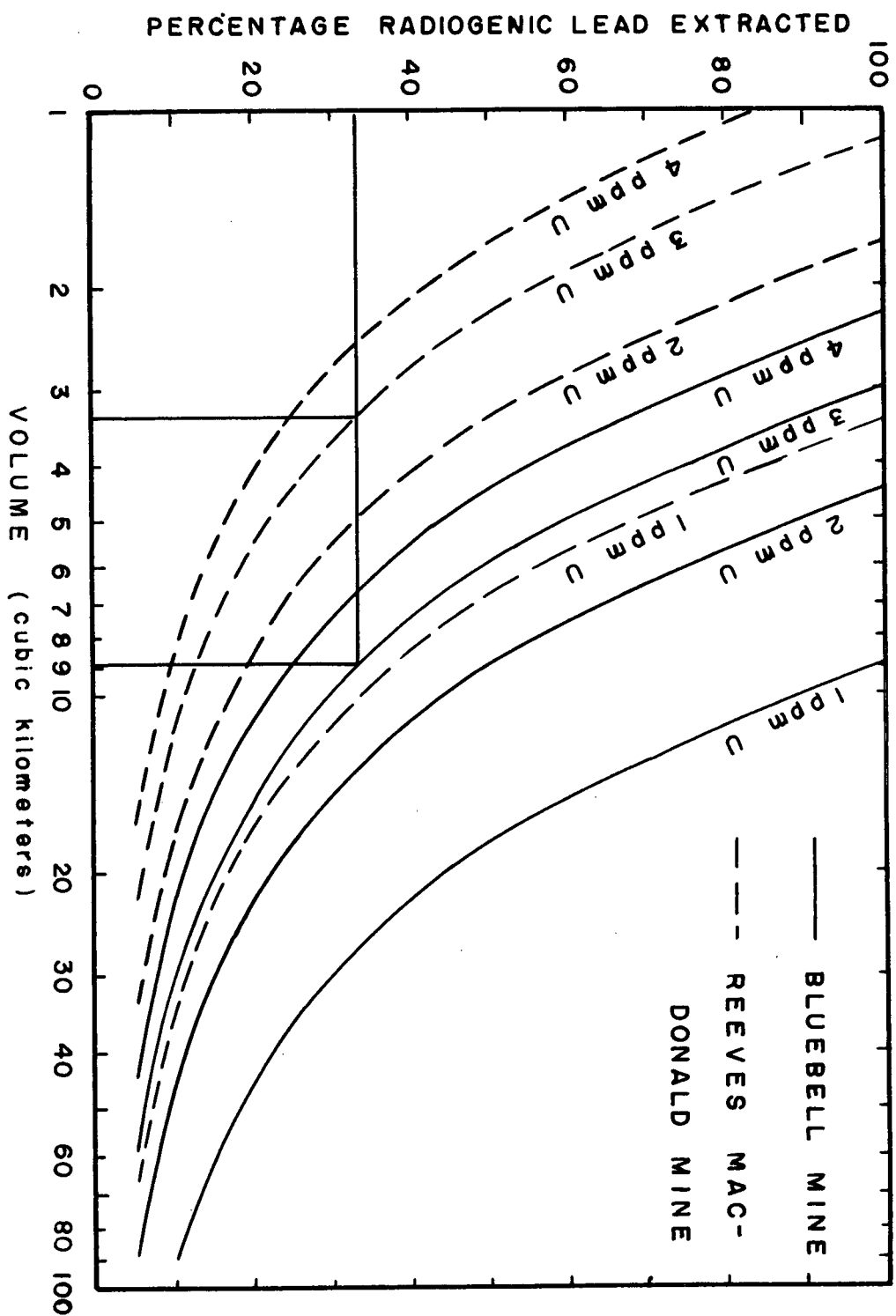
FIGURE A-VII-2: SOURCE VOLUME DATA FOR REEVES MAC-
DONALD AND BLUEBELL MINES

Uranium (ppm)	Volume (Km^3)
1	7.8
2	3.9
3	2.6
4	2.0

Graphs can be constructed for different uranium abundances in source rocks by plotting volume of source rocks versus percentage radiogenic lead extracted (Figure VIII-1). This graphical method of presenting source volume data is more objective than specific volume figures because of the uncertainty that must be attached to any estimate of percentage extraction of radiogenic lead from source rocks.

Reeves Macdonald and Bluebell Mines

Calculations for Reeves Macdonald and Bluebell mines were done in a manner similar to those for Jersey mine, and will not be outlined. Data used in volume calculations, and step-by-step results obtained throughout the calculations for both mines are listed in Table VIII-1. Results are shown graphically in Figure VIII-2.

Discussion

Assuming that laboratory leaching experiments approximately indicate the amount of radiogenic lead that is extracted from source rocks (i.e. about

one-third to one-half the lead present), and that 3 ppm is the uranium abundance in source rocks, graphs in Figures VIII-1 and VIII-2 give the volumes listed in Table VIII-2. These figures (Table VIII-2) indicate an order of magnitude of volume of source rocks necessary to generate the radiogenic component of Kootenay arc anomalous lead deposits. If Kootenay arc leads developed according to a multi-stage growth history the foregoing calculation would give volume estimates of source rocks for all the anomalous lead (i.e. both components). Thus an estimate of Pb abundances in source rocks at the time of formation of source rocks can be calculated by distributing total mass of anomalous lead throughout the calculated volumes. Calculated lead abundances of source rocks of some Kootenay arc deposits range from 22-50 ppm (Table VIII-2) and agree well with the mean crustal abundance of lead (about 20 ppm). A possible inference is that ore deposits can be derived from crustal rocks by unknown processes of metal concentration.

Ideally the volume calculations outlined offer a possible test of a multi-stage growth model for a particular suite of leads, by allowing comparison of calculated volumes with geological estimates based on suspected sources. This is not practical because of many uncertainties involved in the calculations.

The method of calculation is unique in that volume of source rocks of lead is determined largely on the basis of

      1. interpretation of lead isotopic compositions, and

      2. amount of uranium in the source.

Commonly, volume of a suspected source rock of a metal sulfide deposit is estimated by finding the volume of rock, containing that metal in its normal

Table VIII-2: Volume of source rocks for some Kootenay arc deposits; and lead abundances of source rocks assuming a multi-stage growth history.

Mine	Volume (Km^3)		Lead abundances of source rocks if total lead distributed throughout calculated volumes.
	1/3 radiogenic Pb extracted	1/2 radiogenic Pb extracted	
Jersey	8	5	22 ppm Pb
Reeves Macdonald	3	2	24 ppm Pb
Bluebell	9	6	50 ppm Pb

crustal abundance, required to contain the total amount of that metal assumed present in an ore deposit. This method is much simpler than that outlined by the writer, but it should be emphasized that volumes calculated by either method have the same accuracy. Major causes of uncertainty in volume figures, such as, percentage extraction of metal from the source, and total amount of lead in a deposit, are common to both methods of calculations.

Volume calculations based on lead isotope data give results almost exactly the same as the commonly used simple method mentioned above. Hence, justification for use of the complicated volume calculations presented by the writer is simply that this completely new and independent line of attack leads to the conclusion that "metals in ore deposits could be derived from small volumes of crustal rocks containing those metals in mean crustal abundances even though less than 50 percent of metals present were extracted."

APPENDIX IX

SOLVE FOR K IN TERMS OF RATIOS OF Pb^{207}/Pb^{206}

(where K is the fraction of (Pb^{206} + Pb^{207}) representing
radiogenic component of an anomalous lead).

Symbols are those defined in Appendix VIII.

Given the equation

$$R_a = \frac{(f_o + f_r) - f_o/(1 + R_o) + f_r/(1 + R_r)}{f_o/(1 + R_o) + f_r/(1 + R_r)}$$

then

$$R_a + 1 = \frac{(f_o + f_r)}{f_o/(1 + R_o) + f_r/(1 + R_r)}$$

$$= \frac{(f_o + f_r)(1 + R_o)(1 + R_r)}{f_o(1 + R_r) + f_r(1 + R_o)}$$

$$= \frac{(1 + R_o)(1 + R_r)}{(1 + R_r)f_o/(f_o + f_r) + (1 + R_o)f_r/(f_o + f_r)}$$

but $f_o/(f_o + f_r) = (1 - K)$, and $f_r(f_o + f_r) = K$

therefore

$$R_a + 1 = \frac{(1 + R_o)(1 + R_r)}{(1 - K)(1 + R_r) + K(1 + R_o)} \qquad (IX-1)$$

By multiplying out the denominator on the right hand side of equation
(IX -1) and rearranging, an expression for K, in terms of ratios of $Pb^{207}/$
Pb^{206}, is obtained.

$$K = \frac{(R_r + 1)(R_o - R_a)}{(R_a + 1)(R_o - R_r)} \tag{IX-2}$$