Lead Isotope Abundance Studies on Mineral Occurrences in the British Isles and their Geological Significance

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LEAD ISOTOPE ABUNDANCE STUDIES ON MINERAL OCCURRENCES IN THE BRITISH ISLES AND THEIR GEOLOGICAL SIGNIFICANCE

By S. MOORBATH

Department of Geology and Mineralogy, University Museum, Oxford

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CONTENTS

Lead isotope abundances are reported for ninety-eight galena specimens from Great Britain and Ireland. The analyses were made with a solid-source mass spectrometer. Comparison analyses show excellent agreement with results from other laboratories using solid-source techniques, but differences of 1 to 5 % may occur for individual abundances when comparison is made with laboratories utilizing the lead tetramethyl vapour technique.

The model chosen for calculation of ages from the isotopic composition is that of Holmes and Houtermans, using the published values of Patterson for the isotopic comparison of primeval lead in iron meteorites and modern lead in ocean sediments. This model permits calculation of the parameters uranium-238/lead-204 and thorium-232/uranium-238 in the source of the ores, which may exhibit small regional differences.

The Holmes–Houtermans model ages of three suites of galenas from south-west England, northern England and southern Norway give excellent agreement with published values of the absolute ages of genetically associated igneous rocks. Other models used for interpreting lead isotope abundances do not generally give such satisfactory agreement.

The significance of the isotope data from Great Britain and Ireland is discussed regionally in terms of the age of mineralization as well as the possible correlation and origin of different deposits. Of the ninety-eight leads investigated, eighty-six are assumed to be normal and to obey the conditions of the Holmes–Houtermans model. The remaining twelve are *B*-type leads, as defined by Houtermans, i.e. the model ages are demonstrably older than the true age of mineralization. The main criteria for recognizing normal leads are, first, the close regional grouping of isotope abundances and, secondly, that the model age does not exceed the age of the enclosing sedimentary rocks on the basis of the most recently published geological time-scales of the fossiliferous strata.

Detailed consideration of normal leads suggests the existence of six periods of mineralization in the British Isles, ranging in age from Lower Palaeozoic to Upper Mesozoic. The two most important and clearly defined groups are associated with the Caledonian and Hercynian orogenies, respectively. There is, as yet, no isotopic evidence for Tertiary mineralization in the British Isles.

A discussion of the causes of normal lead isotope abundances indicates that the latter could be the result of large-scale crustal homogenization processes in continental geosynclinal-orogenic belts. However, there is not enough critical evidence to identify definitely the source of normal lead ores with either crust or mantle.

B-type leads probably arise by comparatively localized remobilization and regeneration of lead from metamorphic basement complexes with high lead/uranium ratios, or low radiogenic lead content. The source of such leads frequently appears to be somewhat heterogeneous and ore solutions may not have the opportunity for extensive mixing before the site of deposition is reached. However, *B*-type leads in some cases give an approximation to the true age of the basement rocks from which they are derived. Processes of this type probably account for the *B*-type leads in the north-west and central highlands of Scotland and in County Galway, western Ireland, where the occurrences are situated in metamorphic basement rocks.

No cases have been definitely recognized within the British Isles in which lead has a negative, or anomalously young, model age (*J*-type leads). The results presented in this paper do not support the view of Russell and co-workers that most vein-type deposits which have traversed sedimentary rocks exhibit *J*-type anomalies—a consequence of their suggestion that *B*-type leads, as defined by Houtermans, should be regarded as normal leads.

1. Introduction

Since the first mass-spectrometric demonstration of the variation of lead isotope abundances in lead minerals by Nier (1938) and Nier, Thompson & Murphey (1941), it has become evident that this variation is the result of addition of radiogenic lead-206, lead-207 and lead-208 (respectively the stable end-products of the uranium-238, uranium-235 and thorium-232 radioactive decay series) to pre-existing lead in the ultimate source of lead ores. In addition, this pre-existing lead contains the isotope lead-204, the absolute amount of which has remained unchanged throughout geological time, since it is not generated by any known radioactive process. Furthermore, its own half-life of approximately $1{\cdot}4 \times 10^{17}$ years is extremely long compared to the age of the earth (Riezler & Kauw 1958). Since common lead minerals, such as galena, contain negligible quantities of uranium and thorium, the addition of radiogenic lead must have occurred before the lead was concentrated from the source rock to form the mineral.

The considerable number of lead isotope measurements in post-war years, together with the earlier ones of Nier, prompted a number of theoretical papers in which several distinct models were proposed to calculate the age of the earth and to obtain a relation between the isotopic composition of common lead and the age of ore mineralization (Holmes 1946, 1947*a*, 1949; Houtermans 1947; Alpher & Herman 1951; Damon 1953; Collins, Farquhar & Russell 1954; Russell, Farquhar, Cumming & Wilson 1954; Russell & Allan 1955). Such attempts involved calculations or assumptions regarding the isotopic composition of primeval lead, as well as reference to abundance-time curves obtained from leads of known geological age.

Important advantages were made in the years 1953 to 1956 by Patterson and his co-workers, who measured lead isotope abundances in iron and stony meteorites, in geologically recent basalt-flows and in modern ocean sediments (Patterson, Brown, Tilton & Inghram 1953; Patterson, Goldberg & Inghram 1953; Patterson, Tilton & Inghram 1955; Patterson 1956). It was assumed that the isotopic composition of lead from the metal and sulphide-phases of meteorites, which contain negligible uranium and thorium, represented primeval lead of the solar system and of the earth. From the difference between the primeval lead isotope abundances in meteorites and the modern terrestrial abundances, Patterson calculated the best age for the earth-meteorite system to be $4{\cdot}55 \pm 0{\cdot}07 \times 10^{9}$ years.

This work helped to narrow the choice of suitable earth models and facilitated their application in the interpretation of lead isotope abundances in lead minerals (Houtermans 1953; Geiss 1954; Eberhardt, Geiss & Houtermans 1955; Russell & Farquhar 1960*a*). A summary of the theory and application of lead isotope studies has been given in a recent book by Russell & Farquhar (1960*b*).

From a geological viewpoint one of the most important applications of lead isotope data is the determination of the absolute age of sulphide mineralization and correlation of such deposits in different areas and geological environments. In view of the inherent assumptions and errors, a so-called 'common' lead age determination cannot be as precise as a conventional isotopic age determination, but it is found that in many cases the ages obtained are in good agreement with other methods of age determination and with known geological relationships. For many lead ores which conform with a simple earth model (i.e. which have a 'normal' model age), this method of age determination may rival the conventional methods in importance since the age of mineralization frequently cannot be obtained in any other way.

Conjectures regarding the age of British sulphide mineralizations have been made for many years. With a few exceptions the only definite evidence is the upper limit set by the age of the enclosing rocks. Dunham (1952*a*) has provided a valuable review of the geological evidence for the age relations of the epigenetic mineral deposits of Great Britain.

The present paper contains ninety-eight lead isotope analyses on galena specimens from Great Britain and Ireland. These analyses are all new, except for eight galenas measured at Toronto University from English and Scottish localities (Russell & Allan 1955; Russell & Farquhar 1960*b*). The experimental disagreements between the Oxford and Toronto results are extremely serious and will be discussed in a subsequent section. The present work is therefore in the nature of a detailed reconnaissance in which the general aim has been to apply these comparatively recently developed methods to problems of geological interest within the British Isles, a relatively small area in which the general geological setting is as clearly established as in any area of the world.

The Holmes–Houtermans model has been used for the interpretation of the British and Irish lead isotope abundances in preference to the models of Russell and his co-workers. The data can then be used to calculate variations in the uranium/lead and thorium/uranium ratios of the source material of the ores and to provide some additional information on the possible origins of several types of deposit.

Some of the lead isotope data have been published in a preliminary communication (Moorbath 1959), in which average figures are given for galenas from Cornwall–Devon, northern Pennines, Lake District, north-west Wales and Aberdeenshire. These will be described individually in the present paper, together with many additional results.

A complete list of the galena specimens with brief geological descriptions, is found in the appendix.

2. Earth models for the interpretation of lead isotope abundances

Three models which have been widely used in the interpretation of lead isotope abundances are now briefly described. Detailed formulations of the models have been given by the authors cited and a comprehensive summary of these, and other, models has been presented by Russell & Farquhar (1960*b*). In this section only the formal aspects are emphasized, whilst possible geological processes leading to the validity of the models are described in subsequent sections.

(*a*) *Holmes–Houtermans model*

Holmes (1946) and Houtermans (1947) assumed that originally the earth was fluid and homogeneous. At that time, uranium, thorium and lead were uniformly distributed and the isotopic composition of 'primeval' lead was everywhere the same. Subsequently, the earth became more rigid and small regional differences arose in the uranium/lead ratio. In any particular region, however, this ratio did not change again except for the radioactive decay of uranium to lead. At the time of formation of a common lead mineral, the lead was separated from uranium and thorium so that its isotopic composition has remained constant until the present time. The detailed mathematical formulation has been given by Geiss (1954). The abundances of the lead isotopes formed in accordance with the model are given by

$$\frac{y-y_0}{x-x_0}=\frac{1}{137\cdot 8}\frac{(e^{\lambda_2 t_0}-e^{\lambda_2 t})}{(e^{\lambda_1 t_0}-e^{\lambda_1 t})}, \tag{1}$$

where

x, y = measured 206/204 and 207/204 abundance ratios;
x_0, y_0 = primeval 206/204 and 207/204 abundance ratios;
λ_1, λ_2 = decay constants of uranium-238 and uranium-235;
t_0 = age of the earth (i.e. commencement of regional differences in the uranium/lead ratio);
t = time of formation of the lead mineral (i.e. model age);
1/137·8 = present-day ratio uranium-235/uranium-238.

To determine the model age of a lead ore, the observed values of the isotope abundance ratios are substituted in equation (1) which can be solved for t, provided that the other quantities are known. The values for x_0 and y_0 are assumed to be identical with the abundance ratios in iron meteorites, measured by Patterson and his co-workers (Patterson, Brown, Tilton & Inghram 1953; Patterson, Tilton & Inghram 1955; Patterson 1956). These values, together with abundance ratios of lead from modern ocean sediments and of comparatively young lead ores dated by independent methods were used by the above authors and Houtermans (1953) on the one hand, and by Holmes (1956) on the other, to calculate ages for the earth of $4{\cdot}55 \pm 0{\cdot}07 \times 10^9$ years and $4{\cdot}50 \pm 0{\cdot}10 \times 10^9$ years, respectively. Thus, all the quantities in equation (1) are known, with the exception of t.

A graphical solution of equation (1) is simplest and it is customary to construct a graph on which the model ages may be read directly from a plot of 206/204 against 207/204. In such an 'isochron' chart, leads of the same model age but with different abundance ratios (due to regional differences in uranium/lead ratio of the source material) lie along straight lines. The origin of all isochrons represents the primeval abundance ratios in iron meteorites, whilst the zero isochron also passes through the abundance ratios of modern ocean sediments, as measured by Patterson and his co-workers. The isochron diagram used in this work is shown in figure 1. The parameters and constants used to construct the isochron chart are given in table 1.

The equations for calculation of the ratios uranium-238/lead-204 and thorium-232/uranium-238 in the source of the lead ores are as follows

$$V_p = \frac{x - x_0}{e^{\lambda_1 t_0} - e^{\lambda_1 t}}, \tag{2}$$

where V_p is the uranium-238/lead-204 at the present time, and x, x_0, λ_1, t_0 and t have the same meaning as in equation (1).

Furthermore,

$$K_p = \frac{z - z_0}{x - x_0} \frac{e^{\lambda_1 t_0} - e^{\lambda_1 t}}{e^{\lambda_3 t_0} - e^{\lambda_3 t}}, \tag{3}$$

where K_p is the thorium-232/uranium-238 ratio at the present time

z = measured 208/204 abundance ratio,
z_0 = primeval 208/204 abundance ratio,
λ_3 = decay constant of thorium-232,

and x, x_0, λ_1, t_0 and t have the same meaning as in equation (1). The values of these additional constants are given in table 1.

A lead ore is defined to be 'normal' when the model age represents the true age of mineralization. Houtermans and his co-workers also recognize two types of 'anomalous' leads—those to which anomalous amounts of radiogenic lead have been added (*J*-type) and those giving model ages older than the rocks in which the leads occur (*B*-type).

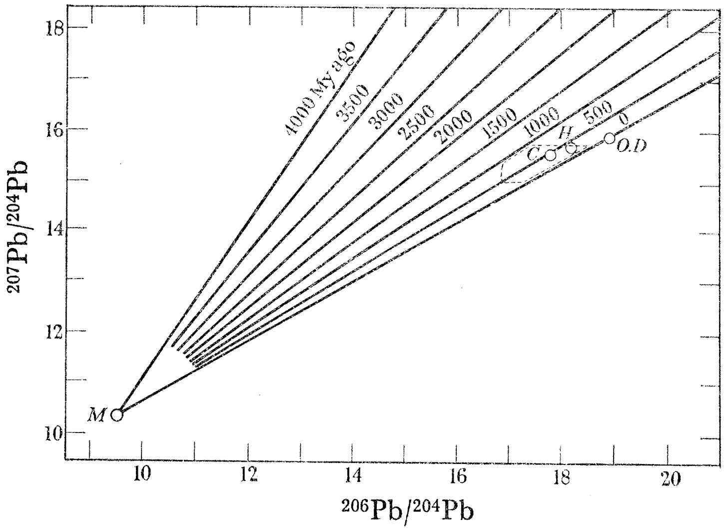

FIGURE 1. Holmes–Houtermans isochron diagram. All leads so far measured from the British Isles, whether normal or anomalous, fall in the area enclosed by the discontinuous lines. *M*, Isotopic composition of lead in iron meteorites (Patterson *et al.*); *O.D.*, Ditto in modern ocean sediments (Patterson *et al.*); *H*, Hercynian lead average for Devon and Cornwall (280 million years); *C*, Caledonian lead average for Aberdeenshire (470 million years).

TABLE 1. CONSTANTS FOR CALCULATION OF HOLMES–HOUTERMANS MODEL PARAMETERS

primeval $^{206}Pb/^{204}Pb$ ratio, x_0 = $9{\cdot}50^{(1)}$
primeval $^{207}Pb/^{204}Pb$ ratio, y_0 = $10{\cdot}36^{(1)}$
primeval $^{208}Pb/^{204}Pb$ ratio, z_0 = $29{\cdot}49^{(1)}$
modern $^{206}Pb/^{204}Pb$ ratio = $18{\cdot}93^{(1)}$
modern $^{207}Pb/^{204}Pb$ ratio = $15{\cdot}73^{(1)}$
modern $^{208}Pb/^{204}Pb$ ratio = $38{\cdot}80^{(1)}$
age of earth, t_0 = $4{\cdot}50 \times 10^9\,y$
decay constant ^{238}U, λ_1 = $1{\cdot}541 \times 10^{-10}\,y^{-1\,(2)}$
decay constant ^{235}U, λ_2 = $9{\cdot}72 \times 10^{-10}\,y^{-1\,(3)}$
decay constant ^{232}Th, λ_3 = $0{\cdot}499 \times 10^{-10}\,y^{-1\,(4)}$
modern ratio $^{238}U/^{235}U$ = $137{\cdot}8$

(1) Patterson *et al.* (1953, 1955); Patterson (1956).
(2) Kienberger (1949).
(3) Fleming, Ghiorso & Cunningham (1952).
(4) Kovarik & Adams (1938).

The Holmes–Houtermans model has been used throughout the present work to interpret the lead isotope abundances in galenas from the British Isles. A comparison of Holmes–Houtermans model ages with ages obtained by other models for three groups of independently dated galenas is given in table 4, § 5.

An important advantage of the Holmes–Houtermans method is the comparative insensitivity to small errors in the measured lead-204 abundance.

(*b*) *Russell–Farquhar–Cumming model*

This model is based on the work of Alpher & Herman (1951), who assumed a homogeneous distribution of uranium, thorium and lead in the source of lead ores. In contrast with the Holmes–Houtermans model, this implies a constant uranium/lead and thorium/lead ratio in the source material throughout the world. This leads to equations of the type

$$x = x_p - V_p(e^{\lambda_1 t} - 1), \tag{4}$$

$$y = y_p - \frac{V_p}{137\cdot 8}(e^{\lambda_2 t} - 1), \tag{5}$$

$$z = z_p - W_p(e^{\lambda_3 t} - 1), \tag{6}$$

where

x_p, y_p, z_p = abundance ratios 206/204, 207/204, 208/204 for very young or modern leads;
x, y, z = measured 206/204, 207/204, 208/204 abundance ratios;
V_p = uranium-238/lead-204 ratio at the present time;
W_p = thorium-238/lead-204 ratio at the present time;
t = age of the lead mineral;
$\lambda_1, \lambda_2, \lambda_3$ = decay constants of uranium-238, uranium-235 and thorium-232, respectively.

Russell *et al.* (1954) showed that these equations could be used for dating purposes only if some allowance was made for failures of the basic assumptions of a homogeneous earth. They calculated possible errors from this cause and showed that for ages older than about 1000 millions years the errors were sufficiently small to obtain useful ages. Younger ages have relatively large possible errors. More recently, Russell & Farquhar (1960*b*) have presented a revised set of empirical constants for these equations (based on work by Cumming) with consequent reduction in the errors for young samples. This revision arose from the recognition that early isotopic analyses by different laboratories contained systematic differences in the measurement of lead-204.

This method yields two independent model ages for a single sample, namely, from the 206/204 and 208/204 ratios. Mass-spectrometric errors are more important than in the Holmes–Houtermans method, due to the larger effect of the lead-204 uncertainty on the age.

(*c*) *Russell–Stanton–Farquhar model*

This model has been described by Russell & Farquhar (1960*a*, *b*). It is based on certain theories (Stanton 1955*a*, *b*; Stanton & Russell 1959) regarding the origin of one group of lead–zinc–copper deposits which are of the 'conformable' type. The metals in these deposits are presumed to have been derived from volcanoes and concentrated in near-shore sediments around islands in active island arcs. In particular, the volcanic lead is assumed to have come from great depths, probably within the mantle, thus providing the possibility of a uniform uranium–thorium–lead source. Such leads are considered to be normal, since they have neither traversed sedimentary rocks nor been in contact with surface rocks of high radioactivity. The assumptions of the model are as follows:

(1) All conformable lead ores precisely represent samples of lead existing in the mantle at the time of their formation.

(2) The mantle is uniform in uranium, thorium and lead on a broad scale.

(3) All vein-leads have migrated through surface rocks and have had the possibility of becoming contaminated with radiogenic lead and are to some extent anomalous.

Consequently, all conformable leads should have 206/204 and 207/204 ratios that lie along a single growth curve connecting primeval lead at the one end with modern terrestrial lead at the other. A further model age for conformable leads can be obtained from the 208/204 ratio. The mathematical formulation has been presented by Russell & Farquhar (1960*a*, *b*). In neither of the models proposed by Russell and co-workers does the isochron concept of Holmes and Houtermans have any meaning, since the distribution of uranium, thorium and lead is considered to be homogeneous.

It is doubtful whether any lead deposits in the British Isles could be regarded as conformable using Stanton's geological criteria. The majority are vein deposits of epigenetic type, occurring within a continental-geosynclinal environment characterized by great thicknesses of sedimentary and metamorphic rocks.

3. Experimental procedure

Isotopic measurements were carried out using a Metropolitan-Vickers MS-5 solid-source mass spectrometer with a 90°, 12-inch radius analyzer tube. Electron multiplier detection was used throughout. A square-root-of-the-mass correction was applied to all abundance ratios to correct for electron multiplier discrimination (Higatsberger, Demorest & Nier 1954). The validity of this correction was established by comparison of normal rubidium and strontium abundance ratios with values obtained in other laboratories by conventional plate-collection techniques (Nier 1950; Aldrich, Herzog, Holyk, Whiting & Ahrens 1953).

Lead sulphide, in finely precipitated form, was used for the isotope measurements. In most cases samples were prepared by direct precipitation of the sulphide from a nitric acid solution of galena at pH 5 to 6, followed by successive washing and centrifuging. In a few cases, however, where the galena was fine-grained and intimately associated with other sulphide minerals, a dithizone extraction or sulphate precipitation was carried out in order to extract and purify the lead, before conversion to sulphide.

The ion source was of the thermal emission type, with lead sulphide slurry evenly distributed on the outer two filaments of a tungsten triple filament. The rate of sample evaporation from the two surfaces was controlled by a stabilized current through the centre (ionizing) filament. The mass spectrum consisted of the ion-beams $^{204}\mathrm{Pb}^+$, $^{206}\mathrm{Pb}^+$, $^{207}\mathrm{Pb}^+$ and $^{208}\mathrm{Pb}^+$. A detailed description and review of the thermal emission ion source in solid-source mass spectrometry has been given by Palmer (1958).

To ensure the validity of the measurements, it was necessary to establish the absence of isotopic fractionation, memory and background effects. Even during prolonged runs on a single sample, no observable isotopic fractionation of lead isotopes was observed during volatilization from the filament. Before loading a sample, blank filaments were scanned under normal operating conditions for lead. In no case were peaks of lead obtained on the most sensitive range of the instrument, showing the absence of lead contamination in the source-region of the mass spectrometer and on the filament. During every run, checks were undertaken to ensure the absence of background contamination by frequent scanning over twenty to thirty mass numbers on either side of the lead mass range using the most sensitive range of the instrument. This indicated the absence of organic contaminants and of mercury vapour from the diffusion pumps. In many cases, however, peaks were observed at mass numbers 203 and 205 in the ratio 29·5:70·5, which usually decreased rapidly in intensity before optimum lead emission commenced. These were due to thallium, a common trace constituent of galenas.

The simplicity of the lead spectrum, together with absence of observable memory and background effects, exhibit some contrast with other methods of lead isotope abundance measurements, such as the lead-tetramethyl gas technique used by Canadian and American workers (Bate, Miller & Kulp 1957) and the lead-sulphide vaporization technique employed by German and Swiss workers (Ehrenberg, Geiss & Taubert 1955).

4. Results

(a) *Intercalibration and comparison analyses*

As a check on the lead isotope analyses presented in this work, a series of intercalibration and intercomparison analyses was carried out on samples measured at other laboratories. The results are presented in table 2, which also indicates the techniques employed.

The errors quoted for the Oxford results represent twice the standard error for a series of measurements, equivalent to a 95 % confidence level. These errors correspond closely in magnitude with those given by the Lamont and Bonn workers. The Toronto workers do not usually quote errors, and detailed comparison with Nier's data is not possible since his errors are rather greater than those of other laboratories. Most of the Oxford results represent the average of a total of at least fifty scans for two separate runs. For the Ivigtut sample, however, six runs were available, carried out at different times over a period of more than one year.

We consider first the intercalibration analyses, i.e. analyses of the same sample by different workers. Five sets of data are available for the Ivigtut sample. However, true intercalibration was carried out with Harwell only, although no estimate of error is available from Harwell. The other measurements were done on different samples from Ivigtut. However, galenas from a number of localities within the Ivigtut ore body and from surrounding granite pegmatites show no isotopic variation (Moorbath, unpublished data). Consequently, the measurements from all laboratories should be comparable.

It is evident that the Ivigtut 206, 207 and 208 abundances are in good agreement for the five laboratories, but that the 204 abundances of Lamont and Toronto are 1 to 2 % lower than the rest. Nevertheless, the 204 measurement cannot be associated with the same relative precision as the heavier isotopes, due to its much lower abundance.

The intercalibrations with Lamont were made possible by kind co-operation of Dr B. J. Giletti and Dr D. S. Miller. The first two Lamont analyses were quoted by Bate & Kulp (1955). The agreement is not too satisfactory and several of the quoted abundances lie outside the limits of error. Thus the Casapalca 204 and 207 abundances differ by about 2 and 1 %, respectively, between Oxford and Lamont. With the Joplin sample, the 206 abundances differ by about 1 %. No clear systematic error appears from these limited data, and the differences are strongly reflected in the abundance ratios. The two comparison analyses with Lamont (i.e. analyses on different samples from the same locality) on Stantrg and Laurion are in better agreement. The Lamont data on these two specimens

TABLE 2. COMPARISON ANALYSES WITH OTHER LABORATORIES

sample	laboratory method	204	206	207	208	206/204	207/204	208/204	207/206 × 100	208/206 × 100
Ivigtut, Greenland	Oxford, PbS*	1·548 ± 0·003	22·49 ± 0·003	22·64 ± 0·02	53·32 ± 0·003	14·53 ± 0·05	14·63 ± 0·04	34·44 ± 0·08	100·7 ± 0·2	237·1 ± 0·4
	Harwell, PbS*	1·56	22·50	22·61	53·33	14·42	14·49	34·19	100·5	237·0
	Nier, PbI$_2$	1·55	22·51	22·60	53·34	14·52	14·58	34·41	100·4	237·0
	Lamont, Pb(CH$_3$)$_4$	1·528	22·45	22·66	53·36	14·69	14·83	34·92	100·9	237·7
	Toronto, Pb(CH$_3$)$_4$	1·518	22·54	22·68	53·24	14·85	14·94	35·07	100·6	236·2
Casapalca, Peru, Lamont, 91, (GLB-121)	Oxford, PbS*	1·360 ± 0·006	25·12 ± 0·03	21·20 ± 0·03	52·32 ± 0·04	18·47 ± 0·10	15·59 ± 0·09	38·47 ± 0·20	84·4 ± 0·2	208·3 ± 0·4
	Lamont, Pb(CH$_3$)$_4$*	1·333 ± 0·004	25·22 ± 0·06	20·98 ± 0·06	52·47 ± 0·07	18·92 ± 0·10	15·74 ± 0·09	39·36 ± 0·17	83·2 ± 0·3	208·0 ± 0·8
	Nier, PbI$_2$*	1·35	25·42	21·13	52·11	18·82	15·65	38·62	83·1	205·0
Joplin, Mo. Lamont 114N, (GLB-74)	Oxford, PbS*	1·245 ± 0·005	27·53 ± 0·04	19·78 ± 0·03	51·43 ± 0·05	22·11 ± 0·12	15·89 ± 0·09	41·31 ± 0·20	71·9 ± 0·2	186·8 ± 0·5
	Lamont, Pb(CH$_3$)$_4$*	1·247 ± 0·006	27·25 ± 0·06	19·90 ± 0·03	51·60 ± 0·07	21·85 ± 0·16	15·96 ± 0·10	41·38 ± 0·26	73·0 ± 0·3	189·4 ± 0·6
	Nier, PbI$_2$*	1·27	27·47	20·01	51·3	21·63	15·75	40·3	72·8	187
Stantrg, Yugoslavia	Oxford, PbS	1·346 ± 0·005	25·26 ± 0·03	21·08 ± 0·03	52·13 ± 0·04	18·77 ± 0·09	15·66 ± 0·08	38·86 ± 0·18	83·5 ± 0·2	207·1 ± 0·4
	Lamont, Pb(CH$_3$)$_4$	1·341	25·15	20·98	52·53	18·75	15·64	39·17	83·4	208·9
Laurion, Greece	Oxford, PbS	1·347 ± 0·006	25·40 ± 0·04	21·01 ± 0·03	52·24 ± 0·06	18·86 ± 0·11	15·60 ± 0·09	38·78 ± 0·22	82·7 ± 0·3	205·7 ± 0·5
	Lamont, Pb(CH$_3$)$_4$	1·343 ± 0·005	25·25 ± 0·04	21·05 ± 0·02	52·36 ± 0·06	18·80 ± 0·10	15·67 ± 0·08	38·99 ± 0·18	83·4 ± 0·2	207·4 ± 0·5
Maubach, Germany	Oxford, PbS	1·377 ± 0·005	25·09 ± 0·03	21·26 ± 0·03	52·27 ± 0·05	18·22 ± 0·09	15·44 ± 0·08	37·96 ± 0·17	84·7 ± 0·3	208·3 ± 0·5
	Bonn, PbS	1·377	25·07	21·28	52·27	18·21 ± 0·05	15·46 ± 0·04	37·97 ± 0·10	84·9 ± 0·2	208·5 ± 0·4
Siegerland, Germany	Oxford, PbS	1·380 ± 0·006	24·99 ± 0·03	21·34 ± 0·02	52·29 ± 0·04	18·11 ± 0·10	15·46 ± 0·09	37·89 ± 0·19	85·4 ± 0·2	209·2 ± 0·4
	Bonn, PbS	1·377	24·98	21·37	52·27	18·14 ± 0·07	15·52 ± 0·08	37·95 ± 0·20	85·5 ± 0·2	209·1 ± 0·3

* Analyses on the same sample. Otherwise, analyses on samples from the same locality

TABLE 3. COMPARISON OF OXFORD AND TORONTO LEAD ISOTOPE DATA ON BRITISH GALENAS

Oxford no.	locality	laboratory	204	206	207	208	206/204	207/204	208/204	207/206 × 100	208/206 × 100
6	Perranzabuloe, Cornwall	Oxford	1·372 ± 0·004	25·04 ± 0·04	21·29 ± 0·03	52·31 ± 0·04	18·25 ± 0·08	15·52 ± 0·06	38·13 ± 0·14	85·0 ± 0·2	208·9 ± 0·5
		Toronto	1·344	25·16	21·38	52·12	18·72	15·91	38·78	85·0	207·2
10	Rotherhope Fell, Cumberland	Oxford	1·377 ± 0·003	25·06 ± 0·03	21·33 ± 0·02	52·33 ± 0·03	18·20 ± 0·06	15·49 ± 0·05	37·93 ± 0·10	85·1 ± 0·2	208·4 ± 0·4
		Toronto	1·326	24·89	21·44	52·34	18·77	16·17	39·47	86·1	210·3
56	Silver Ridge Mine, Kirkcudbright	Oxford	1·380 ± 0·005	24·96 ± 0·05	21·35 ± 0·04	52·31 ± 0·07	18·09 ± 0·10	15·47 ± 0·08	37·91 ± 0·19	85·5 ± 0·3	209·6 ± 0·7
		Toronto	1·359	24·98	21·43	52·23	18·38	15·77	38·43	85·8	209·1
57	Wanlockhead, Dumfries	Oxford	1·382 ± 0·003	25·00 ± 0·02	21·38 ± 0·02	52·25 ± 0·02	18·09 ± 0·05	15·47 ± 0·04	37·81 ± 0·09	85·5 ± 0·2	209·0 ± 0·2
		Toronto	1·352	25·04	21·42	52·19	18·52	15·84	38·60	85·5	208·4
58	Nutberry Hill, Lanark	Oxford	1·388 ± 0·004	24·95 ± 0·02	21·38 ± 0·02	52·28 ± 0·02	17·98 ± 0·07	15·40 ± 0·05	37·67 ± 0·13	85·7 ± 0·2	209·5 ± 0·4
		Toronto	1·340	25·77	21·28	51·61	19·23	15·88	38·51	82·6	200·2
60	Ballygrant, Islay	Oxford	1·400 ± 0·003	25·00 ± 0·03	21·40 ± 0·02	52·21 ± 0·04	17·86 ± 0·06	15·29 ± 0·05	37·29 ± 0·11	85·6 ± 0·2	208·8 ± 0·4
		Toronto	1·370	24·97	21·52	52·14	18·23	15·71	38·06	86·2	208·8
61	Strontian, Argyll	Oxford	1·390 ± 0·003	25·07 ± 0·03	21·38 ± 0·02	52·16 ± 0·04	18·04 ± 0·06	15·38 ± 0·05	37·53 ± 0·11	85·3 ± 0·2	208·1 ± 0·4
		Toronto	1·358	25·59	21·34	51·71	18·84	15·71	38·08	83·4	202·1
74	Tyndrum, Perthshire	Oxford	1·409 ± 0·003	24·68 ± 0·04	21·57 ± 0·03	52·34 ± 0·04	17·52 ± 0·06	15·31 ± 0·06	37·15 ± 0·10	87·4 ± 0·3	212·1 ± 0·5
		Toronto	1·375	24·77	21·59	52·27	18·01	15·70	38·01	87·2	211·0

Oxford analyses: PbS—solid technique.
Toronto analyses: Pb(CH$_3$)$_4$—gas technique (Russell & Farquhar 1960*b*).

was taken from an unpublished manuscript by Bate, Gast, Kulp & Miller, by kind permission of Professor J. L. Kulp. The individual abundances agree within about 0·5%. For the Lamont data Bate & Kulp (1955) claim an internal precision of 0·2% for the heavier isotopes and 0·5% for 204. The data are, furthermore, said to be comparable with other laboratories to within 0·5% for 206, 207 and 208 and 1% for 204. This would apply to the Lamont–Oxford comparison for Stantrg and Laurion, but not for Casapalca and Joplin.

The comparison analyses between Bonn and Oxford on Maubach and Siegerland galenas are in excellent agreement. There is little doubt that these represent strictly comparable measurements. All abundances and ratios lie within the errors. The Maubach data are taken from Ehrenberg & Mürtz (1958) and the Siegerland data from Ehrenberg & Horlitz (1954).

Although the data presented above are not sufficient to be regarded as conclusive, it seems fair to say that in some cases the solid-source and tetramethyl techniques do not give satisfactory agreement. The error does not appear to be systematic, except for a possible suppression of 204 in the gas method, already noted by previous workers. However, table 2 shows that this does not happen in all cases. On the other hand, the results of solid-source measurements are in close agreement, with the exception of Nier's data.

The suspicion regarding possible discrepancy between the solid-source and tetramethyl techniques is amplified by a series of lead isotope measurements on eight British galenas, published originally by Russell & Allen (1955) and later slightly revised by Russell & Farquhar (1960*b*). Specimens from the same eight localities were re-measured during the present work. The two sets of analyses are presented in table 3. In all cases the Toronto 204 abundances are 3 to 5% lower than the corresponding Oxford values. The agreement for the 206, 207 and 208 abundances is variable. In several cases it is good (nos. 56, 57, 74) in others it is mediocre (nos. 6, 10, 60) and in two cases there is gross discrepancy between the two sets of values (nos. 58, 61).

The general effect of the discrepancies is to raise the Toronto 206/204, 207/204 and 208/204 ratios considerably above the Oxford values, whilst in the case of samples 58 and 61 there is disagreement outside all reasonable error in the 207/206 and 208/206 ratios. (No errors are quoted for the Toronto analyses.)

It will become evident in §6 that seven of the eight samples give normal model ages when the Oxford measurements are used in conjunction with the Holmes–Houtermans model. However, the Toronto measurements on British leads do not give plausible model parameters with any of the three earth models described in §2, so that Holmes (1956) was forced to regard them as anomalous.

It is concluded that a detailed intercalibration programme between laboratories using the solid-source and tetramethyl methyl techniques is desirable, in order to elucidate the reason for these serious discrepancies. The placing of all lead isotope measurements onto a strictly comparable basis would result in closer agreement in model parameters calculated for a given lead from the three earth models described in §2.

(*b*) *Tabulation of isotopic analyses*

The isotopic abundance data for ninety-eight galenas from the British Isles are presented in table 4, in the same order in which they are discussed in §6. For each analysis

Table 4. Tabulation of isotopic analyses

no.	locality	204	206	207	208	207/206 × 100	208/206 × 100	model age (My)	V_p	K_p
				ENGLAND AND WALES						
				Cornwall–Devon						
1	Bere Alston	1·000	18·12 ± 0·07	15·45 ± 0·06	37·89 ± 0·14					
		1·380 ± 0·004	25·01 ± 0·03	21·32 ± 0·02	52·29 ± 0·04	85·2 ± 0·2	209·1 ± 0·4	270 ± 60	9·02	3·91
2	Wheal Rose	1·000	18·13 ± 0·08	15·47 ± 0·08	37·86 ± 0·18					
		1·380 ± 0·005	25·02 ± 0·04	21·35 ± 0·04	52·25 ± 0·06	85·3 ± 0·2	208·8 ± 0·4	290 ± 70	9·05	3·90
3	Vottle Shaft	1·000	18·20 ± 0·07	15·49 ± 0·05	37·88 ± 0·12					
		1·378 ± 0·003	25·08 ± 0·04	21·35 ± 0·03	52·20 ± 0·05	85·1 ± 0·2	208·1 ± 0·6	260 ± 60	9·07	3·87
4	South Terras	1·000	18·24 ± 0·08	15·52 ± 0·06	37·96 ± 0·13					
		1·375 ± 0·004	25·08 ± 0·03	21·34 ± 0·02	52·20 ± 0·03	85·1 ± 0·2	208·1 ± 0·4	270 ± 70	9·13	3·89
5	Mary Anne	1·000	18·24 ± 0·06	15·53 ± 0·06	38·01 ± 0·12					
		1·374 ± 0·003	25·06 ± 0·03	21·34 ± 0·03	52·22 ± 0·04	85·1 ± 0·2	208·4 ± 0·4	280 ± 60	9·15	3·91
6	Lambriggan	1·000	18·25 ± 0·08	15·52 ± 0·06	38·13 ± 0·14					
		1·372 ± 0·004	25·04 ± 0·04	21·29 ± 0·03	52·31 ± 0·04	85·0 ± 0·2	208·9 ± 0·5	260 ± 70	9·13	3·97
7	Penberthy Croft	1·000	18·25 ± 0·07	15·55 ± 0·06	38·14 ± 0·14					
		1·371 ± 0·004	25·02 ± 0·03	21·32 ± 0·02	52·29 ± 0·04	85·2 ± 0·2	209·0 ± 0·4	300 ± 60	9·19	3·98
				Northern Pennines and north-east England						
8	Barbary Mine,	1·000	18·19 ± 0·08	15·50 ± 0·08	38·04 ± 0·16					
	Co. Durham	1·375 ± 0·004	25·01 ± 0·04	21·31 ± 0·02	52·30 ± 0·04	85·2 ± 0·2	209·1 ± 0·4	280 ± 80	9·09	3·95
9	Sedling Mine,	1·000	18·25 ± 0·06	15·56 ± 0·04	38·19 ± 0·11					
	Co. Durham	1·370 ± 0·003	25·00 ± 0·03	21·32 ± 0·02	52·32 ± 0·04	85·3 ± 0·2	209·3 ± 0·4	310 ± 50	9·20	4·00
10	Rotherhope Fell,	1·000	18·20 ± 0·06	15·49 ± 0·05	37·93 ± 0·10					
	Cumberland	1·377 ± 0·003	25·06 ± 0·03	21·33 ± 0·02	52·23 ± 0·03	85·1 ± 0·2	208·4 ± 0·4	260 ± 60	9·07	3·89
11	Settlingstones,	1·000	18·24 ± 0·06	15·53 ± 0·04	38·11 ± 0·10					
	Northumberland	1·372 ± 0·003	25·03 ± 0·03	21·31 ± 0·02	52·29 ± 0·03	85·1 ± 0·2	208·9 ± 0·4	270 ± 60	9·13	3·95
12	Chilton Quarry,	1·000	18·07 ± 0·08	15·43 ± 0·05	37·91 ± 0·13					
	Co. Durham	1·381 ± 0·004	24·95 ± 0·03	21·31 ± 0·02	52·36 ± 0·03	85·4 ± 0·2	209·9 ± 0·4	280 ± 70	8·97	3·85
13	Steetley Quarry,	1·000	18·12 ± 0·07	15·46 ± 0·05	37·87 ± 0·14					
	Notts.	1·380 ± 0·004	25·01 ± 0·03	21·34 ± 0·02	52·26 ± 0·04	85·3 ± 0·2	209·0 ± 0·4	280 ± 60	9·02	3·90
14	Thickley Quarry,	1·000	18·20 ± 0·07	15·54 ± 0·06	38·15 ± 0·13					
	Co. Durham	1·372 ± 0·003	24·97 ± 0·04	21·32 ± 0·04	52·34 ± 0·06	85·4 ± 0·3	209·6 ± 0·5	310 ± 70	9·15	4·00
				Shropshire						
15	White Grit Mine,	1·000	18·38 ± 0·09	15·61 ± 0·07	38·32 ± 0·16					
	Shelve	1·364 ± 0·004	25·07 ± 0·05	21·29 ± 0·03	52·27 ± 0·06	84·9 ± 0·3	208·5 ± 0·7	280 ± 70	9·29	4·00

Table 4 (*cont.*)

no.	locality	204	206	207	208	207/206 × 100	208/206 × 100	model age (My)	V_p	K_p
	Mendip Hills, Somerset									
16	E 27777, in Carb. Lst.	1·000	18·32 ± 0·05	15·55 ± 0·05	38·28 ± 0·10					
		1·367 ± 0·003	25·04 ± 0·02	21·26 ± 0·02	52·33 ± 0·03	84·9 ± 0·2	209·0 ± 0·4	240 ± 50	9·17	4·00
17	E 26572, in Triassic	1·000	18·18 ± 0·06	15·46 ± 0·06	37·97 ± 0·11					
		1·377 ± 0·003	25·04 ± 0·03	21·29 ± 0·03	52·29 ± 0·04	85·0 ± 0·3	208·8 ± 0·4	220 ± 60	9·05	3·93
18	E 26571, in Liassic	1·000	18·28 ± 0·06	15·53 ± 0·05	38·18 ± 0·10					
		1·370 ± 0·003	25·05 ± 0·03	21·28 ± 0·02	52·30 ± 0·03	85·0 ± 0·2	208·8 ± 0·4	240 ± 60	9·14	3·97
	Southern Pennines, Derbyshire									
19	Millclose Mine	1·000	18·33 ± 0·05	15·50 ± 0·05	38·01 ± 0·10					
		1·373 ± 0·003	25·17 ± 0·02	21·28 ± 0·02	52·19 ± 0·03	84·5 ± 0·2	207·4 ± 0·3	170 ± 50	9·07	3·86
20	Riber Mine	1·000	18·42 ± 0·11	15·52 ± 0·06	38·27 ± 0·13					
		1·366 ± 0·004	25·16 ± 0·04	21·20 ± 0·03	52·27 ± 0·03	84·3 ± 0·2	207·8 ± 0·4	150 ± 80	9·13	3·95
21	Wheel's Rake	1·000	18·34 ± 0·07	15·54 ± 0·07	38·22 ± 0·14					
		1·368 ± 0·004	25·09 ± 0·03	21·26 ± 0·03	52·29 ± 0·04	84·7 ± 0·2	208·4 ± 0·4	220 ± 70	9·16	3·96
22	Moletrap Mine	1·000	18·42 ± 0·06	15·56 ± 0·06	38·27 ± 0·14					
		1·365 ± 0·004	25·15 ± 0·03	21·24 ± 0·02	52·24 ± 0·04	84·5 ± 0·2	207·7 ± 0·4	180 ± 60	9·18	3·94
	North Midlands									
23	Bulwell, Notts.	1·000	18·42 ± 0·08	15·57 ± 0·06	38·39 ± 0·14					
		1·363 ± 0·004	25·10 ± 0·03	21·22 ± 0·02	52·33 ± 0·04	84·5 ± 0·2	208·5 ± 0·4	200 ± 70	9·22	4·00
24	Garendon Park, Leics.	1·000	18·48 ± 0·09	15·62 ± 0·07	38·48 ± 0·15					
		1·359 ± 0·004	25·12 ± 0·04	21·23 ± 0·04	52·29 ± 0·05	84·5 ± 0·3	208·2 ± 0·5	210 ± 80	9·29	4·02
25	Alderley Edge, Cheshire	1·000	18·24 ± 0·06	15·48 ± 0·05	38·01 ± 0·11					
		1·375 ± 0·003	25·08 ± 0·02	21·29 ± 0·02	52·26 ± 0·03	84·9 ± 0·2	208·4 ± 0·3	210 ± 60	9·04	3·91
	Isle of Man									
26	Foxdale	1·000	18·30 ± 0·05	15·52 ± 0·04	38·22 ± 0·10					
		1·369 ± 0·003	25·05 ± 0·02	21·25 ± 0·02	52·33 ± 0·03	84·8 ± 0·2	208·9 ± 0·3	220 ± 40	9·12	3·98
27	Laxey	1·000	18·28 ± 0·09	15·51 ± 0·06	38·30 ± 0·15					
		1·368 ± 0·004	25·01 ± 0·05	21·22 ± 0·02	52·39 ± 0·05	84·8 ± 0·2	209·4 ± 0·6	220 ± 60	9·10	4·02
	North Devon									
28	Knap Down Mine	1·000	18·05 ± 0·09	15·49 ± 0·07	37·88 ± 0·14					
		1·381 ± 0·004	24·93 ± 0·05	21·39 ± 0·03	52·31 ± 0·05	85·8 ± 0·3	209·9 ± 0·6	370 ± 80	9·09	3·96
29	Combe Martin 1	1·000	18·05 ± 0·08	15·48 ± 0·08	37·78 ± 0·17					
		1·383 ± 0·005	24·96 ± 0·03	21·41 ± 0·03	52·25 ± 0·04	85·8 ± 0·2	209·3 ± 0·4	360 ± 80	9·07	3·91
30	Combe Martin 2	1·000	18·05 ± 0·10	15·49 ± 0·09	37·98 ± 0·18					
		1·379 ± 0·006	24·89 ± 0·03	21·36 ± 0·03	52·37 ± 0·03	85·8 ± 0·2	210·4 ± 0·4	370 ± 90	9·09	4·02

TABLE 4 (*cont.*)

no.	locality	204	206	207	208	207/206 × 100	208/206 × 100	model age (My)	V_p	K_p
				Lake District						
31	Eagle Crag Vein, Patterdale	1·000 1·372 ± 0·005	18·30 ± 0·10 25·11 ± 0·03	15·48 ± 0·07 21·24 ± 0·02	38·10 ± 0·18 52·28 ± 0·05	84·6 ± 0·2	208·2 ± 0·4	170 ± 80	9·04	3·91
32	Hartsop Hall Mine, Patterdale	1·000 1·368 ± 0·004	18·34 ± 0·08 25·09 ± 0·04	15·54 ± 0·06 21·26 ± 0·02	38·22 ± 0·15 52·28 ± 0·05	84·7 ± 0·2	208·4 ± 0·6	210 ± 70	9·15	3·95
33	Carrock Mine, Grainsgill	1·000 1·370 ± 0·004	18·26 ± 0·08 25·02 ± 0·04	15·49 ± 0·07 21·22 ± 0·03	38·24 ± 0·14 52·39 ± 0·04	84·8 ± 0·2	209·4 ± 0·5	210 ± 70	9·06	4·00
34	Roughtongill, Caldbeck Fells	1·000 1·370 ± 0·002	18·29 ± 0·04 25·06 ± 0·02	15·51 ± 0·02 21·25 ± 0·02	38·20 ± 0·07 52·33 ± 0·02	84·8 ± 0·2	208·9 ± 0·3	220 ± 40	9·11	3·97
35	Driggith Vein, Caldbeck Fells	1·000 1·376 ± 0·006	18·23 ± 0·10 25·09 ± 0·04	15·52 ± 0·09 21·35 ± 0·03	37·92 ± 0·20 52·18 ± 0·06	85·1 ± 0·3	208·0 ± 0·6	260 ± 90	9·13	3·88
36	Barrow Mine, Vale of Newlands	1·000 1·377 ± 0·04	18·16 ± 0·09 25·00 ± 0·05	15·50 ± 0·07 21·35 ± 0·03	37·95 ± 0·15 52·26 ± 0·05	85·4 ± 0·3	209·0 ± 0·6	300 ± 80	9·11	3·94
37	Goldscope, Vale of Newlands	1·000 1·373 ± 0·005	18·22 ± 0·09 25·02 ± 0·04	15·54 ± 0·08 21·34 ± 0·03	38·07 ± 0·18 52·27 ± 0·06	85·3 ± 0·3	208·9 ± 0·6	310 ± 80	9·17	3·96
38	Woodend Mine, Threlkeld	1·000 1·373 ± 0·003	18·18 ± 0·08 24·96 ± 0·05	15·55 ± 0·06 21·35 ± 0·03	38·10 ± 0·12 52·32 ± 0·06	85·5 ± 0·3	209·6 ± 0·6	340 ± 70	9·19	4·00
39	Low Hartsop Mine, Patterdale	1·000 1·380 ± 0·005	18·10 ± 0·09 24·98 ± 0·04	15·47 ± 0·07 21·35 ± 0·02	37·89 ± 0·16 52·29 ± 0·04	85·5 ± 0·3	209·3 ± 0·5	310 ± 80	9·06	3·93
40	Greenside Mine, Patterdale	1·000 1·366 ± 0·005	18·27 ± 0·10 24·96 ± 0·05	15·59 ± 0·08 21·30 ± 0·03	38·35 ± 0·17 52·38 ± 0·05	85·3 ± 0·3	209·9 ± 0·6	330 ± 90	9·26	4·07
41	Hensingham Borehole	1·000 1·365 ± 0·005	18·30 ± 0·09 24·98 ± 0·03	15·60 ± 0·07 21·30 ± 0·02	38·36 ± 0·17 52·36 ± 0·04	85·2 ± 0·2	209·6 ± 0·4	320 ± 70	9·27	4·09
42	Shap Blue Rock Quarry, no. 1	1·000 1·375 ± 0·003	18·15 ± 0·07 24·96 ± 0·04	15·55 ± 0·05 21·38 ± 0·02	38·03 ± 0·10 52·29 ± 0·03	85·7 ± 0·2	209·5 ± 0·4	370 ± 60	9·19	3·98
43	Shap Blue Rock Quarry, no. 2	1·000 1·374 ± 0·005	18·15 ± 0·10 24·94 ± 0·04	15·53 ± 0·08 21·34 ± 0·03	38·10 ± 0·18 52·35 ± 0·06	85·6 ± 0·2	209·9 ± 0·6	360 ± 80	9·16	3·97
44	Buttermere Vein	1·000 1·376 ± 0·003	18·06 ± 0·06 24·85 ± 0·03	15·58 ± 0·05 21·44 ± 0·02	38·04 ± 0·11 52·34 ± 0·04	86·3 ± 0·2	210·6 ± 0·4	470 ± 50	9·26	4·05
				North Wales						
45	Halkyn, Flintshire	1·000 1·365 ± 0·005	18·38 ± 0·09 25·09 ± 0·03	15·52 ± 0·08 21·19 ± 0·03	38·35 ± 0·17 52·35 ± 0·04	84·4 ± 0·3	208·7 ± 0·4	170 ± 80	9·12	3·99
46	Parys Mountain Anglesey, no. 1	1·000 1·374 ± 0·003	18·24 ± 0·06 25·06 ± 0·02	15·55 ± 0·04 21·37 ± 0·02	38·00 ± 0·10 52·21 ± 0·03	85·3 ± 0·2	208·3 ± 0·3	300 ± 50	9·18	3·92
47	Parys Mountain, Anglesey, no. 2	1·000 1·368 ± 0·004	18·30 ± 0·08 25·04 ± 0·03	15·58 ± 0·07 21·31 ± 0·02	38·22 ± 0·14 52·28 ± 0·04	85·1 ± 0·2	208·8 ± 0·4	290 ± 60	9·22	3·99
48	Parc Mine, Llanrwst, Caerns.	1·000 1·378 ± 0·004	18·10 ± 0·09 24·94 ± 0·05	15·50 ± 0·06 21·36 ± 0·03	37·98 ± 0·15 52·33 ± 0·06	85·6 ± 0·3	209·8 ± 0·7	340 ± 70	9·09	3·98

TABLE 4 (*cont.*)

no.	locality	204	206	207	208	207/206 × 100	208/206 × 100	model age (My)	V_p	K_p
				North Wales (cont.)						
49	Berthllwyd Mine,	1·000	18·15 ± 0·06	15·63 ± 0·06	38·11 ± 0·12					
	Merioneth	1·372 ± 0·003	24·90 ± 0·03	21·45 ± 0·03	52·29 ± 0·05	86·1 ± 0·3	210·0 ± 0·4	470 ± 60	9·36	4·04
50	Manod Bach Mine,	1·000	18·18 ± 0·10	15·61 ± 0·07	38·40 ± 0·17					
	Merioneth	1·366 ± 0·005	24·84 ± 0·04	21·33 ± 0·02	52·45 ± 0·04	85·9 ± 0·2	211·2 ± 0·4	430 ± 80	9·33	4·15
51	Cowarch Mine,	1·000	18·20 ± 0·06	15·61 ± 0·05	38·08 ± 0·11					
	Merioneth	1·372 ± 0·003	24·97 ± 0·03	21·41 ± 0·02	52·25 ± 0·04	85·7 ± 0·2	209·3 ± 0·4	420 ± 50	9·33	4·00
52	Bronfloyd Mine,	1·000	18·17 ± 0·07	15·63 ± 0·06	38·25 ± 0·13					
	Cardigan	1·369 ± 0·004	24·87 ± 0·03	21·40 ± 0·02	52·36 ± 0·03	86·0 ± 0·2	210·5 ± 0·4	450 ± 60	9·36	4·00
53	Tal-y-bont Mine,	1·000	18·01 ± 0·09	15·51 ± 0·09	37·90 ± 0·15					
	Cardigan	1·381 ± 0·004	24·87 ± 0·05	21·42 ± 0·03	52·34 ± 0·05	86·1 ± 0·3	210·4 ± 0·7	430 ± 80	9·14	4·00
54	Bryn Glas Mine,	1·000	18·21 ± 0·07	15·60 ± 0·05	38·11 ± 0·12					
	Montgomery	1·373 ± 0·003	24·88 ± 0·04	21·42 ± 0·02	52·33 ± 0·05	86·1 ± 0·2	210·3 ± 0·5	450 ± 50	9·29	4·05
55	Daren Mine,	1·000	18·03 ± 0·06	15·47 ± 0·05	37·29 ± 0·10					
	Cardigan	1·381 ± 0·003	24·90 ± 0·03	21·36 ± 0·02	52·36 ± 0·03	85·8 ± 0·2	210·3 ± 0·4	360 ± 60	9·05	3·99
				SCOTLAND						
				Southern Uplands						
56	Silver Ridge Mine,	1·000	18·09 ± 0·10	15·47 ± 0·08	37·91 ± 0·19					
	Kirkcudbright	1·380 ± 0·005	24·96 ± 0·05	21·35 ± 0·04	52·31 ± 0·07	85·5 ± 0·3	209·6 ± 0·7	320 ± 80	9·05	3·95
57	Wanlockhead,	1·000	18·09 ± 0·05	15·47 ± 0·04	37·81 ± 0·09					
	Dumfries	1·382 ± 0·003	25·00 ± 0·02	21·38 ± 0·02	52·25 ± 0·02	85·5 ± 0·2	209·0 ± 0·2	320 ± 50	9·05	3·91
58	Nutberry Hill, Lanark	1·000	17·98 ± 0·07	15·40 ± 0·05	37·67 ± 0·13					
		1·388 ± 0·004	24·95 ± 0·02	21·38 ± 0·02	52·28 ± 0·02	85·7 ± 0·2	209·5 ± 0·4	310 ± 60	8·93	3·89
				Argyllshire						
59	Mulreesh, Islay	1·000	17·85 ± 0·09	15·34 ± 0·08	37·39 ± 0·17					
		1·397 ± 0·005	24·93 ± 0·04	21·43 ± 0·03	52·24 ± 0·05	86·0 ± 0·2	209·5 ± 0·5	310 ± 90	8·81	3·81
60	Ballygrant, Islay	1·000	17·86 ± 0·06	15·29 ± 0·05	37·29 ± 0·11					
		1·400 ± 0·003	25·00 ± 0·03	21·40 ± 0·02	52·21 ± 0·04	85·6 ± 0·2	208·8 ± 0·4	270 ± 60	8·72	3·75
61	Strontian	1·000	18·04 ± 0·06	15·38 ± 0·05	37·53 ± 0·11					
		1·390 ± 0·003	25·07 ± 0·03	21·38 ± 0·02	52·16 ± 0·04	85·3 ± 0·2	208·1 ± 0·4	230 ± 60	8·88	3·78

Table 4 (*cont.*)

no.	locality	204	206	207	208	207/206 × 100	208/206 × 100	model age (My)	V_p	K_p
				Caithness, Orkney, Shetland						
62	Halkirk Bridge,	1·000	18·13 ± 0·06	15·50 ± 0·05	37·95 ± 0·10					
	Caithness	1·378 ± 0·003	24·98 ± 0·03	21·36 ± 0·02	52·29 ± 0·03	85·5 ± 0·2	209·3 ± 0·4	320 ± 50	9·09	3·95
63	Gie-Uisg Geo,	1·000	18·13 ± 0·05	15·50 ± 0·05	37·83 ± 0·08					
	Caithness	1·380 ± 0·002	25·02 ± 0·03	21·39 ± 0·03	52·21 ± 0·04	85·5 ± 0·2	208·7 ± 0·4	320 ± 50	9·09	3·89
64	Shapinsay, Orkney	1·000	17·78 ± 0·09	15·33 ± 0·07	37·42 ± 0·17					
		1·398 ± 0·005	24·86 ± 0·03	21·43 ± 0·02	52·32 ± 0·04	86·2 ± 0·2	210·5 ± 0·4	370 ± 70	8·80	3·87
65	Vidlin, Shetlands	1·000	17·84 ± 0·09	15·30 ± 0·07	37·60 ± 0·17					
		1·394 ± 0·005	24·87 ± 0·04	21·33 ± 0·02	52·41 ± 0·05	85·8 ± 0·2	210·7 ± 0·6	280 ± 70	8·73	3·91
66	Dury Voe, Shetlands	1·000	17·89 ± 0·11	15·30 ± 0·08	37·64 ± 0·20					
		1·392 ± 0·006	24·91 ± 0·04	21·30 ± 0·02	52·40 ± 0·05	85·5 ± 0·2	210·3 ± 0·6	250 ± 80	8·74	3·90
				Aberdeenshire						
67	Glen Gairn, no. 1	1·000	17·76 ± 0·09	15·39 ± 0·09	37·48 ± 0·19					
		1·396 ± 0·006	24·80 ± 0·03	21·48 ± 0·03	52·32 ± 0·04	86·8 ± 0·2	211·0 ± 0·4	460 ± 90	8·93	3·91
68	Glen Gairn, no. 2	1·000	17·74 ± 0·06	15·39 ± 0·05	37·50 ± 0·11					
		1·396 ± 0·003	24·76 ± 0·03	21·49 ± 0·02	52·35 ± 0·04	86·8 ± 0·2	211·4 ± 0·4	480 ± 50	8·95	3·95
69	Craigant' Seabhaig,	1·000	17·87 ± 0·08	15·44 ± 0·06	37·69 ± 0·14					
	Ballater Pass	1·389 ± 0·004	24·82 ± 0·04	21·45 ± 0·02	52·35 ± 0·04	86·4 ± 0·2	210·9 ± 0·5	440 ± 70	9·01	3·96
				Sutherlandshire						
70	Borolan	1·000	17·64 ± 0·07	15·29 ± 0·06	37·29 ± 0·13					
		1·404 ± 0·004	24·76 ± 0·03	21·47 ± 0·03	52·36 ± 0·04	86·7 ± 0·3	211·5 ± 0·4	430 ± 60	8·75	3·88
				Central Highlands						
71	Meall Luaidhe,	1·000	17·87 ± 0·07	15·37 ± 0·06	37·40 ± 0·14					
	Perthshire	1·396 ± 0·004	24·94 ± 0·03	21·45 ± 0·02	52·21 ± 0·04	86·0 ± 0·2	209·3 ± 0·4	360 ± 70	8·88	3·81
72	Clachan Beag,	1·000	17·67 ± 0·08	15·39 ± 0·05	37·32 ± 0·14					
	Argyllshire	1·401 ± 0·004	24·75 ± 0·04	21·56 ± 0·02	52·29 ± 0·04	87·1 ± 0·2	211·3 ± 0·5	530 ± 70	8·93	3·89
73	Tomnadashan,	1·000	17·55 ± 0·06	15·32 ± 0·04	37·25 ± 0·10					
	Perthshire	1·406 ± 0·003	24·68 ± 0·03	21·54 ± 0·02	52·38 ± 0·03	87·3 ± 0·2	212·2 ± 0·4	530 ± 60	8·81	3·92
74	Crom Allt, Tyndrum,	1·000	17·52 ± 0·06	15·31 ± 0·06	37·15 ± 0·10					
	Perthshire	1·409 ± 0·003	24·68 ± 0·04	21·57 ± 0·03	52·34 ± 0·04	87·4 ± 0·3	212·1 ± 0·5	550 ± 70	8·80	3·88
75	Ardtalanaig, Perthshire	1·000	17·12 ± 0·06	15·23 ± 0·06	37·90 ± 0·12					
		1·418 ± 0·004	24·40 ± 0·02	21·60 ± 0·02	52·59 ± 0·03	88·5 ± 0·2	215·5 ± 0·3	680 ± 60	8·68	4·03

TABLE 4 (*cont.*)

no.	locality	204	206	207	208	207/206 × 100	208/206 × 100	model age (My)	V_p	K_p
				North-west Highlands						
76	Loch Garbhaig,	1·000	16·96 ± 0·05	15·04 ± 0·04	38·53 ± 0·11					
	Ross-shire	1·398 ± 0·003	23·71 ± 0·02	21·02 ± 0·02	53·87 ± 0·03	88·7 ± 0·2	227·2 ± 0·3	650 ± 50	8·34	4·95
77	Letterewe,	1·000	16·96 ± 0·07	15·04 ± 0·05	38·87 ± 0·12					
	Ross-shire	1·393 ± 0·003	23·51 ± 0·04	20·95 ± 0·03	54·14 ± 0·05	89·1 ± 0·3	230·3 ± 0·6	710 ± 60	8·35	5·21
78	Allt na Ciad Eilig,	1·000	16·96 ± 0·06	15·17 ± 0·05	37·79 ± 0·10					
	Ross-shire	1·410 ± 0·003	23·92 ± 0·03	21·39 ± 0·02	53·28 ± 0·03	89·4 ± 0·2	222·7 ± 0·4	800 ± 60	8·58	4·57
79	Rois-bheinn,	1·000	16·88 ± 0·07	15·21 ± 0·08	36·36 ± 0·16					
	Inverness-shire	1·440 ± 0·005	24·30 ± 0·02	21·90 ± 0·04	52·36 ± 0·05	90·1 ± 0·2	215·5 ± 0·4	910 ± 80	8·69	3·85
				East Inverness-shire, Morayshire						
80	Struy, Inverness	1·000	18·32 ± 0·04	15·45 ± 0·04	38·18 ± 0·08					
		1·371 ± 0·002	25·12 ± 0·02	21·18 ± 0·02	52·34 ± 0·03	84·3 ± 0·2	208·4 ± 0·3	120 ± 40	8·99	3·93
81	St Aethans' Well,	1·000	18·20 ± 0·05	15·41 ± 0·03	38·17 ± 0·09					
	Moray	1·374 ± 0·003	25·00 ± 0·02	21·17 ± 0·02	52·45 ± 0·02	84·7 ± 0·2	209·8 ± 0·3	160 ± 60	8·93	3·99
82	Stobfield, Moray	1·000	18·23 ± 0·08	15·42 ± 0·06	38·24 ± 0·13					
		1·372 ± 0·004	25·01 ± 0·03	21·16 ± 0·02	52·47 ± 0·03	84·6 ± 0·2	209·8 ± 0·4	140 ± 70	8·94	4·00
				NORTHERN IRELAND						
83	Castleward, Co. Down	1·000	18·07 ± 0·07	15·43 ± 0·06	37·75 ± 0·13					
		1·384 ± 0·004	25·01 ± 0·02	21·35 ± 0·03	52·25 ± 0·03	85·4 ± 0·2	208·9 ± 0·3	280 ± 60	8·97	3·88
84	Conlig Mine, Co.	1·000	18·00 ± 0·08	15·50 ± 0·07	38·01 ± 0·14					
	Down	1·379 ± 0·004	24·82 ± 0·04	21·38 ± 0·03	52·42 ± 0·05	86·1 ± 0·3	211·2 ± 0·5	420 ± 70	9·11	4·06
				EIRE						
				South-east Ireland						
85	Glendalough, Co.	1·000	18·29 ± 0·11	15·56 ± 0·09	38·25 ± 0·21					
	Wicklow	1·368 ± 0·006	25·02 ± 0·05	21·29 ± 0·03	52·33 ± 0·06	85·1 ± 0·3	209·2 ± 0·7	280 ± 90	9·20	4·01
86	Glenmalure,	1·000	18·30 ± 0·07	15·53 ± 0·07	38·16 ± 0·14					
		1·370 ± 0·004	25·07 ± 0·03	21·28 ± 0·03	52·28 ± 0·04	84·9 ± 0·2	208·5 ± 0·5	240 ± 70	9·15	3·95
87	Barristown,	1·000	18·24 ± 0·13	15·53 ± 0·09	38·17 ± 0·20					
	Co. Wexford	1·371 ± 0·006	25·01 ± 0·06	21·29 ± 0·03	52·33 ± 0·06	85·1 ± 0·4	209·2 ± 0·7	280 ± 80	9·15	4·16

Table 4 (*cont.*)

no.	locality	204	206	207	208	207/206 × 100	208/206 × 100	model age (My)	V_p	K_p
				South-east Ireland (cont.)						
88	Avoca Mine, Co.	1·000	18·02 ± 0·08	15·53 ± 0·06	37·92 ± 0·15					
	Wicklow, no. 271	1·380 ± 0·004	24·87 ± 0·04	21·43 ± 0·02	52·33 ± 0·05	86·2 ± 0·2	210·4 ± 0·5	440 ± 70	9·17	4·01
89	Avoca Mine,	1·000	18·04 ± 0·09	15·55 ± 0·08	38·04 ± 0·18					
	no. D.P. 21	1·377 ± 0·005	24·84 ± 0·04	21·41 ± 0·03	52·38 ± 0·06	86·2 ± 0·3	210·9 ± 0·6	450 ± 70	9·20	4·05
90	Avoca Mine,	1·000	18·12 ± 0·08	15·59 ± 0·07	38·13 ± 0·15					
	no. 3*c*	1·373 ± 0·004	24·88 ± 0·04	21·41 ± 0·03	52·35 ± 0·06	86·1 ± 0·2	210·4 ± 0·6	440 ± 70	9·27	4·06
91	Avoca Mine,	1·000	17·99 ± 0·10	15·49 ± 0·09	37·83 ± 0·20					
	no. 8A, 548 ft.	1·383 ± 0·006	24·88 ± 0·03	21·42 ± 0·04	52·32 ± 0·05	86·1 ± 0·3	210·3 ± 0·4	420 ± 80	9·10	3·97
				Western Ireland						
92	Abbeytown, Co. Sligo	1·000	18·27 ± 0·13	15·60 ± 0·11	38·19 ± 0·25					
		1·369 ± 0·008	25·01 ± 0·03	21·35 ± 0·03	52·27 ± 0·06	85·4 ± 0·2	209·0 ± 0·5	340 ± 90	9·27	4·00
93	Sheefry Mine,	1·000	17·89 ± 0·08	15·35 ± 0·06	37·66 ± 0·14					
	Co. Mayo	1·391 ± 0·004	24·88 ± 0·04	21·35 ± 0·02	52·38 ± 0·05	85·8 ± 0·2	210·5 ± 0·6	310 ± 70	8·83	3·92
94	Clements Mine,	1·000	17·30 ± 0·08	15·44 ± 0·07	37·13 ± 0·14					
	Co. Galway	1·411 ± 0·004	24·41 ± 0·04	21·79 ± 0·03	52·39 ± 0·05	89·3 ± 0·2	214·6 ± 0·6	860 ± 70	9·09	4·04
95	Glengowla Mine,	1·000	17·47 ± 0·11	15·34 ± 0·09	37·15 ± 0·20					
	Co. Galway	1·409 ± 0·006	24·62 ± 0·04	21·62 ± 0·04	52·35 ± 0·05	87·8 ± 0·3	212·6 ± 0·6	620 ± 80	8·86	3·92
96	Cloosh Mine,	1·000	17·46 ± 0·09	15·40 ± 0·09	36·96 ± 0·18					
	Co. Galway	1·412 ± 0·005	24·66 ± 0·05	21·74 ± 0·04	52·19 ± 0·07	88·2 ± 0·4	211·6 ± 0·8	700 ± 80	8·97	3·84
97	O’Flaherty’s Shaft,	1·000	17·45 ± 0·11	15·30 ± 0·07	36·82 ± 0·17					
	Co. Galway	1·417 ± 0·005	24·73 ± 0·06	21·68 ± 0·02	52·17 ± 0·06	87·7 ± 0·3	211·0 ± 0·7	580 ± 80	8·77	3·75
98	Lough Corrib Shore,	1·000	17·91 ± 0·11	15·37 ± 0·09	37·52 ± 0·20					
	Co. Galway	1·393 ± 0·006	24·95 ± 0·40	21·41 ± 0·03	52·26 ± 0·06	85·8 ± 0·3	209·5 ± 0·5	320 ± 80	8·86	3·85
				GERMANY						
99	Turandot Mine,	1·000	18·11 ± 0·10	15·46 ± 0·09	37·89 ± 0·19					
	Siegerland	1·380 ± 0·006	24·99 ± 0·03	21·34 ± 0·02	52·29 ± 0·04	85·4 ± 0·2	209·2 ± 0·4	290 ± 90	9·03	3·92
100	Maubach, Duren	1·000	18·22 ± 0·09	15·44 ± 0·08	37·96 ± 0·17					
		1·377 ± 0·005	25·09 ± 0·03	21·26 ± 0·03	52·27 ± 0·05	84·7 ± 0·3	208·3 ± 0·5	180 ± 80	8·97	3·89

the isotopic composition is reported in two ways, first, with lead-204 = 1·000 in the top line, and, secondly, with the percentage abundance in the bottom line. The ratios 207/206 and 208/206 are also given, in each case multiplied by 100. These ratios are not affected significantly by the relatively large uncertainty in the 204 abundance. The quoted errors signify twice the standard error for each series of measurements, representing a 95% confidence level. For more than one-half of the samples two runs were available, each consisting of twenty to thirty individual mass-spectrometer scans. Duplicate runs were generally carried out at intervals of several weeks or months and in nearly all cases agreed within the experimental error. In the very few cases where duplicate runs lay just outside these errors, a third run was carried out as a check. Duplicate runs were averaged together, weighting each run according to the number of scans comprising it and weighting each isotope abundance inversely as the square root of the standard error associated with it. The errors in table 4 clearly show with which analyses the greatest precision is to be associated.

The parameters, model age (in million years), uranium-238/lead-204 (V_p) and thorium-232/uranium-238 (K_p), the latter two calculated to the present time, are also listed in table 4. The errors of the model ages are calculated from the experimental errors only. The average errors of V_p and K_p are in the region 0·10 to 0·14 and 0·05 to 0·08, respectively.

5. COMPARISON OF MODEL AGES OF GALENAS WITH THE ABSOLUTE AGES OF GENETICALLY ASSOCIATED IGNEOUS ROCKS

The best test of the validity and significance of a model age, and of the assumptions used in its calculation, is provided by comparison with the absolute ages of genetically associated rocks determined by other methods. Table 5 presents average model ages for

TABLE 5. COMPARISON OF MODEL AGES WITH ABSOLUTE AGES

1	2	3	4	5	6	7	8	9
					Russell-Cumming-Farquhar model		Russell-Stanton-Farquhar model	
locality	potassium–argon age (My)	rubidium–strontium age (My)	uranium–lead age (My)	Holmes–Houtermans model age (My)	206/204 age (My)	208/204 age (My)	207/206 age (My)	208/204 age (My)
Shap granite Westmorland	391 ± 7(1)	381 ± 7(1)	—	370 ± 50	370	500	190	420
Hercynian granites, Devon and Cornwall	271 ± 5(1)	277 ± 5(1)	288 ± 10(2)	280 ± 30	340	550	120	480
Oslo igneous province, Norway	259(3)	—	259(3)	250 ± 30	270	380	60	310

(1) Kulp, Long, Giffin, Mills, Lambert, Giletti & Webster (1960).
(2) Darnley, Smith, Chandler, Dance & Preece (1960).
(3) Faul, Elmore & Brannock (1959).

three different areas, together with published age determinations on associated igneous rocks by the potassium–argon (column 2), the rubidium–strontium (column 3) and the uranium–lead methods (column 4). The Holmes–Houtermans model age, obtained with the assumptions outlined in §2, is given in column 5, whilst the model ages obtained by the Russell–Cumming–Farquhar method are shown in columns 6 and 7. Finally, the Russell–Stanton–Farquhar model ages are given in columns 8 and 9, although this method is claimed only for certain types of conformable lead ore and not for vein deposits of the type under discussion. The model ages in columns 6 to 9 were obtained from the tables of Russell & Farquhar (1960*b*). The three sets of data in table 5 are now briefly discussed.

(*a*) *Shap, Westmorland*

The Caledonian Shap granite is associated with a small, late-stage mineralization with fluorite, chalcopyrite, pyrites, bismuthinite, blende, galena and barytes which, in places, extends out into the surrounding metasomatized Borrowdale volcanics (Firman 1957). The absolute age of the Shap granite has been determined by Kulp, Long, Giffin, Mills, Lambert, Giletti & Webster (1960) by potassium–argon and rubidium–strontium measurements on biotites. Two galenas have been measured from the mineralization (nos. 42 and 43, table 4).

(*b*) *Devon and Cornwall*

It is well established that in south-west England there is a very close connexion between granite emplacement and mineralization (e.g. Dines 1956). Potassium–argon and rubidium–strontium ages on biotites from the Hercynian Dartmoor granite have been reported by Kulp *et al.* (1960). A concordant uranium–lead age has been obtained by Darnley, Smith, Chandler, Dance & Preece (1960) for a uraninite from Geevor, Cornwall. Seven galenas have been measured from Cornwall and Devon (nos. 1 to 7, table 4).

(*c*) *Oslo Permian igneous province, Norway*

Two galena specimens were measured, kindly provided by Dr F. M. Vokes of the Mineralogisk-Geologisk Museum, Oslo. They are from an undoubted Permian vein-type deposit on the north-western edge of the Oslo igneous province near Grua, about 40 Km due north of Oslo. Faul *et al.* (1959) have published potassium–argon and uranium–lead ages for minerals from the southern part of the Oslo Province.

It is concluded from the comparisons presented in table 5 that the Holmes–Houtermans method can give reliable model ages for post-Cambrian lead deposits, within the limitations of experimental error.

The Russell–Cumming–Farquhar and Russell–Stanton–Farquhar methods give variable model ages, mostly of the right order. In particular, the 206/204 model ages obtained by the Russell–Cumming–Farquhar method are in rather good agreement with the Holmes–Houtermans model ages. It seems likely that a slightly different choice of constants in the equations for these two models would give better general agreement with the age of mineralization of many lead ores in the age-range under discussion. Furthermore, as pointed out in §4, the Holmes–Houtermans model on the one hand, and those of Russell *et al.* on the other, may not be based on strictly comparable mass-spectrometric measurements. However, the present author considers that the fundamental inability of the Russell *et al.* models to allow for variation in the primary uranium–lead ratio will tend to limit their range of application, especially for young leads.

6. Regional discussion of isotope abundances

This section is devoted to a regional discussion of the British and Irish lead isotope data in terms of the calculated parameters model age, uranium-238/lead-204 (V_p) and thorium-232/uranium-238 (K_p) of the Holmes–Houtermans model.

The four subsections deal with England, Wales, Scotland and Ireland, respectively. This is an arbitrary division as far as the isotope data are concerned, since many similar groups are thereby separated. However, in §7 the entire data are summarized in terms of possible periods of mineralization in the British Isles and Ireland. The discussion follows the same order as the tabulation of results in table 4. For the sake of convenience the parameters, model age, V_p and K_p are given again for each sample; furthermore, the weighted mean of the model ages is also given for each group, as well as the arithmetical means of V_p and K_p. The principal mineral occurrences in Great Britain and Ireland, together with the galena specimen numbers, are shown in figure 2.

The model ages are interpreted in terms of the recently published geological time-scales of Holmes (1960) and Kulp (1960), which are summarized in table 6.

Table 6. Geological time-scale of fossiliferous strata

	according to Holmes (1960)		according to Kulp (1960)	
	period (My)	duration (My)	period (My)	duration (My)
Cretaceous	70–135	65	70–135	65
Jurassic	135–180	45	135–180	45
Triassic	180–225	45	180–220	40
Permian	225–270	45	220–270	50
Carboniferous	270–350	80	270–350	80
Devonian	350–400	50	350–400	50
Silurian	400–440	40	400–430	30
Ordovician	440–500	60	430–490	60
Cambrian	500–600	100	490–(600)	110 (?)

(*a*) *England*

(i) *Cornwall–Devon*

no.		model age (My)	V_p	K_p
1	Bere Alston	270 ± 60	9·02	3·91
2	Wheal Rose	290 ± 70	9·05	3·90
3	Vottle Shaft	260 ± 60	9·07	3·87
4	South Terras	270 ± 70	9·13	3·89
5	Mary Anne	280 ± 60	9·15	3·91
6	Lambriggan	260 ± 70	9·13	3·97
7	Penberthy Croft	300 ± 60	9·19	3·98
	mean:	280 ± 30	9·10	3·92

The galena samples are from localities within the zone of mineralization of the Hercynian granites of south-west England. The geology of this area, with special reference to metalliferous mineralization, has been described by Dines (1956).

There are two mineralogically and structurally distinct sets of veins in this area. The first trends largely in an E.N.E. and E.–W. direction and, in these veins, all stages of zoning can be followed from cassiterite and wolfram, through chalcopyrites to galena, blende and chalybite. Dunham (1952*a*) states that there can be no doubt as to the age of this mineralization. These veins were subsequently cut and shifted by a series of veins

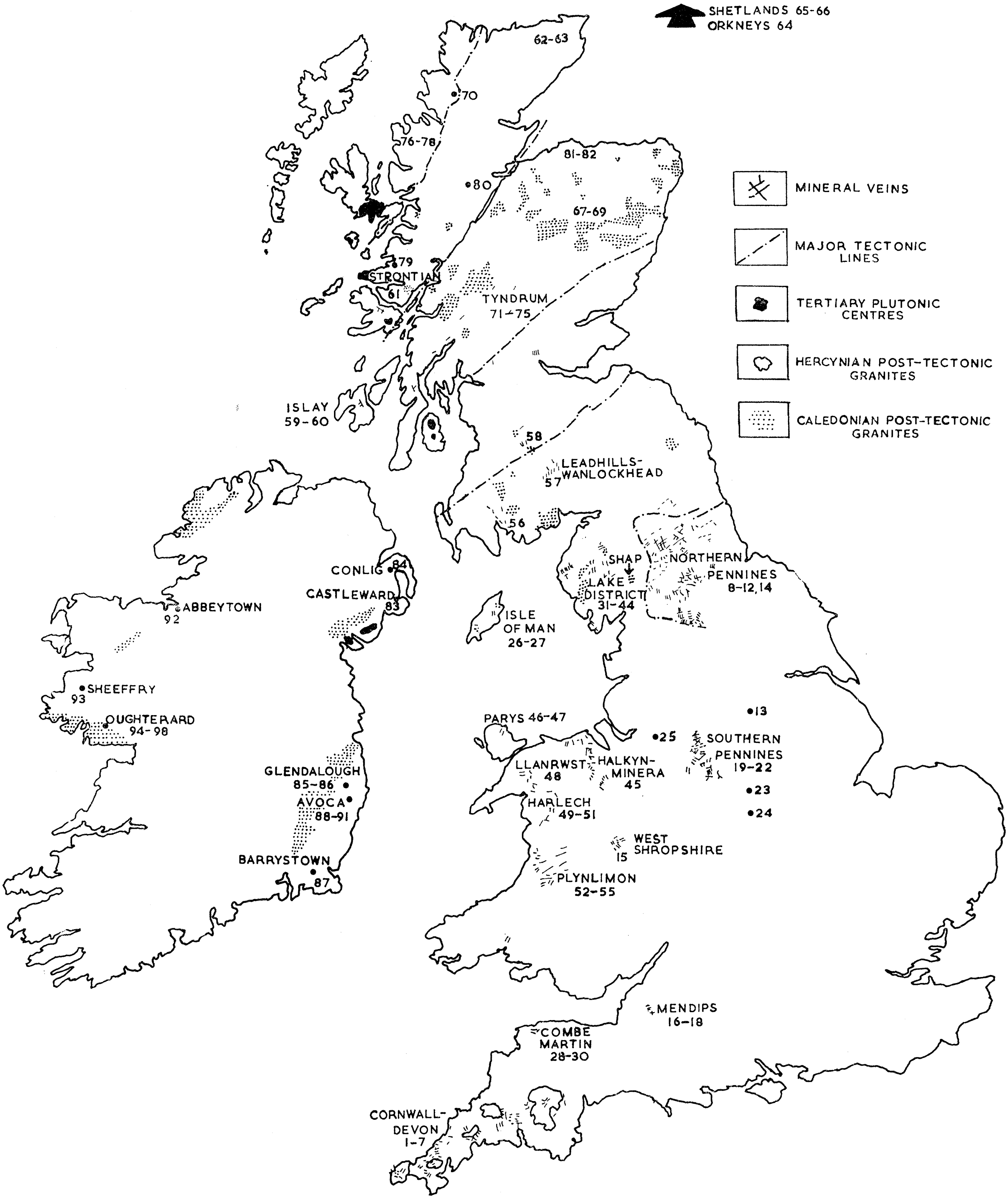

FIGURE 2. Map of the British Isles showing principal mineral occurrences and specimen numbers of galenas measured in the present work.

with a dominantly N.–S. trend which carry upper zone minerals, including galena, blende, fluorite, barytes and occasional uranium, nickel and cobalt minerals. Several early workers considered the N.–S. veins to be Tertiary in age (Collins 1896; Hill 1901; Hill & MacAlister 1906). Dunham (1952*a*), however, does not consider that there is any direct support for Tertiary mineralization and suggests that the N.–S. fractures originated in Permian times.

The isotopic abundance ratios and model parameters for the seven samples lie within the experimental errors, so that there is no significant isotopic variation within this group. Specimens 3, 6 and 7 are from the earlier E.–W. veins and specimens 1, 2, 4 and 5 represent the later N.–S. set. It thus appears most unlikely that there is a considerable age difference between the two sets and Dunham's suggestion of a late Carboniferous or Permian age for the N.–S. and E.–W. veins appears the most reasonable hypothesis.

(ii) *Northern Pennines and north-east England*

no.		model age (My)	V_p	K_p
8	Barbary Mine	280 ± 80	9·09	3·95
9	Sedling Mine	310 ± 50	9·20	4·00
10	Rotherhope Fell	260 ± 60	9·07	3·89
11	Settlingstones	270 ± 60	9·13	3·95
	mean:	280 ± 30	9·13	3·95
12	Chilton Quarry	280 ± 70	8·97	3·85
13	Steetley Quarry	280 ± 60	9·02	3·90
14	Thickley Quarry	310 ± 70	9·15	4·00
	mean:	290 ± 40	9·05	3·92

The lateral mineral zoning of the stratigraphically proven post-Carboniferous northern Pennine ore field corresponds closely with the outer zones of the Cornwall–Devon field and Dunham (1952*a*) considers that this, together with the general similarity in geochemical assemblage, should take precedence over other arguments in assessing the age of the Pennine deposits. Consequently, he postulates a Hercynian age for the mineralization, which is also suggested by various lines of structural evidence (Dunham 1948, 1959*b*). Gravity surveys over the northern Pennine area by Bott (1957) and Bott & Masson-Smith (1953), demonstrated the presence of a strong negative anomaly centrally situated beneath the Alston block, interpreted as a granitic stock or batholith in the basement rocks at a depth of not more than 3500 ft. These workers originally advocated a post-Carboniferous age for the unexposed Weardale granite and attributed the Pennine mineralization to it. On the other hand, Holmes (1953) suggested that the alternative of a Caledonian age for the Weardale granite was more in keeping with the geological environment.

Recently, a borehole has proved the existence of the Weardale granite at a depth of 1281 ft. directly below Lower Carboniferous (Visean) strata (Dunham, Bott, Johnson & Hodge 1961). Absolute age measurements on the granite by the potassium–argon and rubidium–strontium methods yielded a weighted mean of 362 ± 6 million years thus confirming a pre-Carboniferous age and demonstrating that the northern Pennine mineralization is not connected with the emplacement of the Weardale granite (Dodson & Moorbath 1961). Dunham *et al.* suggest that (1) the mineral veins were fed from some source beneath that part of the granite so far drilled and (2) the buried pre-Carboniferous cupolas served to localize the upward flow of mineralizing fluids into the Carboniferous rocks.

The model parameters agree within the limits of error for the four specimens from the northern Pennine orefield, nos. 8, 9, 10 and 11. There is, furthermore, close agreement with the mean parameters of the Cornwall–Devon mineralization. No reasonable doubt can remain that the two ore fields are geochronologically and geochemically equivalent.

A Hercynian age for the northern Pennine mineralization is in contradiction to the conclusions of Trotter (1944), who postulates a Tertiary age, partly on the basis of structural evidence. Both he and Fowler (1956) also consider the existence of widespread, small amounts of fluorite, barytes, blende and galena in the Magnesian Limestone, east of the ore field, as indicating post-Permian, possibly Tertiary, mineralization. This mineralization is in some places certainly epigenetic, although it does not occur in well-defined veins. In other places it appears to be syngenetic. Dunham (1952*a*) suggests that the Pennine mineralization was actually in progress during deposition of the Permian Magnesian Limestone and that some of the mineralizing fluids found their way into the Zechstein Sea.

Three measurements are available on galenas from the Lower Permian, nos. 12, 13 and 14. The Chilton and Steetley specimens occur as disseminated aggregates in the Magnesian Limestone; the Thickley specimen is from a thin persistent layer near the top of the Lower Permian Durham Marl Slate, which has been considered equivalent with the German Kupferschiefer by Deans (1948). He regards this mineralization as syngenetic and of sedimentary origin.

There is no significant difference between the mean model parameters of the three specimens and those of the northern Pennine ore field. The mineralization is therefore interpreted as Hercynian, of Lower Permian age. The respective theories of Dunham and Deans regarding the mineralization in the Permian Limestone and Marl Slate are not contradicted by the isotope data. The data do not support a Tertiary age for the mineralization.

(iii) *Shelve*, *Shropshire*

no.		model age (My)	V_p	K_p
15	White Grit Mine	280 ± 70	9·29	4·00

The mineral veins of west Shropshire traverse pre-Cambrian (Longmyndian) and Ordovician strata (Dines 1958, 1959). There is no critical evidence for the age of mineralization, save that it is post-Ordovician and later than a suite of dykes considered to be of probable Silurian age.

The model age suggests Hercynian mineralization, i.e. probably Lower Permian, in common with the other areas so far discussed.

(iv) *Mendip Hills*, *Somerset*

no.		model age (My)	V_p	K_p
16	in Carboniferous Limestone	240 ± 50	9·17	4·00
17	in Upper Triassic	220 ± 60	9·05	3·93
18	in Lower Jurassic	240 ± 60	9·14	3·97
	mean:	230 ± 30	9·12	3·97

The youngest horizon affected by large-scale mineralization in the Mendip Hills is the Dolomitic Conglomerate of Upper Triassic (Keuper) age. Small amounts of galena and blende furthermore occur in Lower Jurassic rocks. Several workers have favoured a hydrothermal origin for the sulphides in the Carboniferous Limestone, probably contemporaneous with the Cornwall–Devon mineralization, whereas the sulphide occurrences in the latter rocks were presumed to have been derived from the primary vein deposits by a combination of mechanical erosion and chemical solution (Dewey 1921). On the other hand Dunham (1952*a*) regards all the sulphides as epigenetic and possibly due to mineralization from 'fossil' hydrothermal fluids trapped in suitable reservoirs since the main Permo-Carboniferous mineralizing episode and released at a later time.

The most recent account of the Mendip ore field is that of Green (1958), who states that 'the large size of the ore deposits, particularly of galena, in the Keuper Dolomitic Conglomerate, their relationship to structural controls favouring the ascent of ore solutions from below, and the evidence from surface workings that the vein system is continuous with that in the adjacent Carboniferous Limestone, are held to show that these ore deposits are primary in origin'. Green considers that a Tertiary age for the mineralization is not out of the question, but '...the ascription of a post-Keuper age for the mineralization must be regarded as no more than a suggestion, since the erosion of the Mesozoic cover has removed so much of the evidence. The main difficulty of assigning a Jurassic or later date to it is the relatively very small amounts of lead–zinc minerals in the post-Keuper rocks in spite of post-Triassic earth-movements.'

The model parameters for samples 16, 17 and 18 are in good agreement. The specimens are from occurrences in the Carboniferous Limestone, in Keuper Dolomitic Conglomerate and in the Lower Lias Limestone, respectively. The average model age of 230 ± 30 My is significantly lower than the value obtained for the Cornwall–Devon mineralization, and supports the suggestion of Triassic mineralization in the Mendips. Furthermore, the close agreement between V_p and K_p for Cornwall–Devon and the Mendips does not contradict Dunham's fossil hydrothermal hypothesis. The mineralization may have been associated with early movements along the Mendip Axis, which was to assume great significance in Jurassic times. A Tertiary age for the Mendip mineralization is improbable.

The fact that specimen 18 from the Lower Lias Limestone shows no significant isotopic difference from the other two specimens, cannot, without evidence, be regarded as implying a post-Liassic mineralization for the major Mendip occurrences. The minor occurrences in the Lower Jurassic might be derived or regenerated from older deposits. In any case the absolute time differences involved are too small for any definite conclusions regarding this point, without sufficient further measurements for a statistical comparison.

(v) *Southern Pennines, Derbyshire*

no.		model age (My)	V_p	K_p
19	Millclose Mine	170 ± 50	9·07	3·86
20	Riber Mine	150 ± 80	9·13	3·95
21	Wheels' Rake	220 ± 70	9·16	3·96
22	Moletrap Mine	180 ± 60	9·18	3·94
	mean:	180 ± 40	9·13	3·93

The mineralization occurs in the Carboniferous Limestone Series (Lower Carboniferous) and has been described by Carruthers & Strahan (1923), Schnellmann & Willson (1947), Shirley (1948) and Varvill (1959). There is no field evidence for genetic association with igneous rocks.

The four isotope analyses and model parameters are in good agreement, except for the rather higher model age of sample 21. The mean model age is significantly lower than that of the northern Pennines, so that there appears to be no direct genetic connexion between the two orefields. The V_p and K_p values, however, do no differ significantly for the two groups.

It is postulated that the southern Pennine mineralization is Mesozoic in age. The error quoted for the mean model age would permit assignment of the mineralization to any time between approximately the Middle Triassic and the Upper Jurassic, as judged from the latest time-scales of Holmes (1960) and Kulp (1960).

(vi) *North Midlands*

no.		model age (My)	V_p	K_p
23	Bulwell, Notts.	200 ± 70	9·22	4·00
24	Garendon Park, Leics.	210 ± 80	9·29	4·02
25	Alderley Edge, Cheshire	210 ± 60	9·04	3·91
	mean:	210 ± 40	9·18	3·98

The Bulwell galena (no. 23) is from a persistent occurrence in the topmost 2 in. of the Permian Lower Magnesian Limestone, covering an area of several square miles. Deans (personal communication) considers that lead-bearing solutions were evidently trapped below the impervious Marl of Middle Zechstein (Upper Permian) age, so that the galena is clearly Middle Zechstein or younger. Deans regards the mineralization as 'derived from minor disseminations of syngenetic galena in the Lower Magnesian Limestone and Grey Beds (local equivalents of the Marl Slate), which were redistributed in later Permian times, probably Middle Zechstein, possibly still later'.

The Garendon Park galena (no. 24) occurs as a dissemination in Triassic Keuper Marl in the Charnwood district of Leicestershire.

The Alderley Edge sample (no. 25) is from the well-known Cheshire deposit, where workable oxidized copper minerals occur as impregnations in conglomerate and sandstone at the bottom of the Keuper division of the Triassic, with minor galena and appreciable amounts of arsenic and vanadium (Dewey & Eastwood 1925). This deposit is analogous in many ways with the 'Red Bed' copper deposits of the United States and of Western Europe. Dewey & Eastwood postulated a sedimentary, syngenetic origin for Alderley Edge, but Dunham (1952*a*) considers that the substantial barytes deposits nearby are difficult to explain on this hypothesis.

Behrend (1948) suggested that the great Mechernich lead deposit in Triassic sandstone, in Germany, is a hydrothermal deposit fed by nearby veins in older rocks. Dunham states that neither hypothesis appears quite satisfactory for the British deposits, but that the 'fossil water' hypothesis may furnish an explanation.

The average model age for this group of three specimens is consistent with Mesozoic mineralization of probable Upper Triassic age. The mean value of V_p and K_p agrees closely with previous groups.

With regard to the origin of the Bulwell galena, it appears unlikely that this is a simple redistribution of galena from the Lower Magnesian Limestone as suggested by Deans, since the Bulwell mineralization belongs to the younger age group, whilst his so-called 'syngenetic' galenas (e.g. no. 14) belong to the 280 ± 30 My Hercynian age-group.

It is not possible to make any definite assertions from the isotope measurements, regarding the origin of the Alderley Edge deposit. It is of interest, however, that the isotopic composition of lead from the German Mechernich deposit agrees within experimental error with the Alderley Edge galena (table 4, no. 100). It was pointed out above that this is considered to be a hydrothermal deposit, fed by veins (Behrend 1948). This, of course, does not rule out a sedimentary origin for Alderley Edge, although it appears unlikely that a sedimentary mechanism of ore genesis of the type envisaged by Dewey & Eastwood is sufficient to produce the relatively large-scale mixing required to give a lead isotope composition yielding a model age probably very close to the true age of mineralization. A sedimentary origin in a relatively restricted, non-marine and arid environment seems more likely to yield anomalous model parameters.

(vii) *Isle of Man*

no.		model age (My)	V_p	K_p
26	Foxdale	220 ± 40	9·12	3·98
27	Laxey	220 ± 60	9·10	4·02
	mean:	220 ± 30	9·11	4·00

There are two important sets of veins in the Isle of Man, one trending E.–W. (Foxdale) and the other trending N.–S. (Laxey). The former set has been followed downwards from the Manx Slates (Cambrian?) into granite; however, no genetic connexion between granite and veins has been demonstrated, except that granite forms a favourable wall rock for the mineralization. The occurrence has been described by Carruthers & Strahan (1923) and Dewey & Eastwood (1925).

The mean model age for the two galenas is post-Hercynian and indicates possible affinity with the Mendip–Alderley Edge–Southern Pennine groups discussed previously which were considered to be Mesozoic (Upper Triassic?) in age.

(viii) *Combe Martin area, North Devon*

no.		model age (My)	V_p	K_p
28	Knap Down Mine	370 ± 80	9·09	3·96
29	Combe Martin no. 1	360 ± 80	9·07	3·91
30	Combe Martin no. 2	370 ± 90	9·09	4·02
	mean:	370 ± 50	9·08	3·96

The geology of this mineralization has been described by Dines (1956). There is little doubt that the Combe Martin lead–silver ores are different in several respects from the typical Cornwall–Devon lead–zinc lodes associated with the Hercynian granites. The following is a brief comparison of the two mineralizations, kindly supplied by F. W. Dunning of the Geological Survey of Great Britain.

Combe Martin		Cornwall–Devon
	Mineralogy	
Milky, massive quartz and massive chalybite are the only gangue minerals		Gangue includes clear, crystalline quartz, fluorite, barytes, calcite, crystalline chalybite—the typical Hercynian assemblage
	Texture	
Mostly medium-to fine-grained aggregates, frequently sheared, with tectonic inclusions of quartz and chalybite. No vughs		Coarse-grained, crustified ores with crystalline vughs. No shearing
	Occurrence	
Veinlets and pods, lenses, along bedding-planes and shears, parallel to strike. Much discontinuity		Tabular fissue-veins, cutting across beds

The isotopic data for the three samples are in close agreement. The mean model age is considerably higher than for the Hercynian Devon–Cornwall group, and there is little doubt that the Combe Martin mineralization occurred earlier, possibly in late Devonian times. (The country rocks in this area consist of Devonian slates.) The parameters V_p and K_p once again show no significant deviation from previously quoted values for other groups.

There is some independent geological evidence for a pre-Hercynian age of these deposits (F. W. Dunning, personal communication).

(*a*) There are no similar occurrences in the Carboniferous Culm Series.

(*b*) There is no doubt that the principal folding in North Devon is Asturic, i.e. Stephanian. If the mineralization is earlier, then it must have been affected by these movements. The ores are, in fact, strongly sheared.

(ix) *The Lake District and adjoining areas*

no.		model age (My)	V_p	K_p
		group 1		
31	Eagle Crag Vein	170 ± 80	9·04	3·91
32	Hartsop Hall Mine	210 ± 70	9·15	3·95
33	Carrock Mine	210 ± 70	9·06	4·00
34	Roughton Gill	220 ± 40	9·11	3·97
35	Driggith Vein	260 ± 90	9·13	3·88
	mean:	210 ± 40	9·10	3·94
		group 2		
36	Barrow Mine	300 ± 80	9·11	3·94
37	Goldscope Lode	310 ± 80	9·17	3·96
38	Woodend Mine	340 ± 70	9·19	4·00
39	Low Hartsop Mine	310 ± 80	9·06	3·93
40	Greenside Mine	330 ± 90	9·26	4·07
41	Hensingham Borehole	320 ± 70	9·27	4·09
	mean:	320 ± 30	9·18	4·00
		group 3		
42	Shap Blue Rock Quarry no. 1	370 ± 60	9·19	3·98
43	Shap Blue Rock Quarry no. 2	360 ± 80	9·16	3·97
	mean:	370 ± 50	9·18	3·98
		group 4		
44	Buttermere Vein	470 ± 50	9·26	4·05

The extensive Lake District mineralization has been studied by many geologists, whilst Dunham (1952*a*) has reviewed the geological evidence for its age. Most of the veins occur in tightly folded Cambro-Ordovician Skiddaw slates and in the overlying Ordovician Borrowdale lavas and pyroclastics. There appears to be no demonstrable connexion between the major lead, copper, zinc and barium deposits of the Lake District and the Caledonian granitic intrusions. The only definite exception is the Shap granite of Westmorland, which carries its own small late-stage mineralization (Firman 1957). The other case of association with a Caledonian intrusion is the wolfram-bearing deposit at Carrock Mine, Grainsgill, Cumberland, which may represent late-stage mineralization from the Skiddaw granite.

There is a limited extension of the Lake District veins into Lower Carboniferous strata in the marginal parts of the area, although this is not sufficiently widespread to be a really diagnostic criterion. Dixon (1928) and Trotter (1944) suggests that the presumed Tertiary haematite deposits of west Cumberland represent the outer zone of the Lake District non-ferrous ore field and that the latter is therefore Tertiary in age. From a geochemical viewpoint Dunham (1952*a*) considers this to be unlikely. A general consideration of the geological evidence suggests that the greater part of the Lake District mineralization could be Hercynian, as was already posulated by Finlayson (1910).

Turning to the isotopic data, it is found that the geological conclusions outlined above are partially substantiated, although several complications arise. Groups 1 and 2 probably represent the major part of the Lake District mineralization. Group 1 (210 ± 40 My) may be approximately contemporaneous with the Mendip–Alderley Edge–Isle of Man mineralizations, discussed previously, i.e. possibly Upper Triassic and in any case, Mesozoic. The veins of this group trend E.–W. (nos. 31, 33), E.N.E.–W.S.W. (nos. 34, 35) and N.N.E.–S.S.W. (no. 32). The Driggith vein sample (no. 35) is included in this group because it is thought to represent the eastward extension of the Roughton Gill vein (no. 34). A somewhat greater error is associated with the Driggith sample.

Group 2 (320 ± 30 my) appears to pre-date the Hercynian (Lower Permian) mineralization of Cornwall–Devon, northern Pennines, etc., and may well be Lower or Middle Carboniferous in age. The Hensingham galena (no. 41) occurs in the lower Carboniferous Limestone. The veins of this group trend N.–S. (nos. 36, 37, 40) and N.N.W.–S.S.E. (nos. 38, 39).

The galena from the E.–W. vein at Carrock Mine (no. 33) gives a model age of 210 ± 70 My suggesting that this mineralization is not genetically associated with the Caledonian Skiddaw granite. The vein cuts and displaces the N.–S. wolfram-bearing veins which are generally considered to be cogenetic with the Skiddaw granite but, unfortunately, do not contain galena.

Group 3 consists of two leads from the Shap granite mineralization. The Shap granite is post-Upper Silurian (Ludlovian) and pre-Lower Carboniferous (Harker & Marr 1891; Capewell 1955). Its position in the Devonian is not known with certainty. The agreement between the galena model age and the absolute age of the Shap granite (Kulp *et al.* 1960) has already been described in §5.

The galena specimen from the Buttermere vein (no. 44), has been assigned to a separate group in view of its high model age of 470 ± 50 My. It occurs in the western part of the Lake District in the Borrowdale Volcanic Series. The mineralization may be lower Palaeozoic in age, i.e. Ordovician or Silurian, and possibly contemporaneous with mineralizations in North Wales, Aberdeenshire and south-east Ireland which give similar model ages.

At this stage, the major conclusions that can be drawn from the isotopic data are as follows:

(1) The greater part of the Lake District mineralization is not directly connected with the known Caledonian intrusions. Such connexion appears only on a minor scale, for instance, in the case of the Shap granite.

(2) There is no evidence for Tertiary mineralization in the Lake District.

(3) There are two major periods of mineralization, with respective mean model ages of 210 ± 40 and 320 ± 30 My.

(4) There is no significant variation in the parameters V_p and K_p in the source of the Lake District galenas.

A great deal more work is clearly necessary in the Lake District and, in particular, there must be close integration of field and laboratory work. It remains for detailed field work to establish the validity of the conclusions drawn from the model parameters.

(*b*) *Wales*

(i) *Flintshire*

no.		model age (My)	V_p	K_p
45	Halkyn	170 ± 80	9·12	3·99

The geology of the Halkyn ore field has been described by Earp (1958) and Schnellmann (1959). The highest mineralized horizon is the Lowest Coal Measures (Upper Carboniferous).

A single model age suggests that the mineralization is Mesozoic in age and may have a possible affinity with the Southern Pennine group, samples nos. 19–22.

(ii) *Anglesey*

no.		model age (My)	V_p	K_p
46	Parys Mountain 1	300 ± 50	9·18	3·92
47	Parys Mountain 2	290 ± 60	9·22	3·99
	mean:	300 ± 40	9·20	3·96

In this area there are broad belts of intense metasomatism in Ordovician and Silurian shales and in a felsite sill, with introduction of quartz and sulphides, including pyrite, chalcopyrite and the fine-grained, complex bluestone (Greenly 1919; Manning 1959). The latter consists of an aggregate of pyrite, chalcopyrite, chalcocite, blende and galena and is represented by specimens 46 and 47.

The model ages suggests Carboniferous (Hercynian?) mineralization, possibly contemporaneous with Cornwall–Devon and northern Pennines. This conflicts with the geological evidence. Greenly (1919) describes the presence of pebbles of typically silicified and pyritized shale in the basal Carboniferous conglomerate at Lligwy Bay, identical with the unusual altered wall rock at Parys Mountain.

A Hercynian age for the mineralization is, furthermore, unexpected in that the galenas from Merioneth and Cardigan on the mainland all have Caledonian model ages (nos. 49–55) as well as the Avoca deposit of Co. Wicklow in Ireland (nos. 88–91) which closely resembles the Parys Mountain deposit.

The conflict can only be resolved by further fieldwork and isotope analyses. For the present, the author favours the Hercynian age, in which case the basal Carboniferous conglomerate must be assumed to have been mineralized after its deposition.

(iii) *Caernarvonshire*

no.		model age (My)	V_p	K_p
48	Parc Mine, Llanrwst	340 ± 70	9·09	3·98

The veins of this ore field traverse sediments, lavas and pyroclastics of Upper Ordovician age. Smith (1922) writes that the age of mineralization cannot be stated with certainty, but consideration of structure and relation of the faults and lodes to those affecting the Carboniferous rocks suggest it was post-Carboniferous. Archer (1959) is of the same opinion and states that there is no obvious connexion between the mineralized faults and the Caledonian folding of the rocks.

Only a single analysis is available, but the model age suggests possible affiliation with group 2 of the Lake District (nos. 36–41) of probable Lower or Middle Carboniferous age. However, more analyses from this area are clearly essential.

(iv) *Harlech area, Merionethshire and Plynlimon area, Cardiganshire*

no.		model age (My)	V_p	K_p
49	Berthllwyd Mine	470 ± 60	9·36	4·04
50	Manod Bach Mine	430 ± 80	9·33	4·15
51	Cowarch Mine	420 ± 50	9·33	4·00
52	Bronfloyd Mine	450 ± 60	9·36	4·09
53	Tal-y-Bont Mine	430 ± 80	9·14	4·00
54	Bryn Glas Mine	450 ± 50	9·29	4·05
55	Daren Mine	360 ± 60	9·05	3·99
	mean:	430 ± 40	9·27	4·05

The veins in the Harlech Dome area traverse Lower Palaeozoic sediments of Cambrian and Ordovician age (Smith & Dewey 1922; Dewey & Eastwood 1925; Archer 1959). In the Plynlimon area of north Cardiganshire and west Montgomeryshire the veins and ore-bodies occur in faults which traverse great thicknesses of argillaceous and arenaceous strata of Upper Ordovician and Lower Silurian age (Jones 1922; Hughes 1959).

There is little geological evidence regarding the age of the mineralization. Dunham (1952*a*) was tempted to assign a Caledonian age to the high-temperature gold–copper deposits of Harlech, without positive evidence. In the Plynlimon district the vein fractures traverse the Caledonian folds and Jones (1922) suggested that the vein fractures may be partly contemporaneous with the folds. Archer (1959), however, considers that ore deposition in all districts of North Wales (excluding Anglesey) was part of one phase of mineralization, although in some districts there is evidence that this occurred in more than one stage. Both he and Hughes (1959) consider the mineralizations to be post-Carboniferous.

With one exception (no. 55) the isotopic abundances lie within the experimental error of the mean and form a distinct and closely related group. Samples 49, 50 and 51 are from the Harlech Dome area, whilst samples 52, 53, 54 and 55 are from Plynlimon. The mean model age suggests that the mineralization is probably Silurian in age and therefore associated with the Caldeonian orogeny. The veins are certainly post-Lower Silurian from field evidence. The average regional V_p value (9·27) appears to be slightly, but significantly, greater than for previously discussed groups, although the absolute difference does not exceed 2 %.

The sample from the Daren Mine (no. 55) gives a rather lower model age, but there is no published geological evidence to suggest that this is a younger mineralization. It is, therefore, included in this group for the present. Slight isotopic anomaly cannot be ruled out.

(*c*) *Scotland*

(i) *Southern Uplands*

no.		model age (My)	V_p	K_p
56	Silver Ridge Mine, Kirkcudbright	320 ± 80	9·05	3·95
57	Wanlockhead, Dumfries	320 ± 50	9·05	3·91
58	Nutberry Hill, Lanark	310 ± 60	8·93	3·89
	mean:	320 ± 40	9·01	3·92

The largest mineral deposits in Scotland occur in the Leadhills–Wanlockhead area (no. 57), where the veins traverse tightly folded Upper Ordovician sediments (Wilson 1921; MacKay 1959). There are scattered occurrences in other parts of the Southern Uplands (nos. 56, 58).

There is little geological evidence regarding the age of the mineralizations. MacGregor (1944) states that the veins of the Leadhills–Wanlockhead area are parallel to, and on the lines of faults, that cut Permian sandstones and lavas of the Thornhill outlier several miles to the south.

The mean model age for the group, however, suggests Lower or Middle Carboniferous mineralization and possible contemporaneity with group 2 of the Lake District (nos. 36–41) which gave a mean model age of 320 ± 30 My.

(ii) *Argyllshire*

no.		model age (My)	V_p	K_p
59	Mulreesh, Islay	310 ± 90	8·81	3·81
60	Ballygrant, Islay	270 ± 60	8·72	3·75
	mean:	280 ± 50	8·76	3·78
61	Strontian (mean of two samples)	230 ± 60	8·88	3·78

On the island of Islay the veins traverse folded Dalradian Islay Limestone. Tertiary dykes trend N.W. across the island, one of which cuts a vein (Wilson 1921). The mineralization has been described by Barnett (1959).

The mean model age of the two Islay samples indicate Hercynian mineralization, i.e. probably of Lower Permian age. The parameters V_p and K_p are slightly, but significantly, lower than for any previously discussed group from England and Wales. This appears to be a general trend in Scotland, except for the Southern Upland group (nos. 56–58) and Caithness (nos. 62, 63), whose V_p and K_p values conform closely with the southern values.

The main vein at Strontian, although adjacent to the Caledonian Strontian granite, nevertheless, follows a camptonite dyke which is not older than Permo-Carboniferous (Wilson 1921; Phemister 1948). The country rocks are Moine schists. Tertiary dolerite dykes with N.N.W. trend cut the camptonite dykes and mineral veins. From the geological evidence the age is, therefore, uncertain, but probably in the range Permo-Carboniferous to pre-Tertiary.

The model age suggests Permo-Triassic mineralization which could be approximately contemporaneous with several other groups, e.g. Mendips (nos. 16–18), Isle of Man (nos. 26, 27) and the Alderley Edge group (nos. 23–25). Note again, however, the slightly lower V_p and K_p values.

(iii) *Caithness, Orkney, Shetland*

no.		model age (My)	V_p	K_p
62	Halkirk Bridge, Caithness	320 ± 50	9·09	3·95
63	Gie-Uisg Geo, Caithness	320 ± 50	9·09	3·89
	mean:	320 ± 30	9·09	3·92
64	Shapinsay, Orkey	370 ± 70	8·80	3·87
65	Vidlin, Shetland	280 ± 70	8·73	3·91
66	Dury Voe, Shetland	250 ± 80	8·74	3·90
	mean (nos. 65, 66):	270 ± 60	8·73	3·91

There are numerous small, scattered mineral occurrences in the northernmost parts of Scotland (Wilson 1921). Samples 62 and 63 are from veins in the Devonian Old Red Sandstone. The model parameters suggest contemporaneity and close geochemical affinity with the Southern Upland Group (nos. 56–58). The mineralization may be Lower or Middle Carboniferous in age.

The Shapinsay sample (no. 64) occurs in a vein traversing Middle Old Red Sandstone. This may be an older mineralization than that of Caithness, i.e. possibly Middle or Upper Devonian in age. Note the significantly lower V_p value than for Caithness. In this respect the sample is closer to the Shetland leads and the regional Scottish value.

The Shetland galenas (nos. 65, 66) occur in lenses and mineralized cavities in metamorphic rocks of presumed Dalradian age. The mean model age suggests Hercynian mineralization of probable Lower Permian age.

(iv) *Aberdeenshire*

no.		model age (My)	V_p	K_p
67	Glen Gairn 1	460 ± 90	8·93	3·91
68	Glen Gairn 2	480 ± 50	8·95	3·95
69	Craig-ant-Seabhaig	440 ± 70	9·01	3·96
	mean:	470 ± 40	8·96	3·94

There are several minor mineralizations in the Ballater Area of Aberdeenshire which may be associated with post-tectonic Caledonian granites (Russell 1937; Whitehead in Dunham 1952*b*). The veins traverse either the Dalradian metamorphics (nos. 67, 68) or the granite itself (no. 69). The Aberdeenshire granites are considered to be of Silurian age. They contributed abundant material to the nearby Downtonian conglomerate of the Lower Old Red Sandstone (Read 1948).

The average model age of 470 ± 40 My for this group suggests an Ordovician or Silurian age for the mineralization, according to the latest time-scales. Absolute age determinations are not yet available for the granite in the vicinity of the mineralization. The granites could be Ordovician and still post-tectonic, since it appears likely that at least a part of the Dalradian series was last metamorphosed about 470 My ago (Giletti, Moorbath & Lambert 1961). On the other hand, Smales, Webster, Mapper, Wood & Morgan (1958) obtained a rubidium–strontium age of 365 ± 50 My for potassium feldspar from a typical Aberdeenshire granite (recalculated with a rubidium-87 half-life of $4{\cdot}7 \times 10^{10}$ years, see Flynn & Glendenin 1959).

If a substantial age difference is confirmed between the granite and the model age of the mineralization, then other modes of origin would have to be postulated for these ores, involving partial regeneration and remobilization of lead from earlier deposits or from the Dalradian sediments themselves, possibly due to intrusion of the granite.

(v) *Borolan Syenite, Sutherlandshire*

no.		model age (My)	V_p	K_p
70	Borolan Pegmatite	430 ± 60	8·75	3·88

The well-known Loch Borolan laccolith is intrusive into Cambrian strata within the lowermost nappe of the Loch Assynt area in the north-west Highlands (Phemister 1948).

The associated pegmatite contains many unusual and characteristic minerals, as well as specks of galena (Stewart 1941).

The model age is Caledonian, either Ordovician or Silurian. It agrees within the experimental error with the previously described Aberdeenshire group (nos. 67–69). No absolute age determinations are yet available for the Borlan Complex.

(vi) *Central Highlands*

no.		model age (My)	V_p	K_p
71	Meall Luaidhe, Glen Lyon	360 ± 70	8·88	3·81
72	Clachan Beag, Loch Fyne	530 ± 70	8·93	3·89
73	Tomnadashan, Loch Tay	530 ± 60	8·81	3·92
74	Crom Allt, Tyndrum	550 ± 70	8·88	3·88
75	Ardtalanaig, Loch Tay	680 ± 60	8·68	4·03

Numerous mineral occurrences have been described from the central Highlands, some of which were at one time of economic significance, particularly in the Tyndrum area. The mineralizations occur as veins and irregular masses, or as metasomatic replacements, in Dalradian metamorphic rocks. Several of them are associated with members of the widespread series of N.N.E.–S.S.W. faults of this area.

There is no definite geological evidence regarding the age of the deposits. Dunham (1952*a*) considered that the small, metasomatic pyrrhotite-pentlandite deposit of Loch Fyne (no. 72) might be Caledonian, but without positive evidence.

The model age of 360 ± 70 My for the Glen Lyon sample (no. 71) suggests a possible Devonian age for the mineralization, in analogy with several other groups already discussed. In terms of the model parameters, it most closely resembles the Shapinsay, Orkney specimen (no. 64), which came from a vein cutting the Middle Old Red Sandstone.

The next three samples (nos. 72–74) form a closely related group. The model ages of these three specimens, together with that from Ardtalanaig (no. 75) are regarded as significantly greater than the true age of mineralization. The reasons for this assumption are threefold. First, the mineralization are post-tectonic from the field evidence, i.e. they occurred after the Dalradian metamorphism. Absolute age determinations indicate that the last metamorphism of, at least, a part of the Dalradian series in Perthshire occurred not later than about 470 My ago, probably in Lower or Middle Ordovician time (Giletti *et al.* 1961). Secondly, several of the mineralized faults in the area form part of the post-Dalradian fault systems parallel to the Great Glen fault which has moved in Caledonian and, perhaps, Hercynian times. Thirdly, a uraninite from a galena-bearing vein at Tyndrum has given a concordant uranium–lead age of 230 ± 8 My, corresponding to an Upper Permian age (Darnley *et al.* 1960). Although there is some geological evidence to suggest that the galena was in place before the uraninite, the time interval was probably not great.

It appears, therefore, that at least a part of the mineralization in the Dalradian Series of the central Highlands may be post-Hercynian in age so that the model age of the galenas does not represent the time of emplacement. Assuming that there has been no subsequent contamination or mixing, the model age only signifies the date at which the lead was separated from uranium and thorium.

The most likely explanation for the high model ages is that the leads were derived either by remobilization and regeneration of older lead deposits or by a process of extraction and concentration of disseminated lead from the Dalradian rocks themselves. There is some evidence that the Dalradian sediments were already in existence 600 ± 100 My ago (Giletti *et al.* 1961). Localized extraction of normal lead from these originally marine sediments at a much later time could lead to the observed discrepancy between model age and time of mineralization.

Finally, it may be noted that the values of V_p and K_p again lie very close to those of most of the other Scottish groups, giving strong support to the view that the isotopic composition of these leads is very close to normal, so that the observed model age represents the approximate date of *original* formation of the lead, prior to regeneration.

(vii) *North-west Highlands*

no.		model age (My)	V_p	K_p
76	Loch Garbhaig, Ross-shire	650 ± 50	8·34	4·95
77	Letterewe, Ross-shire	710 ± 60	8·35	5·21
78	Allt na Ciad Eilig, Ross-shire	800 ± 60	8·58	4·57
79	Rois-bheinn, Inverness-shire	910 ± 80	8·69	3·85

There are a number of small, non-economic, mineral occurrences in the Lewisian meta-sediments of the Loch Maree area, associated with N.E. and N.N.E. lines of crush and fractures (Wilson 1921). Specimens 76, 77 and 78 represent localities within this area which are less than 1 mile apart.

The isotopic abundance ratios and model parameters for these three specimens differ significantly. The values of V_p differ by about 3 % whilst the K_p values differ by as much as 14 %. The V_p values are between 5 and 10 % lower than for any other group in the British Isles, whilst the K_p values are between about 15 and 30 % higher. These considerations, in addition to the model age discrepancies, can leave no doubt as to the anomalous nature of these leads.

The reason for these anomalies is not fully understood, but a homogeneous source for these ores appears unlikely. This probably excludes direct genetic connexion with igneous activity or regional metamorphism both of which may be expected to yield uniform, normal isotopic compositions. The ores are probably the product of highly localized, relatively small-scale and regionally variable regeneration and remobilization of lead from the surrounding Lewisian meta-sediments. The variation in the V_p and K_p values indicates, moreover, that local mixing of different types of lead has occurred. In any case the combination of rather low V_p values and extremely high K_p values is distinctly unusual and suggests prolonged residence of the lead in a uranium-poor, thorium-rich environment, prior to mineralization.

The model ages for this group may not even approximately represent the actual time of mineralization. In view of the low V_p values it seems likely that the model ages represent an upper age limit for the mineralization, which could be connected with a localized rise of pressure and temperature during Caledonian or Hercynian times. The N.N.E. crush lines and faults in which the mineralizations occur, may represent a local expression of the much more extensive and powerful disturbances in the central Highlands. There is no evidence that these leads are genetically connected with the major Laxfordian metamorphism of the Lewisian metasediments, which occurred about 1600 My ago (Giletti *et al.* 1961).

The remaining sample to be discussed (no. 79) is from a minor occurrence at Roisbheinn in Inverness-shire. Here, galena occurs in N.W.–S.E. crush lines in psammitic banded schists and granulites of the Moine series. The parameters V_p and K_p agree rather closely with those from other Scottish groups, and do not have the anomalous values of the Loch Maree area. This is almost certainly a near-normal lead which has been regenerated at a much later time, since the Moine series was metamorphosed 420 ± 15 My ago (Giletti *et al.* 1961). These authors, furthermore, present evidence that the Moine sediments of the Western Highlands are older than 740 My. The regeneration and remobilization of this lead probably occurred in Caledonian or Hercynian times.

(viii) *East Inverness-shire and Morayshire*

no.		model age (My)	V_p	K_p
80	Struy, Inverness-shire	120 ± 40	8·99	3·93
81	St Aethan's Well, Morayshire	160 ± 60	8·93	3·99
82	Stobfield, Morayshire	140 ± 70	8·94	4·00
	mean:	140 ± 40	8·95	3·97

In the Struy, Strathglass area there are a number of mineral veins traversing Moine Schists, associated with E.–W. crush lines (Wilson 1921). In the Elgin area of Morayshire, irregular galena and fluorite replacements occur within the matrix of Permo-Triassic (in part possibly Jurassic) sandstone (Wilson 1921; Wilson in Dunham 1952*b*).

The three samples form a well-defined and closely related group in terms of model parameters, suggesting derivation from the same source. There can be little doubt that these are normal leads and that the mineralization occurred either in Upper Jurassic or in Cretaceous times. The mean values of V_p and K_p agree closely with the mean values for the neighbouring area of Aberdeenshire, despite the considerable difference in model ages.

These leads form the youngest group yet measured from the British Isles.

(*d*) *Ireland*

(i) *Northern Ireland*

no.		model age (My)	V_p	K_p
83	Castleward, Co. Down	280 ± 60	8·97	3·88
84	Conlig Mine, Co. Down	420 ± 70	9·11	4·06

Only two isotope measurements have been carried out from Northern Ireland, but it is evident that the model ages can be assigned to two of the groups described previously.

The mineralizations occur in Ordovician and Silurian sediments and have been described by Cole (1922) and Fowler (1959). The Conlig lode (no. 84) was at one time of economic importance. Fowler points out that the directions of the veins generally trend in the same directions as dykes and faults of Tertiary age and that there may be a connexion between them and the mineralization. The model ages, however, do not support a Tertiary age. The Castleward specimen has a Hercynian model age, whilst that of the Conlig lode indicates Caledonian mineralization.

(ii) *South-east Ireland*

no.		model age (My)	V_p	K_p
85	Glendalough, Co. Wicklow	280 ± 90	9·20	4·01
86	Glenmalure, Co. Wicklow	240 ± 70	9·15	3·95
	mean:	260 ± 60	9·17	3·98
87	Barristown, Co. Wexford	280 ± 80	9·15	4·16
88	Avoca, South Lode Facies	440 ± 70	9·17	4·01
89	Avoca, South Lode Facies	450 ± 70	9·20	4·05
90	Avoca, Pond Lode Facies	440 ± 70	9·27	4·06
91	Avoca, Pond Lode Facies	420 ± 80	9·10	3·97
	mean (nos. 88–91):	440 ± 40	9·19	4·02

The Glendalough–Glenmalure lead–zinc vein deposits (Cole 1922; O'Brien 1959) occupy joints and faults at the eastern margin of the Leinster granite. The latter is definitely Caledonian and a rubidium–strontium age of 386 ± 10 My has been published by Kulp *et al.* (1960). Although there has been no evidence to establish the age of the veins, they have usually been thought of as geochemically similar and equivalent in age to supposedly Hercynian veins in other parts of the British Isles. Dunning (in Tremlett 1959) states that they correspond closely with the so-called 'Oberharzer' type of quartzo–calcitic lead–zinc veins with minor pyrite, chalcopyrite, barytes and chalybite, which are typical of Hercynian metallogenesis in many parts of Europe. He considers that there was a long time interval between intrusion of the Leinster granite and the latest episode of faulting and formation of the Glendalough–Glenmalure veins. On the other hand, Tremlett (1959) postulates a connexion between the granite and the veins, thus considering a Hercynian age to be unlikely.

The model age of the Glendalough–Glenmalure specimens (nos. 85, 86) indicates a Hercynian (Permo-Carboniferous) mineralization, not directly connected with the intrusion of the Leinster granite.

The Barristown, Co. Wexford, galena (no. 87) is from a vein cutting Lower Palaeozoic sediments of great thickness. The model age is Hercynian and probably contemporaneous with the Glendalough–Glenmalure deposits.

The next group of four specimens (no. 88–91) represent the Avoca deposit of Co. Wicklow. This is the largest working metalliferous mine in Ireland. The ore occurs as large, irregularly lenticular, pyritic bodies with minor galena in weakly metamorphosed Ordovician volcanics and argillaceous sediments about 10 miles S.E. of the Leinster granite batholith. The lenses are roughly concordant with the bedding and shearing of the sediments. The Avoca mineralization has been described by Cole (1922), Wilson (1956) and O'Brien (1959). It is generally considered that the minerals were introduced during some of the movements of the Caledonian orogeny (Tremlett 1959).

The Avoca ore body is complex and there are several distinct facies of mineralization. The two main types are the 'Pond Lode' facies and the 'South Lode' facies. The former occurs in shales and phyllites in which the schistose fabric is undeformed and still well preserved, although the rock matrix has often been intensely disseminated with finely divided sulphides, suggestive of colloidal deposition. The South Lode mineralization is somewhat later and more diffuse and coarser grained than the Pond Lode, consisting of narrow, parallel zones, ribs and veins with varying mineral content.

Of the four isotope measurements, two are on 'South Lode' (nos. 88, 89) and the other two on 'Pond Lode' galenas (nos. 90, 91). The model ages all agree within the experimental error and indicate a Caledonian age for the mineralization, probably contemporaneous with the Harlech–Plynlimon deposits of North Wales. The parameters V_p and K_p for Avoca are in close agreement with those of Glendalough–Glenmalure, North Wales and the great majority from England.

(iii) *Co. Sligo, Co. Mayo (west Ireland)*

no.		model age (My)	V_p	K_p
92	Abbeytown, Co. Sligo	340 ± 90	9·27	4·00
93	Sheeffry Mine, Co. Mayo	310 ± 70	8·83	3·92

Apart from Avoca, the only other working metalliferous mine is at Abbeytown, Ballysodare, Co. Sligo (Cole 1922; O'Brien 1959). The mineralization consists of veins and replacements in the Carboniferous Limestone Series (Lower Carboniferous) several hundred feet above the unconformable contact with the underlying metamorphic complex of possible Moinian age.

The model age suggests that the mineralization occurred in Lower or Middle Carboniferous times. Further measurements on this locality are in progress, particularly on galenas from different horizons within the limestone.

The Sheeffry specimen (no. 93) is from a small, isolated vein occurrence, traversing schistose Lower Palaeozoic sediments (Cole 1922). The model age suggests Carboniferous mineralization. The V_p value is slightly lower than for any previously described Irish galenas.

(iv) *Co. Galway (west Ireland)*

no.		model age (My)	V_p	K_p
94	Clements Mine, nr. Maum	860 ± 70	9·09	4·04
95	Glengowla Mine, Oughterard	620 ± 80	8·86	3·92
96	Cloosh Mine, Oughterard	700 ± 80	8·97	3·84
97	O'Flaherty's Shaft, Oughterard	580 ± 80	8·77	3·75
98	Lough Corrib shore, Oughterard (in Carboniferous Limestone)	320 ± 80	8·86	3·85

The first three galenas of this group (nos. 94–96) are from veins traversing the Connemara Schists. The latter are generally considered to be equivalent to the Dalradian Series of the central Scottish Highlands (Charlesworth 1953). Absolute age measurements indicate that the last metamorphism of the Connemara Schists occurred about 470 to 480 My ago, probably in Lower Ordovician times. By analogy with the Dalradian Series, the Connemara sediments were almost certainly in existence 600 ± 100 My ago (Giletti *et al.* 1961).

Specimen 97 is from a vein traversing the Oughterard granite near its junction with the surrounding schists. The age of this granite is not known, but it could be contemporaneous with the Galway granite for which Giletti *et al.* (1961) have obtained a rubidium–strontium age of 365 ± 10 My.

The isotope abundance ratios and model parameters of the four samples do not agree within the experimental error, indicating a localized origin with limited homogenization, or partial mixing of different leads. The model ages are clearly older than the age of mineralization, since the veins are post-tectonic. In analogy with the groups from the central and north-west Highlands of Scotland (nos. 72–75 and 76–79, respectively) it is postulated that these leads were formed by remobilization of older lead from the meta-sediments of the basement complex. This remobilization might have been effected by increased temperature during intrusion and consolidation of the Oughterard granite. Two of the galenas (nos. 95, 96) occur in the schists in the immediate vicinity of the granite, whilst one galena (no. 97) is from a vein cutting the granite. Sample 94 is from a locality probably underlain by granite at shallow depth. If, on the other hand, the lead mineralization in this area had been genetically associated with the granite (cf. Hercynian granites and associated mineralization of Devon and Cornwall), then homogeneous, normal isotope ratios and model parameters would be expected.

The remaining sample from the Oughterard area (no. 98) was collected from a small calcite-galena vein 1 mile north-east of Oughterard village. The vein cuts fossiliferous Carboniferous Limestone which overlies the basement granite and metamorphic rocks at very shallow depth. This sample appears to be normal lead of probable Lower or Middle Carboniferous age. All three model parameters are in close agreement with the Sheeffry Mine lead (no. 93) which occurs about 50 miles to the north. This lead is clearly not related to the other leads of the Oughterard area.

7. Periods of mineralization in the British Isles

(a) *General classification*

An attempt is presented in this section to define approximately the major periods of mineralization which occurred in the British Isles. The regional isotope data have been divided into six groups, corresponding to the mean model ages of all sets of samples which are regarded as normal leads; they are considered to indicate at least six distinct periods of mineralization. These periods represent the best group classification of the model ages, especially when considered in conjunction with the geological field evidence. There is some overlap between adjacent 'periods' in view of the experimental errors involved, particularly where individual samples have to be quoted due to lack of sufficient measurements. In such cases doubt can arise concerning the 'period' to which a sample belongs.

The only model parameters from the British Isles which have been omitted from the discussion are those regarded as rejuvenated *B*-types. These include the central Highlands group (nos. 72–75), the north-west Highland group (nos. 76–79) and the Co. Galway group (nos. 94–97).

With the exception of the Cornwall–Devon group (nos. 1–7) and the Shap granite galena (nos. 42, 43), both discussed in § 5 with reference to independent age measurements, it is impossible to prove the absence of small *B*- or *J*-type anomalies in the remaining leads of the British Isles. Nevertheless, the close regional grouping of the isotope ratios and model parameters, together with the observation that the model ages are not significantly older than the age of the enclosing rocks, suggests the general validity of the present approach. The latest time-scales of Holmes (1960) and Kulp (1960) are given in table 6, p. 315.

	period 1	mean model age (My)	mean V_p	mean K_p
(i)	Buttermere, Lake District, no. 44	470 ± 50	9·26	4·05
(ii)	Harlech–Plynlimon, North Wales, nos. 49–55	430 ± 40	9·27	4·05
(iii)	Aberdeenshire, Scotland, nos. 67–69	470 ± 40	8·96	3·94
(iv)	Borolan, Sutherlandshire, no. 70	430 ± 60	8·75	3·88
(v)	Conlig Mine, Co. Down, no. 84	420 ± 70	9·11	4·06
(vi)	Avoca Mine, Co. Wicklow, nos. 88–91	440 ± 40	9·19	4·02

mean model age for period 1 = 440 ± 30

This is regarded as Ordovician and/or Silurian mineralization, mainly connected with late developments within the Lower Palaeozoic geosyncline. In a few cases the age of mineralization is demonstrably post-Lower Silurian from the field evidence.

	period 2	mean model age (My)	mean V_p	mean K_p
(i)	Combe Martin, North Devon, nos. 28–30	370 ± 50	9·08	3·96
(ii)	Shap granite, Westmorland, nos. 42, 43	360 ± 50	9·18	3·98
(iii)	Shapinsay, Orkney, no. 65	370 ± 70	8·80	3·87
(iv)	Meall Luaidhe, Perthshire, no. 72	360 ± 70	8·88	3·81

mean model age for period 2 = 360 ± 30

This is a relatively minor group of minor mineralizations of probable Devonian (Old Red Sandstone) age. The Shap granite and its mineralization is demonstrably post-Upper Silurian and pre-Lower Carboniferous from the field evidence.

	period 3	mean model age (My)	mean V_p	mean K_p
(i)	Lake District (group 2) nos. 36–41	320 ± 30	9·18	4·00
(ii)	Llanrwst, North Wales, no. 48	340 ± 70	9·09	3·98
(iii)	Southern Uplands, Scotland, nos. 56–58	320 ± 40	9·01	3·92
(iv)	Caithness, Scotland, nos. 62–63	320 ± 40	9·09	3·92
(v)	Abbeytown, Co. Sligo, no. 92	340 ± 90	9·27	4·00
(vi)	Sheeffry, Co. Mayo, no. 93	310 ± 70	8·83	3·92
(vii)	Lough Corrib, Oughterard, no. 98	320 ± 80	8·86	3·85

mean model age for period 3 = 320 ± 20

It is suggested that these mineralizations are of Lower or Middle Carboniferous age and that they could be connected with either the mid-Dinantian (post-C_1 zone, pre-C_2S_1 zone) movements, or the post-Dinantian, pre-Namurian (Sudetian) movements, or possibly with both. Several of the leads actually cut the Lower Carboniferous Limestone Series. These movements are widely recognized in the British Isles and led to the existence of important unconformities within the Carboniferous succession. Several major German deposits are definitely known to be connected with these important precursory movements of the main Hercynian (Permo-Carboniferous) orogeny. This has been established from the geological evidence and is supported by model ages obtained for a number of German leads (Cahen & Jedwab 1958).

	period 4	mean model age (My)	mean V_p	mean K_p
(i)	Cornwall–Devon, nos. 1–7	280 ± 30	9·10	3·92
(ii)	Northern Pennines, nos. 8–11	280 ± 30	9·13	3·95
(iii)	North-east England, nos. 12–14	290 ± 40	9·05	3·92
(iv)	Shelve, Shropshire, no. 15	280 ± 70	9·29	4·00
(v)	Parys Mountain, Anglesey, nos. 46, 47	300 ± 40	9·20	3·96
(vi)	Islay, Argyllshire, nos. 59, 60	280 ± 50	8·76	3·78
(vii)	Shetland Isles, nos. 65, 66	270 ± 60	8·73	3·91
(viii)	Castleward, Co. Down, no. 83	280 ± 60	8·97	3·88
(ix)	Glendalough–Glenmalure, Co. Wicklow, nos. 85, 86	260 ± 60	9·17	3·98
(x)	Barristown, Wexford, no. 87	280 ± 80	9·15	4·16

mean model age for period 4 = 280 ± 20

This group contains several of the most important mineralizations in the British Isles. The Cornwall–Devon group is definitely associated with post-tectonic Hercynian granites. The group is, therefore, regarded as true Hercynian mineralization of probable Upper Carboniferous or Lower Permian age. The Hercynian orogeny directly and indirectly affected much of the British Isles and it is interesting to note that mineralization occurred as far north as the Shetland Isles.

	period 5	mean model age (My)	mean V_p	mean K_p
(i)	Mendip Hills, Somerset, nos. 16–18	230 ± 30	9·12	3·97
(ii)	Southern Pennines, Derbyshire, nos. 19–22	180 ± 30	9·12	3·97
(iii)	North Midlands, nos. 23–25	210 ± 40	9·18	3·98
(iv)	Isle of Man, nos. 26, 27	220 ± 30	9·11	4·00
(v)	Lake District (group 1), nos. 31–35	210 ± 40	9·10	3·94
(vi)	Halkyn, Flintshire, no. 45	170 ± 80	9·12	3·99
(vii)	Strontian, Argyllshire, no. 61	230 ± 60	8·88	3·78

mean model age for period 5 = 220 ± 30

Although there is a somewhat greater spread of individual mean model ages, there is at present not sufficient justification for a further division. This group of mineralization is regarded as Mesozoic in age and almost certainly post-Keuper (Upper Triassic), since several of the leads cut Keuper sediments, e.g. Mendips and Alderley Edge. On the other hand the mineralizations are unlikely to be younger than Lower Jurassic.

	period 6	mean model age (My)	mean V_p	mean K_p
(i)	East Inverness and Moray, nos. 80–82	140 ± 40	8·95	3·97

mean model age for period 6 = 140 ± 40

This minor group is so far only represented by the Struy and Elgin occurrences in East Inverness-shire and Morayshire, where Moine Schists and Permo-Triassic (possibly in part Jurassic) sediments are the respective host rocks. The age of the mineralization is regarded as Upper Mesozoic, possibly Cretaceous.

The general picture of the age relationships of British mineral occurrences that emerges is somewhat more complex than previous workers had envisaged, e.g. Finlayson (1910), who regarded practically all British deposits as Hercynian in age. It is evident, however, that there is also a remarkable degree of concurrence between the geologic and the isotopic evidence. In only one case is there a contradiction between the published geological findings and the isotope measurements, namely, the Parys Mountain mineralization in Anglesey.

The main conclusions, then, are as follows:

(i) On the basis of the model ages it is possible to distinguish six periods of mineralization in the British Isles, ranging in age from Lower Palaeozoic to Upper Mesozoic. It is *not* implied, however, that all the mineralizations of one group are necessarily contemporaneous.

(ii) There is no isotopic evidence for Tertiary mineralization in the British Isles.

(*b*) *Comparison of model ages with other areas, with special reference to Germany and North Africa*

A considerable number of isotopic measurements on German lead ores have been reported (Ehrenberg 1953; Geiss 1954; Ehrenberg & Horlitz 1954; Ehrenberg & Mürtz 1958).

Recently, Cahen & Jedwab (1958) have discussed the model ages of sixty-one German leads in relation to the geological occurrence of the ores, the probable age of mineralization and the age of the sedimentary host rock. In many cases they found that the model ages appeared to be greater than the absolute age of the sedimentary host-rock as judged by the original time-scale of Holmes (1947 *b*). Such leads were regarded as *B*-types and these authors postulate regeneration of older lead or mixing of two types of lead of different ages. A typical example is represented by a suite of four specimens from the Ruhr Valley whose mean model age is 290 ± 40 My. Cahen & Jedwab state that 'these vein-type deposits traverse Upper Carboniferous rocks and the mineralization is regarded as having occurred in Upper Carboniferous times, after the Asturic phase of orogeny. That is, it occurred about 210 My ago. Consequently, lead from the Ruhr valley appears to be regenerated from Devonian or earlier occurrences and probably represents a mixture of Caledonian and Hercynian lead.

In fact, if the German model ages are re-interpreted in terms of the recent extended time-scales of Holmes (1960) and Kulp (1960) then, with a single exception, none of these leads is *B*-type. The model age of 290 ± 40 My for the Ruhr group is consistent with the position of the Upper Carboniferous on these time-scales and the necessity for postulating regeneration and mixing is obviated. It follows, however, that several German leads whose model age is considered by Cahen & Jedwab to agree with the age of mineralization may either be *J*-types, or they may be younger than originally surmized. The probable absence of *B*-type leads could explain why these authors were unable to find any really significant differences in trace-element content in their emission-spectrographic survey of these galenas.

Two German leads have been measured in the present work, mainly for the purpose of inter-laboratory comparison with Bonn (table 2). It was pointed out in § 6 that the Maubach lead (table 4, no. 100) is closely comparable in geological occurrence, isotopic ratios and model parameters with the Alderley Edge lead. The Siegerland lead (table 4, no. 99) has isotopic ratios and model parameters which agree closely with those of the Hercynian leads of the British Isles.

There are areas where older, regenerated lead occurs in younger sediments. *B*-type leads from Europe and North Africa have been described by Cahen, Eberhardt, Geiss, Houtermans, Jedwab & Signer (1958). Examples are: Bleiberg, Austria, lead in Upper Triassic sediments, model age 360 My; Aouli, Morocco, lead in Permo-Triassic sediments, model ages 370 to 420 My; Mibladen, Morocco, lead in Jurassic sediments, model ages 320 to 430 My etc. In most cases, the lead is encountered in comparatively thin sediments overlying metamorphic basement rocks. Cahen *et al.* interpret these occurrences as secondary deposits regenerated from older lead ores according to the general concepts of Schneiderhöhn (1953 *a*, *b*). Cahen *et al.* conclude from their study of normal and *B*-type lead ores from North Africa that '...from the number of leads which fall in the range 400 to 440 My one may consider that 420 My is the approximate age of a "primary" or "juvenile" lead mineralization. One other may have occurred later at *ca.* 290 ± 50 My and could possibly be Hercynian.' These model ages agree well with those of the two principal groups of the British Isles and emphasize the significance of Caledonian and Hercynian mineralization in much of Europe and North Africa.

The views of Russell & Farquhar (1960*b*) concerning *B*-type lead ores are entirely different. They consider that the geological settings of *B*-type leads are very similar to the so-called 'conformable' lead ores of Stanton (1955*a*, *b*; 1960) which form the basis of the Russell–Stanton–Farquhar model, outlined in §3. According to Stanton, conformable lead ores are primary, arriving at the surface of the earth from great depths through volcanoes. Russell & Farquhar (1960*b*) suggest, therefore, that *B*-type leads should be regarded as normal leads and that the parameters of the Holmes–Houtermans equation should be adjusted to give the correct ages of mineralization for *B*-type ores. This means that all 'normal' Holmes–Houtermans leads would give ages that appear too young—in fact, become *J*-types. Russell & Farquhar consider most vein-type lead deposits to be *J*-type anomalies due to having migrated through country rocks containing uranium and radiogenic lead. This hypothesis would invalidate all Holmes–Houtermans normal model ages and parameters, e.g. those from the British Isles, Germany, North Africa and from many other parts of the world, even where reliable, independent evidence for the age of the mineralization is available.

(*c*) *Variation in model parameters V_p and K_p in the British Isles*

The arithmetical average values for V_p and K_p in British leads are

V_p	K_p
9·05	3·95

This includes all measured leads except the *B*-type leads of the central and north-west Highlands of Scotland (nos. 72–75, 76–79) and western Ireland (nos. 94–97). Individual V_p values lie between 8·73 and 9·30 and individual K_p values between 3·78 and 4·16. This represents the maximum spread, but most of the individual group values lie close to the mean. Nevertheless, there appear to be two slightly, but significantly, different sets of V_p values. The first set includes ten groups of leads, ranging from 8·73 to 8·96, with an arithmetical mean of 8·84. This consists of eight Scottish groups and two from western Ireland. The second set comprises twenty-five groups with V_p values ranging from 9·01 to 9·30, with an arithmetical average of 9·14. This includes all groups from England, Wales, east Ireland, but only two groups from Scotland. It is estimated that the average error (based on experimental error only) for the V_p value of a single lead sample is approximately 0·10 to 0·15, whilst for K_p it is about 0·05 to 0·08.

These small regional differences in V_p render the Holmes–Houtermans model more acceptable than those of Russell and co-workers, since the latter cannot take into account regional variations in the primary uranium/lead ratio.

The values of K_p do not appear to differ significantly between the two sets of groups. A more general discussion of this topic is presented in §8.

8. GENERAL DISCUSSION OF LEAD ISOTOPE ABUNDANCES

(*a*) *Geological interpretation of normal leads*

There are two opposing schools of thought concerning the origin of lead ores; the first favours a mantle origin, the second a crustal origin. Wilson, Russell & Farquhar (1956) consider that '...lead ores have arisen from a uniform source. Since the composition of the crust is far from uniform, this source is presumably below the earth's crust.' Furthermore, Russell (1956) writes that '...our present knowledge of the behaviour of lead isotope abundances and the nature of the earth makes the derivation of lead ores from the upper part of the mantle plausible, and their derivation from crustal rocks highly improbable.'

These ideas find a quantitative expression in the Russell–Cumming–Farquhar and Russell–Stanton–Farquhar models, outlined in §2. These models assume a homogeneous distribution of uranium, thorium and lead in the upper part of the mantle and imply a constant uranium/lead and thorium/lead ratio throughout the world in the source material of normal lead ores.

The hypothesis of a mantle origin for lead ores is in general accord with the hypothesis of continental growth or 'accretion' proposed by Wilson (1952, 1954). He postulates an original basic crust with subsequent continual evolution and cumulative production of continental, granitic rocks by additions differentiated from the mantle throughout geological time, followed by the cycle denudation–sedimentation–granitization, etc., leading to gradual formation of the continents. This hypothesis was based primarily on the observation that the mineral age provinces of North America are progressively younger as they approach the present continental margin. It is evident that if the processes of continental growth have been proceeding throughout geological time, then the observed normal lead isotope ratios could have been primarily determined by their growth within the earth's mantle.

A recent world-wide survey of published mineral dates by Gastil (1960*a*, *b*) tends to refute the supposition that the sialic basement of continent margins is younger than that of continent interiors and fails to confirm the idea that areas of longest stability correspond to continental centres. Even on the North American continent, ages of more than one thousand million years have now been discovered within a short distance of the continental margins. Mineral dates therefore indicate that at least parts of some continents have extended to at least their present margins since early pre-Cambrian time. Furthermore, at various localities in all parts of the world mineral dates as well as structural and stratigraphic relations indicate that along certain mobile belts, older sialic terrains have been remobilised several times during recorded geological time. These findings support the views of Stille (1944, 1951, 1955) regarding regeneration and restoration of the geosynclinal state, as well as those of Kuenen (1950) who considers that geosynclinal troughs usually develop on continental areas underlain by a thick sialic crust. It is likely that no part of the continents can be regarded as permanently stable, many newer mountain chains being built upon the ruins of older. Knopf (1960) has summarized some relevant aspects of geosynclinal theory.

From his survey, Gastil (1960*b*) concludes that 'locally sialic nucleation and accretion probably have taken place. Locally, there have been movements in the pattern of mobility away from continental interiors. But for the earth as a whole during the past two or three thousand million years processes of accretion have been incidental to the migration of earth-girdling mobility. Thus, continents appear to be primitive earth features....' A mechanism for an early differentiation of the earth's crust has been given by Vening Meinesz (1957).

The above considerations suggest the serious possibility that the majority of leads may not have had a significant subcrustal history.

Russell & Kollar (1960) have emphasized that a detailed interpretation of lead isotope abundances must involve rather broad assumptions about the development of the earth and particularly its surface regions, so that careful consideration must be given to the basic assumptions underlying particular models chosen. It is suggested here that the basic assumptions of the Holmes–Houtermans model do not contradict the hypothesis of a crustal origin for lead ores and are in general accord with the absolute age evidence for repeated rejuvenation of ancient fold-belts. This is clearly relevant to the model assumptions that small regional differences in the uranium/lead ratio have been preserved until lead was extracted from a given 'region' to form a lead mineral.

(*b*) *Discussion of crustal origin for lead ores*

A mantle origin for lead ores fails to account for the general association of lead with granitic, metamorphic and sedimentary rocks, rather than with basic rocks and basic volcanic activity. In some respects, at least, a mantle origin is unrealistic from a geological viewpoint and it is advisable to consider other possibilities which must, nevertheless, take into account the observed regularities in lead isotope abundances. Shaw (1957) considers that the assumption of a homogeneous mantle origin is not necessary for these regularities. The following discussion is based on the views of Shaw, to which only limited reference has been made by subsequent authors.

During the early differentiation and formation of the earth's sialic crust the elements uranium, thorium and, to a certain extent lead, would be expected to be concentrated near the surface. On general geochemical grounds the bulk of the three elements is likely to have been present in the original granitic rocks, although relatively minor occurrences of lead ore (of nearly meteoritic isotope composition) and uranium and thorium minerals presumably occurred locally. In the course of time, radiogenic lead accumulated and during erosion, transportation and sedimentation, thorough mixing of primeval and radiogenic lead occurred, so that the ensuing sediments contained lead with an isotope abundance characteristic of the time of deposition. This is analogous with the lead from modern ocean sediments, whose isotopic composition represents a close approximation to the present crustal average (Patterson, Goldberg & Inghram 1953; Marshall 1957; Chow & Patterson 1959).

Subsequently, the sediments may have been subjected to metamorphism, orogenesis and renewed erosion, a cycle repeated at intervals throughout geologic time. Whenever a mountain range was eroded, the ensuing sediments received lead from the previous sediments, plus an addition of radiogenic lead from decay of uranium and thorium in the eroded continental rocks.

A considerable degree of separation of uranium, thorium and lead must have occurred during erosion, transporation and sedimentation in different parts of the sedimentary column (Adams & Weaver 1958). Nevertheless, it is probable that during subsequent regional homogenization processes within a sufficiently large volume of geosynclinal material, no permanent separation of the three elements would occur, particularly if magma is formed from the partially molten sediments. The effects which become dominant at various levels are production of true granite magma, granitization, migmatization and regional metamorphism with subsequent formation of a new mountain belt in place of the original geosyncline. In such a case, the overall uranium/lead and thorium/uranium ratios for a particular mountain belt may represent the original crustal ratios, modified only by radioactive decay. During these processes hydrothermal ore fluids could also be formed, in some cases as an integral part of magmatic evolution. An example of this is the Cornwall–Devon area of south-west England where Hercynian post-orogenic magmatic granites are closely associated with large-scale mineralization. In such a case the isotopic composition of lead is uniform and obeys the model, due to the previous crustal homogenization processes.

In other areas, the regional effects during the later stages of geosynclinal development may not suffice to produce magma, but might nevertheless result in the formation of hydrothermal ore-bearing fluids from the mixed sediments at depth, so that ore deposits with uniform and normal lead isotope abundances could be obtained. It has been suggested by several workers (Schneiderhöhn 1953*a*, *b*; Andreatta 1954; Hawley 1956) that hydrothermal solutions can develop in the crust under deep-seated metamorphic conditions, with formation of new epigenetic deposits. Verhoogen (1946), too, considers that igneous rocks and ore deposits are not necessarily always cogenetic, but may represent different degrees of the same, underlying processes. A possible example is the Harlech–Plynlimon Caledonian mineralization of North Wales in the Lower Palaeozoic geosyncline which, judging from field evidence, is not connected with igneous rocks to a depth of several thousand feet below the present surface of folded and faulted sediments. The mineralized areas concerned correspond closely with the region of maximum sedimentation (Jones 1955). It is possible that this, and other, mineralizations of period 1 (mean model age 440 ± 30 My) represent distant expressions of the Caledonian metamorphism of the Moine Series in Scotland which has been dated at 420 ± 15 My (Giletti *et al.* 1961).

The processes just outlined are probably adequate to account for the existence of widespread deposits which obey the Holmes–Houtermans model. Although the crust is heterogeneous, such processes as erosion, transportation, sedimentation, mobilization, orogenesis, etc., tend to produce homogeneity. There is plenty of evidence that many sediments (and metamorphic rocks) contain sufficient lead to play the role assigned to them in these processes (Shaw 1954; Wedepohl 1956). Somewhat similar considerations already led Holmes (1956) to suggest that normal leads might be extracted from crustal blocks of normal average sialic rocks.

Some lead has, of course, been brought to the surface by volcanic activity throughout geological time. This may well be derived from the upper part of the mantle. It is subsequently incorporated into sediments and finally concentrated into ore deposits by the processes outlined above. However, the quantitative contribution of this is likely to be small. Thus, Marshall (1957) has postulated the introduction of primeval lead from the mantle into the crust at an approximately linear rate throughout geological time to account for the slight, but apparently systematic increase in the source uranium-238/lead-204 ratio with the model age of lead ores.

In view of the plausibility of a crustal origin for lead ores it is of interest to speculate on the possible isotopic relationships within the following four classes of ore deposits proposed by Schneiderhöhn, (1953 *a*, *b*):

(i) Ore deposits of pre-Cambrian shield areas.
(ii) Post-Cambrian primary hydrothermal ore deposits.
(iii) The 'regenerated' younger ore deposits in Alpine-type mountain chains.
(iv) The secondary hydrothermal ore deposits in Mesozoic-Tertiary cover strata.

Of these, only the last three concern us here. Schneiderhöhn accepts the hypothesis that orogenies have been metallogenetic epochs and that the primary ore deposits (ii) derive from magmas generated by, or associated with, such orogenies. The regenerated ores (iii) are supposed to develop when older, already folded rocks, their associated ore deposits and presumably the lead disseminated throughout the sediments and metamorphic rocks, are involved in subsequent alpine-type folding and metamorphism. These processes could lead to solution, homogenization and transportation into higher horizons. It is possible that these two groups of leads have, in fact, attained sufficient homogenization to be isotopically indistinguishable, and are characterized by normal lead isotope abundances. This appears to be borne out, on the whole, by the numerous normal leads reported from all parts of Europe, including Great Britain and elsewhere, in Caledonian, Hercynian and Alpine deposits which may or may not be accompanied by igneous activity.

In contrast with the above groups, we may consider the secondary hydrothermal ore deposits (iv) with low temperature features, which occur in Mesozoic and Tertiary cover rocks overlying older basement complexes in parts of Europe and North Africa. Typical examples occur at Raibl (Italy), Bleiberg (Austria), Aouli-Mibladen (Morocco), etc. The cover sediments have not been subjected to orogeny, but only to widespread epi-orogenic warping and fracturing which follow a tectonic pattern of persistent trend in the underlying basement, with successive rejuvenations. Schneiderhöhn suggests that thermal waters (in some cases possibly related to Tertiary vulcanism) have dissolved metals from the deeper-lying rocks, transported and deposited them at favourable sites in the cover strata. In such cases isotopically somewhat variable *B*-type leads can result, representing localized, post-organic solutions derived from older, sometimes heterogeneous, sources, which may never have had the possibility of extensive intermingling before the site of deposition is reached (Cahen *et al.* 1958). It is believed that the leads of the central and north-west Highlands of Scotland (nos. 72–75, 76–79), as well as several from western Ireland (nos. 94–97), are of this general type. The regeneration of the Scottish and Irish *B*-type leads may be attributed to tectonic and metamorphic events, or igneous intrusions, as described in the relevant regional discussions. It was also pointed out that the model ages obtained for some of these leads almost certainly represent an approximation to the absolute age of the rocks of the basement complex from which they are derived.

It is a necessary condition in cases of this type that the source from which these secondary *B*-type leads are derived has a rather lower uranium/lead ratio than typical for normal leads. The reasons for this remains a subject for future research, but it is probably significant that the average lead content of the most common metamorphic rocks, i.e. mica-schists and gneisses, exceeds that of igneous rocks and of shallow-water sediments. Furthermore, in several instances the lead content appears to increase with the degree of metamorphism (Shaw 1954; Wedepohl 1956). The average figures given by Wedepohl are as follows: for igneous rocks, granite 0·0019 %, granodiorite 0·0015 %, diorite 0·0010 %, basalt 0·0006 %, ultrabasic rocks 0·0003 %; for shallow-water sediments, non-pelagic argillaceous rocks 0·0020 %, sandstones 0·0007 %, limestones 0·0009 %. In the case of metamorphic rocks the lead content increases from greenschists, amphibolites and granulites (0·0010 %) to mica-schists and gneisses (0·0023 %).

According to the limited data available, the content of uranium and thorium in metamorphic rocks does not differ markedly from that in granite or corresponding sedimentary rocks (Adams, Osmond & Rogers 1959).

(*c*) *Evidence for origin of lead ores from the uranium/lead and thorium/uranium ratios, and from sulphur isotope ratios*

The average values uranium-238/lead-204 (V_p) and thorium-232/uranium-238 (K_p) calculated for British lead ores are extremely close to the values found by other workers for normal leads from all over the world. The variation in these parameters for all normal leads does not exceed about 10 %. It is of interest to compare these values with some typical published uranium, thorium and lead analyses of igneous rocks. Table 7 presents such data for average igneous rocks. Further uranium and thorium analyses are given by Adams *et al.* (1959).

TABLE 7. AVERAGE URANIUM, THORIUM AND LEAD CONTENT OF IGNEOUS ROCKS

	uranium (p.p.m.)	thorium (p.p.m.)	lead (p.p.m.)
granites, acidic rocks	3·0 ± 0·3(1)	13 ± 2(1)	19(3)
	3·8(2)	—	19(4)
granodiorite, intermediate rocks	1·4 ± 0·2(1)	4·4 ± 1·2(1)	15(3)
diorite	—	—	10(3)
gabbro, basalt	0·96 ± 0·11(1)	3·9 ± 0·6(1)	6(3)
			9(4)

(1) Evans & Goodman (1941).
(2) Senftle & Keevil (1947).
(3) Wedepohl (1956).
(4) Sandell & Goldich (1943).

The mean value $V_p = 9·05$ for British and Irish leads corresponds to a weight ratio lead/uranium = 6·9. It is apparent from the values quoted in table 7 that this is in the general range for acidic and basic igneous rocks. Similarly, the mean value $K_p = 3·95$ for British and Irish leads, corresponding to a weight ratio thorium/uranium = 3·9, is close to the average ratio in granitic and basic rocks, which is generally between 3 and 4 (Adams *et al.* 1959). Larsen & Gottfried (1960) have, furthermore, shown that there is generally no significant variation in the thorium/uranium ratio in differentiated rock series ranging from basic to acid members. Murray & Adams (1958) quote a value of 3·8 ± 0·8 from their studies of orthoquartzitic, clay-free sands, which they consider likely to be near the crustal average.

It is evident that the lead/uranium and thorium/uranium ratios for the source of lead ores, as calculated from lead isotope abundances, are approximately equal to those of average acidic or basic igneous rocks, as well as to those obtained for stone meteorites, which are often equated cosmologically and geochemically with the earth's mantle (Patterson, Brown, Tilton & Inghram 1953; Patterson 1955, 1956; Holmes 1956).

Catanzaro & Gast (1960) conclude from their study of lead extracted from pegmatitic microclines that the isotopic composition of such lead in most cases yields model ages consistent with the true age of crystallization of the pegmatite. They suggest that such lead has been derived from the mantle followed by only a short, crustal history. From five measurements by other workers of the uranium-238/lead-204 ratio in granites, granodiorites and basalts they suggest that '...the average value of the uranium-238/lead-204 ratio would appear to be somewhat higher in the upper crust than in the mantle. The range observed in the crust is certainly very much wider than in the apparent range for the source of lead.' The present author considers this view to be premature on the basis of so few samples. A comparison of normal lead model parameters with the average of several hundred lead/uranium and thorium/uranium ratios from acid and basic igneous rocks suggests that the parent source of normal leads cannot yet be identified with any particular part of the earth. This approach neither specifically favours nor contradicts a crustal (or mantle) origin.

Ault & Kulp (1960) have shown that sulphur associated with normal leads tends to show a restricted range of sulphur-32/sulphur-34 ratios in any given deposit, although the average ratio of different deposits of this type may differ significantly from each other, lying either above or below the crustal average. They conclude that most sulphide ore solutions have their immediate origin in the crust of the earth rather than in the mantle and that the deviation of the sulphur-32/sulphur-34 ratio in a given deposit from the crustal average of 22·13 depends on the sedimentary sulphide to sulphate ratio in the crustal material from which the deposit is derived. Ault & Kulp state:

'If the ore-forming fluids are essentially all derived from geosynclinal deposits undergoing metamorphism or fusion, then there would not necessarily be any relation between normal ore leads and the sulphur isotopic content. This holds for the important post-Cambrian deposits because the time spent by the lead in the sedimentary environment is too short to appreciably affect its isotopic composition whether it resides in a relatively high uranium/lead environment such as shale (which characteristically has a high sulphur-32/sulphur-34 ratio) or in a low uranium/lead environment such as evaporites or limestone (which have a low sulphur-32/sulphur-34 ratio). The data show a fairly narrow spread in the sulphur-32/sulphur-34 ratio for normal leads. This probably reflects the fact that these leads are generally derived from a fairly large volume of crust that has been fused and the sulphur isotopes are homogenized close to the average crustal value.'

Ault & Kulp believe that the lead component of the lead sulphide ores has arisen from the mantle because 'normal leads show no evidence of having spent a large part of their history in an environment with uranium lead ratio greater than basalt'. It was pointed out previously that the average uranium/lead ratios of granitic and basaltic rocks do not appear, from the published analyses, to differ sufficiently to be able to regard one or the other as the source of normal leads. From the data of Ault & Kulp it appears at least equally likely that normal leads associated with a restricted set of sulphur isotope compositions are themselves products of crustal homogenization processes of the type outlined earlier. It remains for future research to decide whether there is any correlation between respective minor regional variations in the measured sulphur-32/sulphur-34 ratio and in the uranium-238/lead-204 ratio calculated from the Holmes–Houtermans model.

(*d*) *Anomalously young* (*J-type*) *leads*

The '*J*-type' leads (from Joplin, Missouri) can be recognized by one or more of the following criteria:

(i) Anomalously young, or negative, model ages.

(ii) Discrepancies between the lead-206/lead-204 and lead-207/lead-204 ratios on the one hand and the lead-208/lead-204 ratio on the other. There is an excess of lead-206, lead-207 and (sometimes) lead-208 over that expected from the isochron curves.

(iii) Variation of isotopic ratios of lead in samples from a single occurrence or from a set of contemporaneous mineralizations.

There is no evidence that any leads so far measured from the British Isles are of this type. Several points are, however, relevant to the present paper.

To account for *J*-type anomalies in the Mississippi Valley, Bate & Kulp (1955) have proposed a hypothesis of inhomogeneous extraction of lead, enriched in the radiogenic isotopes, from the granitic basement rocks. Russell and his co-workers have provided quantitative studies of several suites of *J*-type leads (Farquhar & Russell 1957; Russell & Farquhar 1957; Stanton & Russell 1959). In a general way, the degree of anomaly depends on the distance from the source to site of deposition, duration of transit and the composition and age (hence radiogenic lead content) and thickness of individual rock units traversed. Such a process may be compared and contrasted with that required for extraction of lead from metamorphic (essentially non-granitic) basement complexes with high lead/uranium ratio to yield *B*-type ores, such as described by Cahen *et al.* (1958) and in the present work.

Stanton & Russell (1959) consider that normal lead is derived from the mantle and that all leads which have travelled finite distances through sedimentary rocks, e.g. vein deposits, are potentially anomalous. As pointed out previously, these authors consider that only two types of lead deposit can be regarded as truly normal, namely: (i) Certain types of 'conformable' deposits in which the lead is considered by Stanton (1955*a*, *b*) to have been derived from the mantle, expelled through volcanoes and either quickly precipitated as sulphide on the sea floor or expelled during diagenesis from associated tuff beds and localized in adjacent iron sulphide-rich sediments. Such deposits are considered to have no direct continental affiliations, but to occur in island arc areas. (ii) The *B*-type lead ores of Houtermans and his co-workers.

According to this viewpoint, nearly all vein-type deposits occurring in areas of crustal thickening are regarded as *J*-type anomalies. This is in contradiction to the numerous normal leads of all ages obeying the Holmes–Houtermans model which occur as epigenetic vein deposits in continental geosynclinal-orogenic areas throughout the world. It seems unlikely that the views of Russell *et al.* can result in substantial further progress regarding the problem of the origin of normal and *B*-type lead ores.

The present author is convinced of the validity of the Holmes–Houtermans classification of lead-ores into *B*-types, normal types and *J*-types. It remains for future research to establish a more definite correlation between the type and degree of anomaly on the one hand, and the geological environment and genesis of the lead ores on the other.

9. Summary and conclusions

A comparison of three earth models frequently used in the interpretation of lead isotope abundances has shown that the Holmes–Houtermans model, when used in conjunction with Patterson's values for the lead isotope composition in iron meteorites and in modern ocean sediments, is capable of yielding ages in good agreement with the age of mineralization as determined by other methods. Thus, the Holmes–Houtermans model ages of three suites of galenas associated respectively with: (i) the Hercynian (Permo-Carboniferous) granites of Devon and Cornwall, (ii) the Caledonian (Devonian) Shap granite of Westmorland, (iii) the Oslo Permian igneous province, give excellent agreement with published absolute age values of genetically associated igneous rocks.

Of the ninety-eight British and Irish galenas investigated, eighty-six are assumed to represent normal leads, in view of the close regional groupings of model parameters. Furthermore, the model age in no case exceeds the absolute age of the enclosing sedimentary rocks on the basis of the recently published time-scales of Holmes & Kulp. The remaining twelve leads are almost certainly '*B*'-types as defined by Houtermans, i.e. the model ages are demonstrably older than the true age of mineralization. These *B*-type leads occur entirely within the metamorphic basement complexes of Scotland and Ireland.

A detailed regional consideration of the isotope data and of the model ages of all presumed normal leads suggests the existence of at least six distinct periods of mineralization within the British Isles. These are respectively: (i) Caledonian mineralization probably mainly of Middle or Upper Silurian age, 440 ± 30 My ago: (ii) Devonian mineralization, 360 ± 30 My ago. (iii) Lower or Middle Carboniferous mineralization, 320 ± 20 My ago. (iv) Hercynian mineralization probably Lower Permian in age, 280 ± 20 My ago. (v) Mesozoic mineralization probably of Upper Triassic age, 220 ± 30 My ago. (vi) Upper Mesozoic mineralization of probable Upper Jurassic or Cretaceous age, 140 ± 40 My ago. Groups (i), (iii), (iv) and (v) are of considerable importance, whilst groups (ii) and (vi) represent relatively minor mineralizations. It is not assumed, however, that all the mineralizations within any one of the six groups are necessarily contemporaneous.

There is no isotopic evidence for Tertiary sulphide mineralization within the British Isles.

A discussion of the causes of normal lead isotope abundances indicates that these could be the result of large-scale crustal homogenization processes in continental geosynclinal-orogenic belts, as suggested by Shaw. The evidence from world-wide absolute age determinations for a relatively early differentiation of the earth's crust and for repeated rejuvenation of older geosynclinal-fold belts suggest that the majority of leads may not have had a significant subcrustal history. On the other hand, in the present state of knowledge it is not possible to identify definitely the source of lead ores with any particular part of the earth, either by comparing the model parameters uranium-238/lead-204 (V_p) and thorium-232/uranium-238 (K_p) with the published analytical data for uranium, thorium and lead in basic and acidic igneous rocks, or by consideration of the published sulphur isotopic ratios on lead sulphide deposits.

B-type leads are assumed to originate by comparatively localized remobilization and regeneration of lead from metamorphic basement complexes of essentially non-granitic character with high lead/uranium ratios or low radiogenic lead content. Such remobilization may be due to tectonic events or to igneous intrusions. The source of *B*-type leads is frequently likely to be somewhat heterogeneous and solutions may not have had the opportunity for extensive mixing before the site of deposition was reached. Thus, although *B*-types tend to exhibit some variation of lead isotope abundances in samples from a single occurrence or from a set of contemporaneous mineralizations, they may give an approximation to the absolute age of the basement rocks or to the primary ore deposits from which they were derived. Processes of this type presumably account for the *B*-type leads in the metamorphic basement rocks of Scotland and Ireland.

No cases have been definitely recognized within the British Isles where lead gives a negative, or anomalously young, model age (‘*J*’-type lead). Leads of this type, widely recognized elsewhere, probably arise from inhomogeneous extraction processes of lead from essentially granitic basement complexes, as suggested by Bate & Kulp. There is, however, very little evidence for the view of Russell *et al.* that most vein-type lead deposits which have traversed finite thicknesses of sedimentary rocks are *J*-type anomalies—a necessary consequence of their suggestion that the *B*-type leads described by Houtermans *et al.* should be regarded as normal leads.

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Appendix: description of analyzed galena samples

The following brief descriptions mention only salient points, such as donor of specimen, full name of locality and comments on the general geology of the sample. A reference to published literature concerning the occurrence is given wherever possible. Map and grid reference are omitted (except for several small, isolated occurrences), but can in almost all cases be obtained from the cited literature references.

(a) *England and Wales*

1. Bere Alston, near Calstock, Devon (Donor: A. W. G. Kingsbury). Late N.–S. cross-course in lead–zinc zone of Gunnislake—Hingston Down Granite, which outcrops between the Dartmoor and Bodmin Moor Granites. County rock Devonian ‘Killas’. (Dines, 1956, pp. 681–685.)

2. Wheal Rose, Porthleven, Cornwall (A. W. G. Kingsbury). N.–S. cross-course in chalybite matrix, 2 miles S.E. of Godolphin Granite and $\frac{3}{4}$ mile S.E. of Porthleven. Country rock Devonian ‘Killas’. (Dines 1956, pp. 241–242.)

3. Vottle shaft, Wheal Kitty, St Agnes, Cornwall (A. W. G. Kingsbury). From higher level of cassiterite-bearing vein, associated with St Agnes Granite, $\frac{1}{4}$ mile N.E. of St Agnes. Country rock Devonian ‘Killas’. (Dines 1956, pp. 462–467.)

4. South Shaft, South Terras Mine, St Stephen-in-Brannel, Cornwall (A. W. G. Kingsbury). From N. to S. cross-course with nickel, cobalt, copper, arsenic, uranium, flanking the southern edge of St Austell Granite. 1 mile S.W. of St Stephen. Country rock Lower Devonian ‘Killas’ and greenstone with elvan dykes. (Dines 1956, pp. 541–543.)

5. Wheal Mary Anne, Menheniot, Liskeard, Cornwall (A. W. G. Kinsbury). N.–S. cross-course with fluorite and barytes, south of Bodmin Moor Granite. $2\frac{1}{2}$ miles S.E. of Liskeard. Country rock Devonian ‘Killas’ and volcanics. (Dines 1956, pp. 617.)

6. Lambriggan, Perranzabuloe, near St Agnes, Cornwall (A. W. G. Kingsbury.) E.–W. vein within outer lead–zinc zone of St Agnes Granite. Country rock Devonian ‘Killas’. (Dines, 1956, p. 493.)

7. Penberthy Croft, St Hilary, Cornwall (A. W. G. Kingsbury). From higher level of an E.–W. vein between Godolphin and Land’s End Granite. Vein carries tin, iron, copper, arsenic in depth. $\frac{3}{4}$ mile N. of St Hilary. Country rock Devonian ‘Killas’. (Dines 1956, pp. 186–187.)

8. Barbary Mine, Ireshope, Weardale, Co. Durham (Professor K. C. Dunham). From vein in Carboniferous Limestone associated with fluorite. (Dunham 1948, pp. 227–228; 1959*a*, p. 134.)

9. Sedling Mine, Weardale, Co. Durham (Professor K. C. Dunham). From vein in Carboniferous Limestone associated with fluorite. (Dunham 1948, pp. 250–251; 1959*a*, p. 133.)

10. Rotherhope Fell, Alston Moor, Cumberland (Professor K. C. Dunham). From vein in Carboniferous Limestone associated with fluorite. (Dunham 1948, pp. 151–153; 1959*a*, p. 135.)

11. Settlingstones, Haydon Bridge, Northumberland (Professor K. C. Dunham). From vein in Carboniferous Limestone associated with witherite, barytes, etc. (Dunham 1948, pp. 322–325; 1959*a*, p. 136.)

12. Chilton Quarry near Ferryhill, Co. Durham (Professor K. C. Dunham). From Lower Permian Magnesian Limestone, associated with barytes, fluorite, minor blende, limonite. The rocks quarried are calcareous Dolomites of the Lowest Permian, 120 ft. above topmost Coal Measures. Several hundred yards south of Ferryhill Station. (Fowler 1956, pp. 258–260.)

13. Steetley Quarry, near Worksop, Notts (F. W. Dunning). Disseminated galena in Permian Magnesian Limestone. No detailed reference available.

14. Thickley Quarry, near Darlington, Co. Durham (T. Deans). From the persistent snygenetic galena layer in the Permian Marl Slate of Co. Durham. Locality about 5 miles S.E. of Chilton Quarry (see sample no. 12) and 7 miles N.N.W. of Darlington. (Deans 1948).

15. White Grit Mine, Shelve, Shropshire (F. W. Dunning). From vein, 1 mile S.W. of Shelve. Country rock consists of flags of the Lower Ordovician Mytton Beds with intruded greenstone dykes. (Dines 1958, pp. 19–21; Dines 1959, p. 295.)

16. Mendip Hills, Somerset (Dr P. A. Sabine). Geol. Survey Specimen E 27777 (= GG 306). Vein in Carboniferous Limestone 1270 yards due E. of cross-roads of Cheddar (B 3371) and Barrington-Castle of Comfort roads (B 3134). 1-in. 280, 6-in. 18 S.E. (E.) Somerset 31/38551. (Green 1958).

17. Mendip Hills, Somerset (Dr P. A. Sabine). Geol. Survey Specimen E 26572 (= GG 363). Just under 1 mile S.E. of road fork marked 'Red Quarr' and about $\frac{3}{4}$ mile E. of Priddy. 1-in. 280, 6-in. 28 N.W. (E.) Somerset 31/570514. Tip from old mine shafts and trenches. Galena in Triassic Keuper Dolomitic Conglomerate. (Green 1958).

18. Mendip Hills, Somerset (Dr P. A. Sabine). Geol. Survey Specimen E 26571 (= GG355). 1140 yards N. 129° E. of cross-roads Cheddar (B 3371) and Barrington-Castle of Comfort (B 3134) roads. 1-in. 280, 6-in. 18 S.E. (E.) Somerset 31/536554. Tip from old mine shafts and trenches. Galena in Jurassic Lower Lias Limestone. (Green 1958).

19. Millclose Mine, Darley Dale, near Matlock, Derbyshire (A. W. G. Kingsbury). From vein in Carboniferous Limestone associated with blende, fluorite, barytes, calcite. (Carruthers & Strahan 1923, pp. 72–75; Shirley 1950; Varvill 1959, p. 189.)

20. Riber Mine, near Matlock, Derbyshire (F. W. Dunning). From vein in Carboniferous Limestone. Characteristic South Pennine mineralization, except that the ore is sheared in places. (Varvill 1959, p. 193.)

21. Wheel's Rake, Youlgreave, Derbyshire (F. W. Dunning). From vein in Carboniferous Limestone, about $2\frac{1}{2}$ miles S. of Bakewell. (Carruthers & Strahan 1923, pp. 65–68; Varvill 1959.)

22. Moletrap Mine, Cromford, near Matlock, Derbyshire (F. W. Dunning). Galena from vein in Carboniferous Limestone. Typical Derbyshire ore with barytes-fluorite gangue. (Carruthers & Strahan 1923, p. 76).

23. R. Sankey's Potteries, Bulwell, Nottinghamshire (T. Deans). Galena concentrate from the widespread and persistent occurrence in the topmost 2 in. of the lower Magnesian Limestone in Notts and south Yorks.

24. Blackrook, near Garendon Park, Charnwood, Leicestershire (F. W. Dunning). Galena disseminated in Triassic Keuper Marl. No detailed reference available.

25. Alderley Edge, Cheshire (F. W. Dunning). Galena impregnation in coarse conglomerate at the base of the Triassic Keuper beds. (Dewey, in Dewey & Eastwood 1925, pp. 5–16.)

26. Foxdale Lode, Isle of Man (A. W. G. Kingsbury). From E.–W. vein traversing Cambrian (?) Manx slates above and granite at depth. Associated with blende, chalcopyrite, quartz, chalybite. (Dewey & Eastwood 1925, pp. 79–80.)

27. Laxey, Isle of Man (F. W. Dunning). From N.–S. vein traversing Cambrian (?) Manx Slates. Associated with blende, chalcopyrite, quartz, chalybite. (Dewey & Eastwood 1925, pp. 80–81.)

28. Knap Down Mine, near Combe Martin, North Devon (A. W. G. Kingsbury). From eastern part of main Combe Martin Lode, trending E. 10° N. Locality is about $\frac{3}{4}$ mile E.N.E. of Combe Martin. Country rock consists of steeply dipping Devonian slates. (Dines 1956, p. 758.)

29 and 30. Combe Martin Silver-Lead Mine, North Devon (F. W. Dunning). Two separate galena specimens from Combe Martin Mine. Country rock consists of steeply dipping Devonian slates. (Dines 1956, pp. 757–758).

31. Eagle Crag Vein, Grisedale Mines, Grisedale, Patterdale, Westmorland (A. W. G. Kingsbury). E.–W. trending copper–lead–zinc–barium vein of Helvellyn Group in Ordovician Borrowdale Volcanics. 2 miles S. of Greenside Mine. (Eastwood 1921, p. 46.)

32. Hartsop Hall Mine, Hartsop Glen, Patterdale, Westmorland (A. W. G. Kingsbury). N.N.E.–S.S.W. Copper–lead–zinc–barium vein of Helvellyn group in Ordovician Borrowdale Volcanics. 400 yards W. of Hartsop Hall and $\frac{1}{2}$ mile S.W. of Brother's Water. (Eastwood 1921, pp. 46–47.)

33. Carrock Wolfram Mine, North Emerson Level, Grainsgill, Cumberland (A. W. G. Kingsbury). From E.–W. vein, traversing Skiddaw Granite, which cuts and displaces the N.–S. Wolfram-bearing veins. Locality is $4\frac{1}{2}$ miles S. of Caldbeck and 3 miles N.W. of Mungrisdale. (Dewey & Dines 1923, pp. 43–46.)

34. Roughtongill South Vein, Balliway Rigg, Higher Roughton Gill, Calderbeck Fells, Cumberland (A. W. G. Kingsbury). From intermediate zone copper–zinc–lead vein, with N.E.–S.W. trend. Country Rock is Ordovician Borrowdale Volcanics. $3\frac{1}{2}$ miles S.S.W. of Caldbeck and 7 miles N.N.E. of Keswick. (Eastwood 1921, pp. 36–41).

35. Driggith Main Vein (30-fathom level), Caldbeck, Cumberland (A. W. G. Kingsbury). E.–N.E. intermediate zone copper–lead–zinc vein, in Ordovician Borrowdale Volcanics. Thought to be eastward extension of Roughtongill South Vein (sample no. 34). At head of Driggith Beck (tributary of Carrock Beck) about $3\frac{3}{4}$ miles S. of Calbeck. (Eastwood 1921, pp. 43–45.)

36. Barrow Mine, Uzzicar, Vale of Newlands, Cumberland (A. W. G. Kingsbury). Outer lead–zinc zone vein in Ordovician Skiddaw Slates. One of a N.N.W.–S.S.E. and N.–S. trending group of veins. On west side of vale of Newlands, near Uzzicar, $\frac{1}{4}$ mile N.N.W. of Stair. (Eastwood 1921, pp. 26–28.)

37. Goldscope Lead Lode, Vale of Newlands, Cumberland (A. W. G. Kingsbury). N.–S. outer lead–zinc zone vein in Ordovician Skiddaw Slates, which cuts and shifts an earlier E.–W. copper vein. Immediately S. of Little Town. (Eastwood 1921, pp. 23–26.)

38. Threlkeld Mine, Woodend Section, Low Level, near Keswick, Cumberland (A. W. G. Kingsbury). Outer lead–zinc–barium zone vein in Ordovician Skiddaw Slates. One of N.N.W.–S.S.E. group of veins. $\frac{1}{2}$ mile N.N.E. of Threlkeld (Eastwood 1921, pp. 11–14.)

39. Low Hartsop Mine, Threshthwaite Glen, Patterdale, Westmorland (A. W. G. Kingsbury). N.N.W.–S.S.E. vein from Helvellyn area in Ordovician Borrowdale Volcanics. Near Brothers' Water at junction of Hayeswater Gill and Pasture Beck. (Eastwood 1921, pp. 47–48.)

40. Greenside Mine, Glenridding, Patterdale, Westmorland (A. W. G. Kingsbury). N.–S. vein from Helvellyn area, in Borrowdale Volcanics. About $1\frac{1}{2}$ miles W. of head of Ullswater. (Eastwood 1921, pp. 14–19.)

41. Hensingham Borehole, Cleator Moor, Cumberland (E. E. L. Dixon). Galena occurs as replacement in Carboniferous Limestone. $1\frac{1}{2}$–2 miles W. and N.W. of the main haematite area of Cleator Moor, but probably not connected with it—no iron is recorded at Hensingham. No detailed reference available.

42 and 43. Shap Blue Rock Quarry, Shap, Westmorland (Dr. R. J. Firman). Two separate specimens of galena from metasomatic aureole of Shap granite, in Ordovician Borrowdale Volcanics. (Firman 1957.)

44. Buttermere Vein, Blackbeck Tarn, Cumberland (Dr R. J. Firman). Vein occurs in a fault and carries galena, quartz, chlorite, pyrite, chalcopyrite, barytes. Country rock is pyroxene-andesite of Borrowdale Volcanic Series; about 600 to 800 ft. above junction with Skiddaw Slates. Fault trends 140°, downthrow 20 to 30 ft. N.E. Locality Blackbeck Tarn, NY201129. 6-in. sheet NY21 S.W., $2\frac{1}{2}$ in. sheet NY 21, 1-in. Keswick sheet. Vein is up to 3 ft. wide, but lead-bearing portion is narrower. The Seathwaite-in-Borrowdale Graphite vein has same trend.

45. Great Halkyn Lode, Flintshire, North Wales (F. W. Dunning). Galena from vein in Carboniferous Limestone. (Smith 1921, pp. 131–132; Schnellmann 1959, p. 235.)

46 and 47. Parys Mountain, Amlwch, Anglesey, North Wales (no. 46 supplied by Dr P. A. Sabine; no. 47 collected by Professor R. M. Shackleton and the author from the mine dumps). Two separate specimens of fine-grained, dense aggregate of galena with a little blende, pyrite and chalcopyrite of the typical 'Bluestone' facies. The specimens come from the broad belt of intense metasomatism which introduced micas, silica and sulphide into Ordovician and Silurian shales. (Greenly 1919; Smith & Dewey 1922, pp. 81–85; Manning 1959, p. 313.)

48. Parc Mine, Llanrwst, Caernarvonshire, Wales (F. W. Dunning). From E.–W. vein in Ordovician Bala Slates and volcanic ashes. 2 miles W. of Llanrwst. (Smith & Dewey 1922, pp. 65–67; Archer 1959, pp. 269–273.)

49. Caegwernog and Berthllwyd Silver-Lead Mine, near Dolgelley, Merioneth, Wales (F. W. Dunning). 'Gold Belt' Mine in Cambrian Strata of Harlech Dome area. Typical of the Merioneth Gold–copper–lead–zinc mineralization. (Dewey & Eastwood 1925, p. 40; Archer 1959, pp. 264–268.)

50. Manod-Bach Silver-Lead Mine, Ffestiniog, Merioneth, Wales (F. W. Dunning). From a vein in Ordovician volcanic ash, accompanied by blende, chalcopyrite, pyrite and quartz. $\frac{1}{4}$ mile from Manod Station. (Smith & Dewey 1922; Archer 1959, pp. 264–268.)

51. Cowarch Mine, near Dinas Mawddwy, Merioneth, Wales (F. W. Dunning). Galena in association with blende, chalcopyrite, pyrite in massive, milky auriferous vein quartz. Characteristic 'Gold-belt' mineral assemblage, although the mine lies rather south of the main belt. No detailed reference available.

52. Bronfloyd Mine, near Aberystwyth, Cardiganshire, Wales (F. W. Dunning) From vein traversing Lower Silurian sediments, on slope west of Nant Silo, $2\frac{1}{2}$ miles S.E. of Bow Street Station. (Jones 1922, pp. 62–64.)

53. Tal-y-bont Mine, near Aberystwyth, Cardiganshire (F. W. Dunning). From vein traversing Lower Silurian sediments. (Jones 1922, pp. 53–55.)

54. Bryn Glas Mine, near Macchynlleth, Montgomeryshire (F. W. Dunning). From vein traversing Upper Ordovician and Lower Silurian sediments. $\frac{3}{4}$ mile east of Ponterwyd, 8 miles S.E. of Macchynlleth. (Jones 1922, p. 132.)

55. Daren Mine, near Abersytwyth, Cardiganshire (F. W. Dunning). From vein in Lower Silurian sediments, $4\frac{3}{4}$ miles E. of Bow Street Station. (Jones 1922, pp. 64–68.)

(*b*) *Scotland*

56. Silver Ridge Mine, Wood of Cree, Kircudbrightshire (Dr A. G. MacGregor). Survey Specimen U 687–MC 1284. $\frac{1}{2}$ mile E. of River Cree and 2 miles upstream from Wood of Cree. Nearly E.–W. vein in Silurian flags and shales somewhat hornfelsed by Cairnsmore of Fleet Granite. (Wilson 1921, pp. 44, 47.)

57. Wanlockhead Mine, Dumfries (Dr A. G. MacGregor). Survey Specimen U 1971. Veins in Ordovician Lowther Group. Grey, sandy, micaceous shales with calcareous layers and intercalated grey, ferruginous gritty beds and greywackes, some calcareous. (Wilson 1921, pp. 10–23; MacKay 1959, pp. 49–64.)

58. Nutberry Hill, Lanarkshire (Dr A. G. MacGregor). Survey Specimen EC 346. Old working on north slope of hill, $\frac{1}{4}$ mile from summit. Veins in Silurian shales, mudstones and greywackes. Nearby, a number of intrusive sheets of felsite and basalt dykes. Veins cut the felsites and are sometimes parallel to the dykes; mutual relations not known. (Wilson 1921, pp. 59–60.)

59. Mulreesh, Port Askaig, Islay, Argyllshire (Dr A. G. MacGregor). Survey Specimen, U 1972. Old workings 2 miles S.W. of Port Askaig; in blue limestone (Islay Limestone) *ca.* 50 ft. thick underlain by black slates and phyllites of Dalradian age. Metalliferous veins in the limestone trend across strike. (Wilson 1921, pp. 65, 71, fig. 9; Barnett 1959, pp. 65–76.)

60. Ballygrant, Islay, Argyllshire (Dr A. G. MacGregor). Survey Specimen U 552. Old Mine *ca.* 200 yards N.E. of village. In Islay Limestone, see sample no. 59. (Wilson 1921, pp. 65, 71, fig. 9; Barnett 1959, pp. 65–76).

61. Strontian Mines, Argyllshire (Dr A. G. MacGregor). Two samples. Survey Specimens MC1361 and U1974. Veins usually associated with decomposed E.–W. Permo-Carboniferous (?) dykes, traversing area of granitic and augen-gneiss and injected Moine schists, lying to the north of the margin of the Caledonian Strontian Granite. (Wilson 1921, pp. 82, 84 and fig. 12).

62. Halkirk Bridge, Thurso, Caithness (Dr A. G. MacGregor). Survey Specimen MC1630, U978. 2-in. vein in north bank of river Thurso, 250 yards downstream from Halkirk Bridge, traversing Old Red Sandstone. No detailed reference available.

63. Gie-Uisg Geo, Caithness (Dr C. D. Waterston). From vein in Old Red Sandstone, associated with blende, pyrites, and calcite.

64. Shapinsay, Orkney Islands (Dr D. Flinn). From vein traversing Middle Old Red Sandstone. Specimen collected by T. S. Traill, *ca.* 1820. Locality N30 500200.

65. Vidlin, Lumnasting, Shetlands (Dr D. Flinn). From $\frac{1}{2}$-in. cavity in actinolite-schist adjacent to a pyrrhotite–blende–chalcopyrite ore body. Locality N41 481668.

66. Dury Voe, Lumnasting, Shetlands (Dr D. Flinn). Calcite–blende–galena lens in Dalradian metamorphic rocks in crush zone of a large tear fault. Locality N41 462635.

67. Glen Gairn, Ballater, Aberdeenshire (Abergairn or Corrie Beg Mine) (Dr A. G. MacGregor). Survey Specimen U1976. N.N.W. vein of calcite, fluorite and argentiferous galena associated with intrusive hornblende schist and thin bands of Dalradian siliceous schists of the Banffshire series. Probably connected with nearby Caledonian Granite. (Russell 1937; Whitehead in Dunham 1952*b*).

68. A further specimen from Abergairn Mine, see no. 67. (Professor F. H. Stewart.) Specimen no. FR663.

69. Craig-an-t' Seabhaig, Ballater, Aberdeenshire (Professor F. H. Stewart). Specimen FR642. Galena from vein in the Granite crags on the north side of Ballater Pass. Probably associated with the Caledonian Granite.

70. Borolan, Sutherland (Professor F. H. Stewart). Specimen no. F.R. 90. Speck of galena from syenite-pegmatite which cuts borolanite in quarry about 200 yards from road beside the Allt a Mhuilinn, Altnacealgach. Associated with sulphatic cancrinite, orthoclase, melanite, lepidomelane, zircon, thorite, allanite and zeolitic alteration products after cancrinite and nepheline. (Stewart 1941; Phemister 1948.)

71. Meall Luaidhe, Glen Lyon, Perthshire (Dr A. G. MacGregor). Survey Specimen T1552. Locality on Kerrowmore farm 1 mile up Allt Bail a Mhuilinn from Glen Lyon. From 2 ft.-thick quartz-vein traversing Dalradian garnet-mica schist with interbedded quartzose and calcareous bands, near the N.N.E.–S.S.W. Killin fault. (Wilson 1921, p. 102.)

72. Clachan Beag, Loch Fyne, Argyllshire (Dr A. G. MacGregor). Survey Specimen MC1286, U689. Old workings at head of Loch Fyne. Metasomatic replacement of Dalradian Limestone with disseminated galena, blende, pyrites in chalybite matrix. (Wilson 1921, pp. 73–74, fig. 10.)

73. Tomnadashan, Loch Tay, Perthshire (Dr C. D. Waterston). On south side of Loch Tay, 1 mile from Ardtalanaig and $7\frac{1}{2}$ miles from Kenmore. Ore developed at junction of a dark-coloured igneous rock intruded by an irregular granitic rock. Both intrude Dalradian schists. Ore occurs in small grains and masses up to 2 to 3 ft. in diameter. Other minerals are chalcopyrite, pyrite, quartz, calcite, chalybite, barytes. (Wilson 1921, p. 140.)

74. Crom Allt, Tyndrum, Pethshire (Dr A. G. MacGregor). Survey Specimen T1759. Old workings on west side of Inveroran road, 1 mile N. of Tyndrum. Veins in Dalradian quartzites and quartz-schists with occasional beds of mica-schist, on W. side of the N.N.E.–S.S.W. Tyndrum-Glen Fyne fault (and associated with it). Veins range from strings up to 20 ft. width. Infillings of massive, white quartz gangue with patches of calcite and barytes. Primary minerals are galena, blende, chalcopyrite and pyrites. (Wilson 1921, pp. 93–102, fig. 14.)

75. Ardtalanaig, Loch Tay, Perthshire (Dr A. G. MacGregor). Survey Specimen U1973. On south shore of Loch Tay; old workings about ½ mile due E. of Milltown Ardtalanaig. Curved, irregular, but approximately N.N.E.–S.S.W. veins, associated with nearby N.N.E.–S.S.W. Loch Tay fault, with infilling of broken country rock which is Dalradian mica-schist and partly felsite. In contact with schist, vein carries quartz, barytes, galena, blende. Where vein traverses felsite (which is probably Caledonian in age) it carries only quartz and galena. (Wilson 1921, p. 104.)

76. Loch Garbhaig, Ross-shire (Dr A. G. MacGregor). Survey Specimens MC1356, U707 and U2298. From stream Allt an Eas Bhain, *ca.* 800 yards N. 28° W. of outflow of Loch Garbhaig on N.W. slopes of Slioch. Vein associated with N.N.E. line of fracture in hornblende-schist (epidiorite) intrusive in Lewisian gneiss. Vein of calcite *ca.* 3 ft. wide carrying galena and chalcopyrite. (Wilson 1921, p. 110.)

77. Letterewe, Loch Maree, Ross-shire (Dr A. G. MacGregor). Survey Specimen U2300. 1-in. 92, 6-in. 58 N.W. Approx. ¾ mile N. 30° E. of Letterewe House. Thin vertical vein of calcite in N.E. crush-line, with galena and pyrites in Lewisian gneiss. (Wilson 1921, p. 110.)

78. Allt na Ciad Eilig, Loch Garbhaig, Ross-shire (Dr A. G. MacGregor). Survey Specimen U2299. 1-in. 92, 6-in. 58 N.E. In stream Allt na Ciad Eilig, 625 yards E. 29° N. of outflow of Loch Garbhaig. Vein and dissemination of calcite associated with crush zone of N.N.E. fault cutting hornblendeschist (epidiorite) intrusive in Lewisian Gneiss. Associated pyrite and blende.

79. Garbh Allt, Rois-bheinn, Inverness-shire (Dr A. G. MacGregor). Survey Specimen U1975. 1-in. 61, 6-in. 148 N.E. Galena from N.W. to S.E. crush lines in psammitic and striped Moine schist, associated with camptonite dykes and carrying galena and blende. This is a district of permeated schists in which some rocks resemble granite-gneiss, similar in aspect to Lewisian types.

80. Struy, Strathglass, Inverness-shire (Dr A. G. MacGregor). Survey Specimen MC1350, U701. Struy old workings, W. side of Strathglass, 2 to 3 miles W.S.W. of Struy Bridge. Veins associated with E.–W. lines of crush in Moine Schist, varying from strings up to 6 ft. in width. They consist of broken country rock with gangue of barytes and calcite. Ores are galena, blende, minor pyromorphite. (Wilson 1921, pp. 108–109.)

81. St Aethans' Well, Burghead, Morayshire (Dr C. D. Waterston). Galena from irregular replacement of the matrix of Triassic sandstone, associated with fluorite. (Wilson 1921, p. 110–111.)

82. Stobfield, Lossiemouth, Morayshire (Dr C. D. Waterson). Galena associated with fluorite, forming irregular replacements of sandstone matrix in Triassic (possibly in part Jurassic) sediments, about ½ mile W. of Lossiemouth. (Wilson 1921, p. 111.)

(*c*) *Northern Ireland*

83. Castleward, Co. Down (A. Fowler). Galena from vein in Silurian sediments. (Cole 1922, pp. 94–95.)

84. Conlig Mine, Co. Down (A. Fowler). Galena from vein in Ordovician or Silurian sediments. (Cole 1922, p. 94; Fowler 1959).

(*d*) *Eire*

85. Ruplagh Mine, Glendalough, Co. Wicklow (F. W. Dunning). Galena from vein traversing margin of Leinster Granite. (Cole 1922, p. 110; O'Brien 1959, p. 12.)

86. Glenmalure, Co. Wicklow (F. W. Dunning). From vein traversing marginal part of Leinster Granite. (Cole 1922, p. 113; O'Brien 1959, p. 12.)

87. Barrystown, Co. Wexford (F. W. Dunning). From vein cutting Lower Palaeozoic sediments of considerable thickness. (Cole 1922, pp. 125–126; O'Brien 1959, pp. 14–15.)

88. Avoca Mine, Co. Wicklow (Dr G. J. Murphy). Specimen no. 271. Galena from South-Lode facies, showing relatively coarse-textured lead–zinc–copper–iron sulphides with quartz. (Cole 1922, pp. 30, 84, 139, 144; O'Brien 1959, pp. 7–9.)

89. Avoca Mine, Co. Wicklow (Dr G. J. Murphy). Specimen no. DP21. Galena from typical South-Lode facies, see no. 88.

90. Avoca Mine, Co. Wicklow (Dr G. J. Murphy). Specimen no. 3C. Galena from Pond-Lode facies, very fine-grained dense aggregate of lead–copper–iron–zinc sulphides without quartz and with general banded distribution. Also known as 'Kilmacooite' facies or 'Bluestone'. References as no. 88.

91. Avoca Mine, Co. Wicklow (Dr G. J. Murphy). Specimen no. B8A, 548 ft. From a small borehole core in lead-zinc rich portion of Pond-Lode facies.

92. Abbeytown, Ballysodare, Co. Sligo (J. Douglas). From replacement in Carboniferous Limestone, *ca.* 700 to 800 ft. above unconformable junction with metamorphic rocks of probable Moine age. (Cole 1922, pp. 95–96; O'Brien 1959, p. 13.)

93. Sheeffry Mine, Co. Mayo (Dr K. C. Burke). From N. to S. lode traversing Lower Palaeozoic sediments. Ore is said to be highly argentiferous. (Cole 1922, pp. 101–102.)

94. Clements Mine, Carrowgarriff, Co. Galway (Dr K. C. Burke). Locality is 2 miles S.E. of Maum and $\frac{1}{4}$ mile N. of the most westerly prolongation of Lough Corrib. Galena from vein traversing Connemara Schists. (Cole 1922, p. 102.)

95. Glengowla Mine, near Oughterard, Co. Galway (Dr K. C. Burke). Locality is south of the road from Oughterard to Clifden in Glengowla townland, 2 miles W. of Oughterard. From vein in Connemara schists, associated with calcite, barytes, blende, fluorite. (Cole 1922, pp. 102–103.)

96. Cloosh Mine, Oughterard, Co. Galway (F. W. Dunning). About $1\frac{1}{2}$ miles S. of Oughterard. Galena from vein traversing Connemara schists, associated with barytes. (Cole 1922, pp. 103–104.)

97. O'Flaherty's Shaft, Oughterard, Co. Galway (S. Moorbath). 1-in. 105, 6-in. Galway 54 N.W. About 1 mile W.S.W. of Oughterard. Small veins and pockets of galena in Oughterard Granite, very near its margin with the schist.

98. Lough Corrib shore, Oughterard, Co. Galway. (S. Moorbath). 1-in. 105, 6-in. Galway 54 N.E. 1 mile N.E. of Oughterard. Galena from 2 to 3 in. wide N.–S. calcite vein, traversing Carboniferous Limestone. The vein actually cuts large fossil clusters (corals, bryozoa, etc.). The unconformable basement is estimated at 200 to 300 ft. below the surface.

(*e*) *Germany*

99. Turandot Mine, Rheinisches Schiefergebirge (F.W. Dunning). From vein deposit traversing Lower Devonian sediments, said to be associated with Lower Carboniferous movements. (Cahen & Jedwab 1958.)

100. Maubach, Düren (F. W. Dunning). Galena from impregnation and dissemination in Triassic sandstone. The mineralization and general geology closely resemble that of Alderley Edge, Cheshire. (Behrend 1948; Cahen & Jedwab 1958.)