LEAD ISOTOPE ABUNDANCE STUDIES
ON GALENA OCCURRENCES
IN NORWAY

By

S. Moorbath and F. M. Vokes

Abstract. Lead Isotope Abundances are reported for thirty-five Norwegian and two Swedish galena specimens. The analyses were made with a solid-source mass spectrometer.

The Holmes-Houtermans model was chosen for calculation of ages from the isotopic composition. This model permits calculation of the parameters U\(^{238}/\)Pb\(^{204}\) and Th\(^{232}/\)U\(^{238}\) in the source of the ores.

The significance of the isotope data is discussed regionally in terms of the mineralisation as well as the correlation and origin of different deposits. Of the thirty-seven leads investigated, thirteen are assumed to be normal and to obey the conditions of the model. These normal leads occur (i) in the Precambrian basement, (ii) along the central axis of the Caledonides, (iii) in the Permian Oslo graben. Twenty-one leads with very variable isotope compositions yield anomalously young or negative model ages ('J-type' anomalies). These occur in a broad area extending from the inner part of the Caledonides east- and south-eastwards to the outer marginal zone of overthrusting along the Swedish border, as well as along the margins of the Oslo province. They are interpreted respectively as normal Caledonian and normal Permian lead which has become progressively contaminated with different amounts of a single radiogenic lead during passage through the country rocks to the site of deposition. The maximum age limits for the rocks which supplied the excess radiogenic component to the Caledonian and Permian leads are 1340 ± 100 m.y. and 1110 ± 200 m.y. respectively, whilst the respective Th/U ratios of these rocks are 1.9 and 1.5.

The remaining three leads are 'B-type' leads, i.e. the model ages are demon-

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strably older than the true age of mineralisation. They are interpreted as older leads remobilised and redeposited at a much later date.

It is suggested that neither the mode of occurrence in the field nor the immediate geological environment is necessarily diagnostic of the type of isotope composition (i.e. Normal, J-type of B-type), or of the type and degree of anomaly. The determining factors appear to be large-scale structural and tectonic features within the earth’s crust as well as the regional (or local) geochemical character of the basement rocks underlying the area in which a given deposit, or group of deposits, occurs.

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1. Introduction.

It has been realised for over twenty years that the variation of lead isotope abundance in common lead minerals is the result of addition of radiogenic Pb$^{206}$, Pb$^{207}$ and Pb$^{208}$ (respectively the stable
end-products of the U\(^{238}\), U\(^{235}\) and Th\(^{232}\) radioactive decay series) to primary common lead in the ultimate source material of lead ores. This primary common lead also contains the isotope Pb\(^{204}\), the absolute amount of which has remained unchanged throughout geological time. Since common lead minerals, such as galena, contain insignificant quantities of uranium and thorium, the addition of radiogenic lead has clearly occurred before the lead was concentrated from the source regions to form the mineral.

After the publication of a number of important theoretical papers in the immediate post-war years, a most significant experimental advance was made by Patterson and co-workers, who measured lead isotope abundance in iron and stony meteorites, in recent basalt-flows and in modern ocean sediments (Patterson, Brown, Tilton and Inghram 1953; Patterson, Goldberg and Inghram 1953; Patterson, Tilton and Inghram 1955; Patterson 1956; Ram Murthy and Patterson 1962). On the assumption that the isotopic composition of lead from the metal and sulphide phases of meteorites represents primeval lead of the solar systems and of the earth, Patterson used the differences between meteoritic and modern terrestrial lead isotope abundances to calculate an age of \(4.55 \pm 0.07 \times 10^9\) y. for the earth-meteorite system. This work limited the choice of suitable earth models for the interpretation of lead isotope abundance variations (Houtermans 1953; Geiss 1954; Eberhardt, Geiss and Houtermans 1955; Russell and Farquhar 1960a).

One of the most important geological applications of lead isotope data is the determination of the absolute age of sulphide mineralisation and the correlation of different deposits. In many cases throughout the world, common lead ages are in excellent agreement with known geological relationships and with the results of independent absolute age determinations. For lead ores which conform with a simple earth model (‘normal’ leads) the common lead method rivals the more conventional methods in importance, since the age of mineralisation frequently cannot be obtained in any other way.

Considerable attention has also been given in recent years to the classification, interpretation and geological significance of so-called ‘anomalous’ leads which do not conform with the simple earth models. Houtermans and co-workers have concerned themselves principally with so-called ‘B-type’ leads, with model ages greater than the age
of emplacement. These have been interpreted as older lead, remobilised and transported to a new site of deposition at a much later time (CAHEN, EBERHARDT, GEISS, HOUTERMANS, JEDWAB, SIGNER 1958). On the other hand, the Canadian workers have been specially interested in 'J-type' leads, with anomalously young or negative model ages, due to contamination of lead ore solutions with excess radiogenic lead during their passage through crustal rocks (STANTON and RUSSELL 1959; RUSSELL and FARQUHAR 1960b). These two types of anomalous lead figure prominently in the present work.

Both groups of workers have tended to correlate the type of lead isotope composition with the mode of field occurrence of the lead ores. Thus Russell et al. postulate that 'concordant' deposits (STANTON and RUSSELL 1959) contain normal lead and that vein deposits are, on the whole J-type leads. Houtermans et al. find that B-type leads are characteristic of low temperature, telethermal deposits. A general survey of the literature, together with the findings in the present study suggest, however, that this may be a considerable oversimplification. The mode of field occurrence can only be correlated with the type of lead isotope composition in so far as both are sometimes an expression of the same fundamental processes of a large scale nature. Cases can be cited of Normal, B-type and J-type leads occurring (separately) in such diverse forms as concordant, metamorphic, metasomatic, vein, replacement, dissemination, impregnation deposits. In the authors' experience, mode of occurrence in the field cannot be reliably correlated with the type of lead isotope composition. The factors which decide whether a given lead deposit is isotopically normal or anomalous, or the type and degree of anomaly, appear to be more directly determined by large-scale structural and tectonic features within the earth's crust and by the regional or local geochemical character of the basement rocks underlying the area in which the deposits occur. This is, on the whole, clearly brought out by this isotopic study of Norwegian lead ores and will be dealt with in detail in the relevant sections below. There is no doubt that anomalous leads frequently yield as much, if not more, geological information than normal leads.

The reader who wishes to follow up this subject is reminded that an excellent summary of the theory and application of lead isotope studies has been given in a recent book by RUSSELL and FARQUHAR (1960b).
2. The Holmes-Houtermans Model for the Interpretation of Lead Isotope Abundances

The various earth models commonly used for the interpretation of lead isotope abundances have been fully described in the Literature. Consequently, only a brief description is given at this stage of the Holmes-Houtermans model, which has been used throughout the present study. The reasons for the choice of the Holmes-Houtermans model in preference to other models have been dealt with in detail in a previous paper (MOORBATH, 1962).

HOLMES (1946) and HOUTERMANS (1947) assumed an originally homogeneous earth in which uranium, thorium and lead were uniformly distributed. The isotopic composition of 'primeval' lead at that time was the same everywhere. As the earth became more rigid, small regional differences arose in the uranium/lead ratio. In any given region, however, this ratio did not change again except for the radioactive decay of uranium to lead. During formation of a common lead mineral, lead is separated from uranium and thorium, so that its isotopic composition thereafter remains constant. GEISS (1954) has presented a detailed mathematical formulation of this model.

The abundances of lead isotopes formed in accordance with the model are given by

\[ y - y_0 \]
\[ x - x_0 \]
\[ \frac{1}{137.8} \frac{(e^{\lambda_2 t} - e^{\lambda_1 t})}{(e^{\lambda_1 t_0} - e^{\lambda_2 t_0})} \]

where,

\[ x, y \] = measured \( ^{206}/^{204} \) and \( ^{207}/^{204} \) abundance ratios;
\[ x_0, y_0 \] = primeval \( ^{206}/^{204} \) and \( ^{207}/^{204} \) abundance ratios;
\[ \lambda_1, \lambda_2 \] = decay constant of \( U^{238} \) and \( U^{235} \);
\[ t_0 \] = age of earth (i.e. commencement of regional differences in the uranium lead ratio);
\[ t \] = time of formation of lead mineral (i.e. model age);
\[ \frac{1}{137.8} \] = present day ratio \( U^{235}/U^{238} \).

This equation can be solved for \( t \), provided that all the other quantities are known. The values for \( x_0 \) and \( y_0 \) are the abundance ratios in iron meteorites, measured by Patterson and co-workers (PATTERSON 1956). These values, together with abundance ratios of lead from modern ocean sediments and of lead from young, independ-
ently dated lead ores have been used by Patterson (1956) on the one hand, and by Holmes (1956) on the other, to yield ages for the earth \( t_0 = 4.55 \pm 0.07 \times 10^9 \text{y} \) and \( t_0 = 4.50 \pm 0.10 \times 10^9 \text{y} \), respectively. Thus all the quantities in equation (1) are known, except \( t \). 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 \( \frac{206}{204} \) vs. \( \frac{207}{204} \). Such a graph is known as a Holmes—Houtermans “isochron” chart.

The equations for calculating the ratios \( \frac{U^{238}}{Pb^{204}} \) and \( \frac{Th^{232}}{U^{238}} \) in the source of lead ores as follows:

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

where \( V_p \) is the \( \frac{U^{238}}{Pb^{204}} \) ratio at the present time, and \( x, x_0, \lambda_1, t_0 \) and \( t \) are the same as before.

Furthermore,

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

where \( K_p \) is the \( \frac{Th^{232}}{U^{238}} \) ratio at the present time and

\[
\begin{align*}
\lambda_1 &= \text{decay constant of } Th^{232}, \\
z &= \text{measured } \frac{208}{204} \text{ abundance ratio;} \\
z_0 &= \text{primeval } \frac{208}{204} \text{ abundance ratio;}
\end{align*}
\]

and \( x, x_0, t_0 \) and \( t \) are the same as before.

The actual constants used for the calculation of the Holmes—Houtermans model parameters in the present work are as follows:

- Primeval \( Pb^{206}/Pb^{204} \) ratio, \( x_0 = 9.50 \) (1)
- Primeval \( Pb^{207}/Pb^{204} \) ratio, \( y_0 = 10.36 \) (1)
- Primeval \( Pb^{208}/Pb^{204} \) ratio, \( z_0 = 29.49 \) (1)
- Age of earth, \( t_0 = 4.50 \times 10^9 \text{y} \).
- Decay Constant of \( U^{238} \), \( \lambda_1 = 1.541 \times 10^{-10} \text{y}^{-1} \) (2)
- Decay Constant of \( U^{235} \), \( \lambda_2 = 9.72 \times 10^{-10} \text{y}^{-1} \) (3)
- Decay Constant of \( Th^{232} \), \( \lambda_3 = 0.499 \times 10^{-10} \text{y}^{-1} \) (4)
- Modern Ratio \( U^{238}/U^{235} = 137.8 \) (5)


It was shown in a previous paper (Moorbath 1962) that the use
of these particular values in equation (1) resulted in excellent agreement between the calculated Holmes—Houtermans model ages of three suites of normal galena leads and independently determined, published, absolute age values of genetically associated igneous rocks. These three suites of lead come from i) the Hercynian (Permo—Carboniferous) granites of Devon and Cornwall, England ii) the Caledonian (Devonian) Shap Granite of Westmorland, England iii) the Permian Oslo igneous province, Norway. Consequently, this apparently self-consistent set of values is used again in the present work, although it is fully realised that small changes in the constants may eventually yield even more consistent model parameters (see, for example, Rama Murthy and Patterson, 1962; Richards, 1962).

3. Experimental Procedure

Isotopic measurements were carried out using a Metropolitan—Vickers MS—5 solid-source mass spectrometer with a 90°, 30.5 centimetre (12-inch) radius analyser tube. Electron multiplier detection was used throughout and a square-root-of-the-mass correction was applied to all abundance ratios to correct for multiplier discrimination. Lead sulphide, in finely precipitated and purified form, was used for the isotope measurements. The ion source was of the thermal emission type, using a tungsten triple filament.

Fuller details of the experimental and analytical procedures have been given elsewhere (Moorbath, 1962).

4. Tabulation of Isotopic Analyses

The isotopic abundance data for the thirty-seven galenas measured in the course of this work are presented in table 1, in the same order in which they are discussed in section 5. For each analysis the isotopic composition is reported in two ways; firstly, with $\text{Pb}^{204} = 1.000$ in the top line and, secondly, with the percentage abundance in the bottom line. The ratios $207/204$ and $208/204$ are also given, in each case multiplied by 100. The quoted errors signify twice the standard error for each series of measurements, representing a 95% confidence level. For about one-half of the samples duplicate runs were available, each consisting of 20—30 individual mass spectrometer scans. Duplicate runs were carried out at intervals of several weeks or months and in
Table 1. Tabulation

<table>
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<th>No.</th>
<th>Locality</th>
<th>204</th>
<th>206</th>
<th>207</th>
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<td>Ettedalsgrubene, Vegårdsheia, Aust-Agder</td>
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<td>22.54 ± 0.03</td>
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<td>16.98 ± 0.11</td>
<td>15.28 ± 0.10</td>
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<td></td>
<td>1.442 ± 0.006</td>
<td>24.49 ± 0.05</td>
<td>22.04 ± 0.05</td>
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<td>Jakobselven, Sørvaranger, Finnmark</td>
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<td>16.91 ± 0.10</td>
<td>15.25 ± 0.09</td>
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<td>1.432 ± 0.006</td>
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<td>21.84 ± 0.03</td>
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<td>25.03 ± 0.05</td>
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<td>1.389 ± 0.006</td>
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of Isotopic Analyses

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<th>208</th>
<th>(\frac{^{207}}{^{206}}) x 100</th>
<th>(\frac{^{208}}{^{206}}) x 100</th>
<th>Model Age (m.y.)</th>
<th>(\frac{^{238}U}{^{206}Pb}) (Vp)</th>
<th>(\frac{Th}{^{232}U}) (Kp)</th>
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<td>34.71 ±0.14</td>
<td>94.9 ±0.3</td>
<td>219.8 ±0.4</td>
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all cases agreed within the experimental error. Duplicate runs were averaged together, weighting each 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 parameters model age (in million years), $U_{238}/Pb_{204}$ ($V_p$) and $Th_{232}/U_{238}$ ($K_p$), the latter two calculated to the present time, are also given in table 1. The errors in the model ages are calculated from the experimental errors only. The average errors in $V_p$ and $K_p$ are in the range 0.10 to 0.15 and 0.05 to 0.10, respectively.

The validity of the Oxford isotope measurements has been established from a series of intercalibration and comparison analyses with different laboratories, some of which have been published in a previous paper (MOORBATH, 1962).

5. Regional Discussion of Lead Isotope Abundances

INTRODUCTION

The 37 galenas whose lead isotope compositions have been measured come from deposits of very varying economic importance. In sampling, the main object has been to provide a coverage, as far as possible, of the main metallogenetic provinces of Norway (see VOKES, 1958). The locations of the galenas sampled are shown on the accompanying map of Norway, Figure 1. Numbers appearing in brackets in the text refer to the numbers on this map.

The geological settings of the deposits which have been sampled are briefly described and lead isotopic compositions determined for each are discussed below. The galenas analysed come partly from specimens collected in the field by one of the writers and partly from
well-localized specimens in the collections of the Mineralogisk-Geologisk Museum, Oslo.

More detailed geological descriptions of the deposits will be found in the Appendix.

A. GALENAS FROM PRECAMBRIAN TERRANES

Of the three Precambrian galenas sampled, one comes from the extreme northeast of the country, namely the valley of the Jakobselv, the river now forming the border with the U.S.S.R. The other two come from deposits in the extensive Precambrian area of southern Norway, west of the Oslo province. All three galenas have isotope ratios which give Precambrian ages on the Holmes—Houtermans model, though obviously because of the immense interval of Precambrian time and somewhat sparse data on absolute ages in the Norwegian Precambrian, it is difficult to say whether or not the ages given by the lead isotope ratios represent the true age of mineralisation at the three localities.

The oldest model age is given by galena from the Espelands (Etterdals) deposit near Vegårsdhei, in Aust-Agder county (1). Age determinations on minerals from the Kongsberg—Bamble rocks in this area of the southern Norwegian Precambrian province (Neumann 1960) indicate that there was a major metamorphic event at about 900—1000 million years ago. There is, however, evidence of an even older event in the history of the area. This consists of a K—Ar age on biotite of 1345 m.y. from a locality near Arendal. Two other apparent ages might also be mentioned, from a locality in the Telemark area, some 60 km NNW of Espeland. One is a Re/Os age on molybdenite of 1560 ± 160 m.y. and the other is a K—Ar minimum age on
feldspar of $1620 \pm 120$ m.y. The lead isotope model age of $1510 \pm 60$ m.y. from Espeland may possibly be related to the latter ages and, together with them, could indicate an orogenic event with accompanying metallization in the southern Precambrian at about $1500-1600$ m.y. ago.

The model age of $920 \pm 80$ m.y. obtained for the galena at the Nordre Bygstøl (Drithol) prospect, Telemark (2) conforms with a number of other age determinations on minerals from both rocks and ore deposits in the Telemark area. Neumann (op.cit) reports that an age of 890 million years, obtained by Polkanov and Gerling on mica from the Telemark granite gneiss “is probably a fair approximation to the age of formation of the older rocks of this suite”.

The possibility therefore exists that an orogeny and metallization occurred in the Telemark area around 900 m.y. ago.

The galena from the Jakobselv, Finnmark, locality (3), is the only analysed representative from the large Precambrian areas of northern Norway (see, however, Gurrogaissa (26)).

The Precambrian Karelian rocks in this area of Norway have so far not been dated absolutely, but recent dating of granites from the same belt in Finland (Kouvo 1958; Wetherill, Kouvo, Tilton and Gast 1962) gives ages of round about 1800 m.y. Thus the model age of the Jakobselv galena, $930 \pm 80$ m.y., is considerably younger than the apparent age of the rocks in the area. It is, however, by no means a Tertiary age as was suggested on tectonic grounds by Haussen, (1926). There is the possibility of remobilized old lead being deposited in the veins in Tertiary times, but it seems more satisfactory, especially in view of the Finnish and Russian data (see below) to regard the lead model age as a concordant late Precambrian one, of the same metallogenic epoch as appeared possible for the Telemark deposits. It is interesting to note that Föyn (1945) considers that the numerous basic dykes in the Varanger region may have been emplaced in late Precambrian times. Thus the fissures now occupied by both the quartz veins and the basic dykes might possibly have been opened up in the Precambrian around 900 m.y. ago. This must remain only a possible suggestion at the present state of knowledge.

Kouvo and Kulp (1961) have published lead isotope data on two galenas from the neighbouring Petsamo area. The mean model age of the two samples is $930 \pm 100$ m.y. when recalculated with the constants listed in section 2. Vinogradov et al. (1961) have published
data on four leads from the Petsamo area and report model ages in the range 950—1000 m.y. However, it is only fair to point out that with the constants used in the present paper, their model ages would reduce to about 800 m.y.

Thus the extremely sparse data on Precambrian galenas, coupled with other age determinations and geological information suggest two possible Precambrian metallogenies, one in the Kongsberg—Bamble region at about 1600 m.y. ago, and the other in Telemark and in the Karelian rocks of the northeast at about 900 m.y. ago.

B. GALENAS FROM THE CENTRAL ZONE OF THE CALEDONIAN OROGENIC BELT

Sixteen galenas have been analysed from the Caledonian metallogenic province in Norway, which is undoubtedly the most important one in the country as regards lead deposits. With one exception the deposits sampled occur in schists of the Nordland facies in the counties of Nordland and Troms and all come from the northern half of the Caledonides, north of the Grong culmination. The lead-bearing deposits of the northern Caledonides are grouped into two main areas, that of southern Nordland (Helgeland) from about latitude 65° 30' N to about latitude 66° 20' N, and the Ofoten area on both sides of the Ofotfjord at about latitude 68° 30' N. These two areas include all but three of the deposits from which galenas have been analysed for this study.

Most of the main types of lead-bearing deposits in the Norwegian Caledonides are represented by the galenas analysed in this study. Geologically they fall into three main type-classes. The first and economically most important one comprises heavily pyritic zinc- and lead-bearing sulphide ore-bodies which lie apparently conformably to the layering of the enclosing metamorphic schists. The producing mines of Bleikvassli and Mofjell contain ores of this type, while the prospects at Malmhaugen and, possibly, Lille Tromsdal, are other representatives. The Swedish occurrences of Tjåter and Ropen (GRIP, 1950; WICKMAN et al, 1963) most likely fall into this class too. These latter deposits lie only some 50 km east of Bleikvassli and are classified by Wickman et al as "replacements in schists". The similar deposits on the Norwegian side are most likely pre- or synorogenic ores which have been folded and metamorphosed by the Caledonian orogeny.
Their ultimate origin is uncertain. Wickman et al relate the Tjåter and Ropen occurrences to the Flöttum type of Carstens, a correlation which has been made by one of the present authors in the case of Bleikvassli (Vokes 1962, p. 902).

The second type is represented by the deposits at Husvik, Tjøtta and at Ravnåsen, as well as by others not included in the present survey. Most of these deposits are of little economic importance. In this class, lead and zinc sulphides, with or without iron sulphides, occur in zones, often of considerable elongation, parallel to the layering of the enclosing metasedimentary rocks, which include limestones and calcareous schists. Calcisilicates are developed in these rocks along the ore zones and the sulphides occur as impregnations, veinlets and occasionally as massive bodies in the calcisilicate zones.

Such deposits have usually been considered as contact metamorphic types due to the proximity, often, of a "granite" massif. However, modern geological opinion is that many of these "Nordland granites" are the transformation products of sediments, rather than magmatic rocks, (see Strand, in Holtedahl 1960, p. 248). These "skarn" deposits may then well be products of the regional metamorphism of impure calcareous rocks in areas where granitization processes have been active. So far insufficient work has been done to determine whether or not the sulphides in these deposits are genetically related to the calcisilicates. Crosscutting relations shown often by the sulphides indicate that they are possibly somewhat later in age.

The third main type of Caledonian lead-bearing ores is represented by the three deposits from the Ofoten basin (Ofotbekken) area of northern Nordland and Troms; Vildalsfjell, Niingen and Djupvik. These small deposits consist almost solely of galena and zincblende and can in places be very massive, compact and rich. They are, however, limited in size and do not appear to offer great economic possibilities.

The remaining galenas from this zone come from deposits of varying types; from the true vein deposits of the old Svenningdal silver mines, from atypical lead-rich concentrations associated with the massive pyritic orebodies at Jakobsbakken, Sulitjelma and Björkåsen, Ofoten and from two small occurrences, Mosbergvik and Kirkerösten, which do not seem to fit into any of the above classes.

The emplacement of these ores has always been assumed to have
Simplified geological map of Norway
showing locations of analysed galenas
(Numbers refer to samples described in text)
been connected with the Caledonian orogeny, though in most cases there is little detailed evidence on which to base age relationships. With the exception of the Svenningdal veins, which are later, these deposits appear to have been affected, to varying degrees, by the Caledonian metamorphism and may have been emplaced at an early age during the orogeny.

The age of the Caledonian metamorphism in northern Norway is indicated by several K/Ar ages reported by Neumann (1960). A mica from the Bindal granite gave an apparent age of 405 m.y. Three biotites from the island of Langøy in Vesterålen gave 423, 430 and 450 m.y. respectively. A muscovite from the Bleikvassli ore body gave 395 m.y. (see also below).

The lead isotope ratios obtained fall into four groups based on their Holmes—Houtermans model ages. The first group, which contains six galenas, gives concordant Caledonian ages. The second group also comprises six galenas (from four deposits) which give model ages younger than Caledonian. The third group has only one galena, giving a negative model age (J-type anomaly). The fourth group comprises three galenas from a limited area, in which the lead isotope ratios yield ages apparently older than the age of the enclosing rocks (B-type anomaly).

(i) Galenas yielding Caledonian model ages

The only Caledonian galena analysed from rocks other than the relatively highly metamorphosed Nordland facies schists and gneisses comes from the small prospect known as Lille Tromsdal (4) in the Grong area of Nord-Trøndelag county. This area is one of the most important in Norway for massive pyritic ores yielding copper and zinc. Lead-bearing deposits are extremely rare. The country rocks are the relatively low grade metamorphic (greenschist facies) volcanic and sedimentary rocks of the so-called Trondheim facies, the area being separated from the type area of the Trondheim district by an erosional gap over the Grong culmination.

The model age of $420 \pm 70$ m.y. for the lead in the galena from Lille Tromsdal is in good accordance with a Caledonian age for the metallization.

At Ravnåsen (5) in Nordland county, some 18 km south of Mosjøen,
there occurs a sulphide showing of a type which seems to be quite characteristic for this part of the Caledonides. The sulphide mineralization occurs in a N—S striking, westerly-dipping belt of metalimestones and calcareous schists along the western side of the large quartzo-feldspathic gneiss massif of Reinfjell.

The model age of 420 ± 60 m.y. for the Ravnåsen galena lead accords well with a Caledonian age of deposition.

*Mo fjell* mine (6) on the outskirts of the town of Mo, is the only mine at present producing in the Nord-Rana area of Nordland. The present company commenced working in 1926, and up to the end of 1960 something over 1,200,000 tons of ore had been won, while known ore reserves are of the order 1 million tons.

The model age of 360 ± 80 m.y. given by the lead from Mofjell appears to be a normal Caledonian one. The area around the mine is one of higher metamorphic grade than prevails in the district as a whole. The country rocks are gneisses, probably of upper amphibolite facies, and the beginning of migmatisation can be observed in many places. It is not unreasonable to suppose that the model age corresponds closely to the age of this metamorphism.

The main ores of the Sulitjelma district, east of Bodø are practically free from lead but at *Jakobsbakken* mine (7) there occurs a galena-rich mineralization, bearing antimony sulphosalts, in the hanging-wall schists of the pyritic copper-zinc ore body. This “antimony rich” paragenesis has been described in detail by *Ramdohr* (1938) who identified over twenty minerals in it. Ramdohr considers the mineralization to be younger than the main ore at Jakobsbakken. The sample of lead yields a concordant Caledonian model age of 390 ± 70 m.y.

The analysed galea from *Björkåsen* mine (8) appears to bear a similar relation to the main ore as does the Jakobsbakken galena. The lead-rich parts occur mainly where the main pyritic ore bodies thin out, or, locally, around irregular quartz enrichments in these ore bodies. The galena is accompanied by chalcopyrite, zincblende and a bismuth bearing mineral.

The lead model age of 400 ± 80 m.y. agrees well with the usually accepted Caledonian age of deposition.

The galena from the small deposit at *Mosbergvik* (9) in the Balsfjord area of the county of Troms, yields a lead model age of 420 ± 90
Fig. 2. Plot of Norwegian Caledonian leads, $^{207}/^{204}$ \(\text{Pb}\) vs. $^{206}/^{204}$ \(\text{Pb}\):

- □ normal leads in Nordland and Nord-Trøndelag;
- ◇ normal leads in Ofoten—Troms—Finnmark;
- △ B-type leads;
- ○ J-type leads; (Note that the slope in this, and subsequent, figures is derived only from the J-type anomalous leads, marked ○).

For further details of this, and other, figures, see text.

m.y., which would indicate a Caledonian age for the emplacement of the lead-zinc mineralization at this locality.

The model ages of the six leads just discussed all lie within the experimental error and average $400 \pm 30$ m.y. Many undoubted Caledonian leads with similar model ages have been reported from the British Isles (Moorbath, 1962), from other parts of Europe and North Africa (Cahen et al., 1958) and elsewhere. Such leads are justifiably classed as isotopically ‘normal’ leads, irrespective of their mode of occurrence or genesis.

The mean $^{238}/^{204}$ Pb value for samples 4, 5, 6 and 7 is 9.06, very close, for example, to the overall value of 9.05 for Caledonian and Hercynian British leads. The values for samples 8 and 9 (see also Gurrogaissa, No. 25) are significantly higher, in the region of 9.5—9.6. There is little doubt that these northernmost leads from the Ofoten, Troms and Finnmark areas are derived from an environment with a significantly higher $^{238}/^{204}$ Pb ratio than the leads to the south, in Nordland and Nord-Trøndelag. This is also evident from Figure 2, in which samples 8 and 9 (and 25) lie significantly further along the 400 m.y. isochron than the southern group, indicating a higher $^{238}/$
Pb$^{204}$ value in the source rocks. On the other hand, the values for Th$^{232}$/U$^{238}$ lie close together for all six samples, averaging 3.90. This is a commonly observed value for isotopically normal leads.

(ii) *Galenas yielding model ages younger than Caledonian*

Galenas from four deposits in Caledonian rocks give model ages which are younger than a normally accepted Caledonian age. All four deposits are from the central Nordland region, the same area in which lie Mofjell and Ravnåsen. Geologically, there is no reason to suspect that the ages of these deposits are other than Caledonian and it is not easy to postulate a mechanism by which the leads could have become enriched in radiogenic isotopes that would not apply equally to Mofjell and Ravnåsen.

The zinc-lead-pyrite ore of *Bleikvassli Mine* (10), some 50 km due south of Mo i Rana is a massive, medium-grained type consisting dominantly of pyrite, with lesser zincblende, galena and pyrrhotite, and minor chalcopyrite, with a gangue of mainly quartz and muscovite. The massive sulphides occur as plates or thin lenses lying concordantly to the layering of the surrounding micaceous schists and gneisses. A recently completed study of the Bleikvassli ore (Vokes, in preparation) indicates that it is a recrystallised, pre- or synorogenic type which reached its present textural appearance and mineralogical composition during Caledonian mountain building processes. Under the circumstances it would be reasonable to expect a Caledonian model age. Nevertheless, the three galenas from the Bleikvassli ore which have been analysed give model ages of, respectively, 80 ± 70, 160 ± 60 and 160 ± 80 m.y., which almost certainly indicates slight contamination with radiogenic lead.

The small prospect called *Kirkerøstene* (11) lies some 30 km north of Bleikvassli. The very irregular, erratic mineralization comprises zincblende, chalcopyrite, galena and pyrrhotite.

On the whole the geological environment at this locality is very similar to that of the Bleikvassli area, except for the greater amount of granitic material. Again there appears to be no reasons to suspect that the mineralization is other than of Caledonian age and the model age of 230 ± 60 m.y. must be regarded as slightly anomalous.

The deposits, at *Husvik, Tjøtta* (12), lie some 25 kn WSW of Mo-
sjøen. The zincblende-galena ores occur along a zone of limestones and calcareous schists in parts of which calcsilicates have developed. The geological environment resembles that of Ravnåsen.

The model age of the Husvik galena is $90 \pm 70$ m.y., although the geological evidence would point to a Caledonian age for the deposits.

At Malmhaugen, in Plurdalen (13) in the Rana district of Nordland, some 20 km ENE of Mo, occurs a narrow zone of pyritic lead-zinc ore which appears to be of minor economic interest.

The Malmhaugen mineralization is interesting because of its striking similarity to the Bleikvassli ore, a type which is by no means common in Norway. The model age of the Malmhaugen galena is $20 \pm 80$ m.y. There is, however, no geological reason to believe that it represents a post-Caledonian metallization.

The six leads of this group are regarded as J-type anomalies, in which the amount of radiogenic lead added has not been sufficient to yield negative model ages. The actual model ages obtained are, therefore, only apparent and bear no direct relation to the age of mineralization. The calculated geochemical parameters will tend to be similarly affected. The characteristic isotopic variability between different deposits is another indication of anomaly. The leads in this group have been plotted in figure 2, but this is discussed in greater detail in section D below.

(iii) Galena yielding a negative model age

In the case of the galena from the old Svenningdalene mines (14), in Nordland county, some 30 km ESE of Mosjøen, the lead isotope ratios show a considerable enrichment of all the radiogenic components over those in the 'normal' Caledonian leads. This is a J-type anomaly in which sufficient radiogenic lead has been added to yield a negative model age.

The Svenningdalene mining area was based on vein deposits, the vein filling being mainly quartz and the main ore minerals argentiferous galena, tennantite-tetrahedrite and rare proustite. The veins may possibly be of very late Caledonian age; they could conceivably be even later. They are of interest as being the one of the few representatives of lead-bearing veins known in the Caledonides of northern Norway and for yielding such highly "anomalous" lead. As will be
seen later similar vein deposits in southern Norway also yield negative ages (see under F, below).

The Svenningdalen J-type lead is plotted in fig. 2 (see Section C below).

(iv) *Galenas yielding a model age older than Caledonian*

The galenas analysed from three deposits in the Caledonian metasedimentary sequence of the Ofoten basin of northern Nordland and southern Troms (see Torgersen 1935) all yield model ages which are much older than the accepted age of their enclosing rocks. These deposits constitute the only group investigated in the present survey which exhibit uniformity both of geological type and lead isotopic composition.

The *Vildalsjell* (15) and *Niingen (Niingstoppen)* (16) galenas from deposits north of Bogen yield leads showing model ages of 730 ± 70 m.y. and 760 ± 50 m.y. respectively. The galena from the *Djupvik* deposits (17) south of the Ofotfjord gives a lead model age of 830 ± 90 m.y. The mode of genesis of the Ofoten basin’s lead-zinc deposits is as yet unknown. They appear to be unrelated to any obvious granite or granitization and their stratigraphical “control” is striking — they are “conformable” deposits as far as the country rocks are concerned. These leads are undoubtedly of pre-Caledonian origin and were remobilized and redeposited during the Caledonian orogeny from the basement complex, which must be assumed to have had a locally low uranium lead ratio, or a low radiogenic lead content. Such leads are usually referred to as B-type leads, or ‘old’ leads, and have been described by CAHEN et al. (1958), RAMA MURTHY and PATTERSON (1961), MOORBATH (1962) and others. Since B-type leads frequently yield model ages which approximate to the age of primary mineralization, it is postulated that the basement rocks from which the lead was remobilised during the Caledonian orogeny had a minimum age of approximately 800 m.y. For further discussion, see section 6.

C. (i) *Galenas from deposits along the southeastern border of the Caledonides.*

Along the eastern and southeastern border of the Caledonian mountain chain in both Sweden and Norway there occurs a series of
lead-bearing deposits. In Sweden at least two of these deposits have formed the basis of significant mining operations, while others hold promising reserves of ore. GRIP (1960) has provided the latest account of the Swedish representatives of this class, together with a theory of ore formation to account for the class as a whole (see later). The deposits of this type in Norwegian territory have so far not been very thoroughly investigated.

The mineralization occurs at or near the sub-Cambrian peneplane, either in Eocambrian sandstones, basal Cambrian deposits or in faults in the Precambrian basement. The ore minerals occur as impregnations in sandstone, quartzite or weathered Precambrian rocks or in quartz and/or calcite veins or lenses in the Precambrian or in the immediately overlying rocks.

Of the galenas analysed in this investigation, three, from Krækkjeheia, Hardangervidda, from Bømarken, Slemmestad and from Tufsingdal, Femund, belong to the type occurring in vein quartz bodies directly related to faults in the Precambrian. Other deposits of this type are found in the Kirkeby area in Hakadal, 20 kilometres NNE of Oslo and at other localities in the Slemmestad area.

Two galenas, from Bråstadelven, near Gjøvik and from Løvbekken, Engerdal, come from impregnations in Eocambrian and basal Cambrian sandstones and are almost identical with the "type" deposits from the Swedish localities, Laisvall and Vassbo (see GRIP, 1960; TEGENGREN, 1962). Analyses of galenas from these last two localities have been included to show the overall similarity of lead isotope ratios in this type of deposit (samples S-1 and S-2). See also WICKMAN et al. (1963).

The most important result of the lead isotope analyses of these galenas is that, with one exception, they give negative model ages, i.e. they exhibit J-type anomalies. The exception is the most westerly of the deposits, at Krækkjeheia, Hardangervidda (18) which gives an apparently Permian model age of $250 \pm 70$ m.y. and may, indeed, have been mineralized in Permian times (SKJESETH and VOKES, 1957). In the area immediately to the west of Oslo, in the Slemmestad and Røyken districts, lead-zinc mineralization has been known for quite a considerable time (see REUSCH, 1884, pp. 106—107; SPJELDNÆS 1955, p. 113). According to Spjeldnæs considerable amounts of galena and other sulphides occur in the coarse Cambrian sediments of the
Røyken district, as well as in veins in the Precambrian rocks. He mentions particularly the occurrences at Slemmestad and at Dalbø (Bømarken = Bø mine in Røyken). At the latter locality (19) mining of the argentiferous galena had taken place on a small scale.

Spjeldnæs compares these deposits to those of the Swedish “Laisvall-type” and discounts a possible origin from the nearby Permian intrusives of the Oslo area. However, in view of the close proximity of these intrusives which are the source rocks of many lead-zinc deposits, a Permian age for the Dalbø galena cannot be discounted at the present.

In the Lake Femund area of central Norway, 145 kilometres southeast of Trondheim, lies a third representative of the vein type Caledonian border zone deposits. This is the one at Tufsingdal (20) which has been worked on a small scale for the silver content of its galena.

The two Norwegian representatives of the disseminated type which have been sampled are at the present time no more than mineralized outcrops in stream exposures and nothing is known of the size and average grade of the mineralization at these places.

The more easterly of the two localities is at Løvbekken, Engerdal (21) some 210 kilometres NNE of Oslo and only 5 kilometres west of the Norwegian—Swedish border (see Skjeeth, 1963). It lies only about 30 kilometres southwest of the producing Swedish mine at Vassbo, Idre, (S-2) the galena from which shows similar isotope ratios.

At Bråstadelven, Vardal, (22) only a few kilometres northwest of the town of Gjøvik on the western shore of lake Mjøsa, a similar outcrop of lead-bearing quartzite and sandstone has been briefly tested by a diamond drill hole.

It is a marked feature of the impregnation-type ores in this region that the host rock always appears to be a calcareous sandstone. This seems to account for the varying stratigraphic position of the mineralization (cf. at Vassbo the mineralization is in the Cambrian because the corresponding Eocambrian member is an impervious non-calcareous quartzite). For further discussion of these leads, see below.

(ii) Galenas from the vicinity of the Precambrian peneplane in northern Norway.

Three galenas from deposits in northern Norway have been analysed. Two of them give isotope ratios very similar to those in the deposits along the southeast border zone of the Caledonides while
the third galena yields a Caledonian model age. Geologically all three deposits appear to occupy similar positions with regard to the Precambrian/Eocambrian peneplane and it seems more than reasonable to assign a similar mode of origin and emplacement to them.

The first deposit lies in the basal Cambrian sediments just above the Precambrian unconformity, while the other two lie in vein structures in the Precambrian rocks in positions which are stratigraphically immediately beneath this unconformity.

The argentiferous lead-zinc deposits at Nasafjell (23) some 60 km northeast of Mo i Rana, which were first worked in the 17th century, lie actually in Swedish territory. However, part of the field does extend westwards across the international boundary and lead isotope analysis of galena from Nasafjell has been included in this study because of the similarity of the deposit to others in the border zone of the Caledonides. The lead isotopic composition of the Nasafjell galena also falls into the group being dealt with in this section, which seems to strengthen the similarity to the other deposits.

Wickman et al. (1963) also mention the similarity in isotopic composition between the Nasafjell lead and leads of the Laisvall type, but they point to "a different mode of occurrence and a different pattern of regional distribution in the orogenic zone". If, however, one considers that all these deposits (including the next two discussed below) have in common a location not far removed from the Precambrian unconformity, then it does seem that they fall into the same distribution pattern and that the similarities in isotopic ratios have a possible geological basis.

Morphologically too, the Nasafjell mineralization shows marked similarities to some of the vein-type deposits along the Caledonian border zone in southeast Norway, e.g., Krækkjeheia.

East and south of the town of Narvik, on both sides of the Norwegian—Swedish border there outcrops a large area of Precambrian rocks in the form of a tectonic window beneath the metasedimentary rocks of the Caledonides. A number of lead-bearing deposits occur within the area of the window. A galena from one of these, at Katterrattvann (24) almost on the Swedish border near the eastern edge of the window, yielded a negative model lead age (J-type anomaly). This is the most anomalous sample in the present study.

The small lead deposit at Gurrogaissa (25) in Finnmark county
lies in Precambrian rocks some 40 km ESE of the head of Porsanger-fjord. The deposit occurs in light- and dark-coloured garnetiferous gneisses of Precambrian age which are referred to the Lapland granulite zone of Eskola. These are overlain to the north by the basal conglomeratic quartzite and Hyolithus shales of the Caledonides. The Gurrogaissa deposit is thus only a short distance stratigraphically beneath the basal Cambrian sediments and corresponds almost exactly in geological position to similar deposits further south, e.g., Katterattvann, Bømarken and Krækkjeheia. However the lead isotopic composition of this galena is different from the others. It gives a model age of $470 \pm 90$ m.y.

D. GENERAL DISCUSSION OF CALEDONIAN LEAD ISOTOPE ABUNDANCES

The galenas from deposits along the central zone of the Caledonides in northern Norway, with the prominent exceptions of Svenningdalen (14) and the three deposits in the Ofoten basin (15, 16, 17) yield model ages which are either normal Caledonian or, to varying extents, younger. The same features are seen in the Swedish representatives from this zone, Tjåter and Ropen, reported by Wickman and his co-workers. There does not appear to be any geological reasons for the lead isotopic differences within the zone. No one particular type of deposit is characterized by any particular grouping of lead isotopic ratios. The lead-rich pyritic ores at Bleikvassli and Malmhaugen show younger, slightly anomalous lead, yet the lead from the Mofjell ore, which strongly resembles these, shows a normal Caledonian age. The skarn-type ore at Ravnásen yields a galena with a normal Caledonian lead isotopic composition, while in the galena from the similar ore at Husvik, the lead shows an excess of radiogenic components. At the present state of knowledge of these deposits, such isotopic differences must remain unexplained.

It may be however pointed out that most of these central Caledonian deposits, especially the Bleikvassli-Malmhaugen type belong to the "conformable" class of geosynclinal deposits as defined by Stanton and Russell (1959) and almost certainly originated in the Caledonian orogeny. Without going into the geological significance of the "conformable" class of ore deposits it can nevertheless be pointed out
that the Norwegian isotopic data do not in every case support Stan­
ton’s and Russell’s hypothesis that ore deposits of this type are char­
acterized by “ordinary” leads and that the model ages of these leads
may represent the true age of mineralization. In a number of cases the
model ages are too young, indicating small additions of radiogenic lead.

If one takes into account occurrences in both Norway and Sweden,
the lead-bearing deposits along the b o r d e r z o n e of the Cale­
donides stretch for a length of over 700 km. The deposits are charac­
terized by similar geological settings, similar mineralogy and, it now
appears, broadly similar lead isotope ratios. All the analysed galenas
from deposits of this type in both Norway and Sweden, with but two
exceptions in Norway, yield lead isotope analyses of the J-anomalous
type, i.e. they show an excess of radiogenic isotopes over the normal
ratios for Caledonian leads. It may be only fortuitous but the two
exceptions occur one at each extremity of the 700 km belt. In the
southwest the small deposit of Krækkjeheia (18) shows a Permian
model age. At the northeastern end the Gurrogaissa (25) deposit
shows a Caledonian model age. In between, all the leads are J-type
anomalous.

In the case of Krækkjeheia, the geological conditions point very
strongly to a Permian age of mineralization (SKJESETH and VOKES
1957) which seems to be supported by the isotopic evidence. It would
seem most in keeping with the facts to regard this deposit as an excep­
tion to the others, as a true Permian deposit which has been localised
at this particular place, and of different origin from the “anomalous”
leads. Against this may be set the considerable distance (120—130 km)
between the deposit and the edge of the Permian igneous province
of the Oslo region. An alternative view would be to regard the Krækkje­
heia lead as basically Caledonian with sufficient radiogenic addition
to give an apparent Permian model age.

In the case of Gurrogaissa it is quite possible that we have a case
of normal Caledonian lead without excess radiogenic addition.

Turning now to the problem of the J-type anomalies, it is clear that
these cannot be without genetic significance. Furthermore, any theory
of genesis must account for the whole of the mineralization along the
700 km border belt of the Caledonides.

GRIp (1960) in his paper on the lead deposits of the eastern border
of the Caledonides in Sweden considers that “any reason to look for
the origin of the mineralising solutions in the Pre-Cambrian basement hardly exists. It is more probable that they have come from the inner part of the (Caledonian) mountain range, from areas undergoing palingenesis at that time". Grip shows that the mineralizations are intimately connected with tectonic structures formed during the overthrusting and that the ore solutions have followed these structures, depositing minerals in pore spaces, in tectonically opened spaces, and as replacements.

The lead isotope analyses appear to substantiate this hypothesis of a distinct source for the solutions which deposited the Laisvall types ores, though of course they cannot prove or disprove a palingenetie origin for these solutions. Whatever their primary mode of genesis, ore forming solutions with a normal Caledonian lead isotope composition have most probably wandered, often for considerable distances, to reach the present sites of deposition in the border zone of the Caledonides and, in the process, have picked up radiogenic lead in the rocks on the way. In a general way, the degree of anomaly of a given lead may be expected to depend on such factors as the distance from the source to site of deposition, duration of transit, composition and age (hence radiogenic lead content) and thickness of individual rock units traversed, as well as on the decreasing amount of extractable radiogenic lead with time during continued passage of the ore solutions (STANTON and RUSSELL, 1959).

Fig. 2 presents the Caledonian lead isotope data in a plot of Pb\textsuperscript{207}/Pb\textsuperscript{204} vs. Pb\textsuperscript{206}/Pb\textsuperscript{204}. The J-anomalous leads lie closely along a straight line whose best fit has been determined by a least squares method. The extension of this line passes through the closely-clustered normal Caledonian leads on the 400 m.y. isochron, in particular samples 5, 6 and 7, which are from the southern part of the central Caledonian belt. It is lead of this isotopic composition which has picked up different amounts of a single radiogenic lead on its passage outwards to the border zones. It is noticeable that lead which has travelled only a short distance from the central regions (e.g. samples 10a, 10b, 10c, 11, 12, 13, 14) has picked up considerably less radiogenic lead than that which has travelled further out towards the border zones (e.g. samples 19, 20, 21, 32, 23, 24, S-1, S-2). However, as previously mentioned, distance is not the only factor which influences the degree of anomaly at a given site.
It is also evident from Fig. 2 that neither the normal leads from the northernmost parts of the Caledonian belt (No. 8, 9, 25), nor the B-type leads from the same general area (No. 15, 16, 17) lie anywhere near the origin of the anomalous lead line. These leads, with their characteristically higher $\text{U}^{238}/\text{Pb}^{204}$ ratio, are not directly related to the anomalous leads.

The slope of the anomalous lead line is 0.09635, which represents the $\text{Pb}^{207}/\text{Pb}^{206}$ ratio of the added radiogenic lead. Assuming an age of 400 m.y. for the Caledonian mineralization it is found that the maximum age limit for the rocks which supplied the excess radiogenic component is $1340 \pm 100$ m.y. No absolute ages of this magnitude have yet been found within the Caledonian belt or along its border zones, but it is well known that the outer mineralizations frequently occur in Eocambrian (or younger) rocks, sometimes demonstrably overlying a Precambrian granitic basement complex. On the Swedish foreland, east of the Caledonian border zone, a number of Precambrian absolute ages in the general range 1000—1800 m.y. have been reported (Magnusson, 1960). Presumably, some of these Precambrian rocks could underlie at least some parts of the Caledonian belt.

Fig. 3 is a plot of $\text{Pb}^{208}/\text{Pb}^{204}$ vs. $\text{Pb}^{206}/\text{Pb}^{204}$ for Caledonian anomalous leads. This shows a slightly greater scatter than the previous plot, as might be expected from the different geochemical coherence of uranium and thorium (which respectively give rise to $\text{Pb}^{206}$ and $\text{Pb}^{208}$) in the upper parts of the earth’s crust. The extension of the line again passes close to the normal Caledonian leads of the southern part of the belt (No. 4, 5, 6, 7), but, in analogy with fig. 2, the anomalous J-type leads are clearly not directly related to the normal or B-type leads of the northern area (No. 8, 9, 25, 15, 16, 17).

The best slope of the $\text{Pb}^{208}/\text{Pb}^{204}$ vs. $\text{Pb}^{206}/\text{Pb}^{204}$ line through the anomalous leads is 0.6733, from which it is possible to calculate the Th/U ratio in the rocks which supplied the excess radiogenic component. This turns out to be 1.9, which is considerably lower than the average crustal value of about 4, widely reported in the literature from direct analytical measurements on rocks and also from isotope analyses of normal leads from all over the world. Russell and Farquhar (1960b) have discussed several cases in which the Th/U ratios, calculated for rocks which supplied excess radiogenic lead to ore solutions, have differed widely from the average crustal value determined for the
source regions of normal leads. The reasons can be explained in terms of the different valencies and hence differing chemical properties and heterogeneous distribution of uranium and thorium under oxidising conditions in near-surface rocks, and also in terms of the different extractibilities of $\text{Pb}^{206}$ and $\text{Pb}^{208}$ from such rocks and minerals. Nevertheless, from the facts that the calculated Th/U ratio is only about one-half of the commonly accepted crustal average and that the scatter on the $208/204$ vs. $206/204$ is comparatively small, one may tentatively conclude that the crustal unit which supplied the excess radiogenic lead is enriched in uranium in preference to thorium.

It has been suggested that the Lower Palæozoic alum shales may have supplied the excess radiogenic lead to the ores along the Caledonian border zone. From the point of view of the age of these shales
there would seem to be no objection to this; they are certainly younger than the calculated maximum age of 1340 m.y. (see above). Few data are available regarding the Th/U ratios in the shales, but it is clear that U is in excess over Th.

The procedures used in this paper for calculating age limits and geochemical ratios from anomalous leads have been described by Russell and Farquhar (1960b).

E. GALENAS FROM THE PERMIAN IGNOUS PROVINCE OF THE OSLO REGION

The ore deposits directly connected with the Permian igneous province of the Oslo region are numerous, though generally small in size and of little economic importance at the present time. The comparatively rich ore occurrences gave rise to mining activities of some consequence as early as the middle of the 17th century. (Smaller workings are said to date back as far as the 12th century). Initially, interest was centred in the silver-bearing lead deposits of the area, but later ores of iron, copper, zinc, molybdenum and bismuth have been worked on varying scales.

All the mines and workings are disused at the present day and most of them are inaccessible. However, descriptions of many of them were published by J. H. L. Vogt (1884), while Goldschmidt (1911) described all the more important ones, many of which were still being worked at that time.

All the ores occur in close spatial connection with the magmatic rocks of the area, and Goldschmidt concluded that they were all contact-pneumatolytic, formed by the interaction of magmatic emanations with the enclosing sedimentary rocks, mostly limestones, more rarely, shales.

The Permian age of the Oslo igneous activity was determined as recently as 1931 through the discovery by Holtedahl of Permian fossils in the sediments just below the lavas. Neumann (1960, p. 181) tabulates a list of apparent ages determined on minerals from Oslo region rocks, without comment. The ages range from 355 to 216 m.y. Among them are two K-Ar ages on biotites from the deep eruptives of 259 and 284 m.y. respectively.
Four galenas from deposits in the Oslo region have been analysed, two from the Grua area yielding Permian model ages and one each from the Konnerudkollen and Lier areas, both of which yield a negative model age.

Of the Grua area galenas, that from Skjærpemyr (26) gave a model lead age of 260 ± 70 m.y., and that from Mutta (27) one of 240 ± 50 m.y. Both these deposits are of the contact metamorphic type, closely associated with the Permian igneous rocks of the area.

The Dalen mine (28) in the Konnerudkollen mining area, was developed on an ore-bearing porphyry dyke, which appears to have cut through a contact metasomatic deposit at depth and carried fragments of it upwards. The galena from this mine yields a lead model age of about zero m.y. Enrichment in the radiogenic lead isotopes may possibly have occurred during the rejuvenation of the deposit by the porphyry dyke, a quite late phase of the young Drammen granite, which is known to be radioactive in parts.

The small deposit at Bø in Lier (29) is a vein type deposit in a fault zone and may also be genetically related to the Drammen granite. The galena from this deposit yields a negative model age.

F. GALENAS FROM VEINS IN THE KONGSBERG—BAMBLE AREA OF THE PRECAMBRIAN OF SOUTHERN NORWAY

A number of vein deposits carrying galena, along with other ore minerals, occurs in the Precambrian rocks of the Kongsberg—Bamble area immediately west of the edge of the Permian province of the Oslo area. Structural features show that they are definitely post-Precambrian and most geologists have regarded them as of Permian age, and connected with the metallization of the Oslo province. The lead isotope compositions of four galenas from this class are markedly similar and seem to support the geological evidence for a common origin. All four samples are J-type anomalies, showing marked enrichment in the radiogenic isotopes of lead.

Three of the galenas analysed come from vein deposits in the Kongsberg area, while the fourth comes from the disused mining area at Tråk in Bamble, 10 km southwest of Porsgrunn.

The galena from Kronlokken prospect (30) some 3 km NE of Kongs-
Fig. 4. Plot of Norwegian Permian leads, $^{207}/^{203}$ vs. $^{206}/^{204}$.  
- normal leads;  
- J-type leads.

berg was selected as a representative of the earlier sulphide-bearing quartz-breccia veins of the Kongsberg area.

Galenas from Gottes Hülfe in der Not (31) and Bratteskjerpet (32) provided analyses of leads from the younger, formerly productive, veins showing the assemblage, calcite-native silver-nickel and cobalt arsenides. In places, for example, in Gottes Hülfe, the calcite veins intersect a quartz-breccia vein which is then often enriched in silver.

At Tråk, in Bamble, (33) the deposits consist of N—S striking quartz-breccia veins and seem to be very similar in geological characters, and possibly genesis, to the quartz-breccia veins of the Kronløkken type.

The Permian lead isotope data are presented graphically in fig. 4 which is a plot of $\text{Pb}^{207}/\text{Pb}^{206}$ vs. $\text{Pb}^{206}/\text{Pb}^{204}$. The anomalous lead line is based on only six points (No. 28, 29, 30, 31, 32, 33), but the overall scatter is not very great. The slope of this line, determined by least squares, is 0.08197. On the assumption that all the leads were emplaced 250 m.y. ago, it is found that the upper limit of the age of the rocks that supplied the excess radiogenic component is $1110 \pm 200$ m.y. In a general way this is consistent with the results
of absolute age determination in southern Norway. Thus, Neumann (1960) states that "two epochs have been more important than others . . . . one from 900 to 950 m.y. ago and another at 1100 m.y. ago. It is surprising that during the reconnaissance work done so far there has been no indication of rock-forming processes at times 1400 m.y. and 1800 m.y. ago, so common in other parts of the world, and also in areas not too far away." However, as mentioned previously, a few older ages have since been found in another part of Telemark and also near Arendal.

The extension of the anomalous lead line in fig. 4 passes through the locus of the three normal Permian leads (No. 18, 26, 27) which lie on the 250 m.y. isochron. It is clearly lead with this isotopic composition which has picked up excess radiogenic lead on its passage through the basement or lower supra-crustal rocks which underlie and surround the Oslo Graben.

A plot of $^{208}/^{204}$ vs. $^{206}/^{204}$ for the Permian leads (fig. 5) bears a close qualitative resemblance to fig. 4, except that the scatter is
greater, for reasons outlined in the previous section. A least squares analysis of the six anomalous lead points (No. 28, 29, 30, 31, 32, 33) gives a slope of 0.5313, which corresponds to a Th/U ratio of 1.5 in the rocks which supplied the excess radiogenic lead. This is much lower than the crustal average of about 4, but is close to the value of 1.9 which was calculated in the previous section for the basement rocks which supplied excess radiogenic lead to normal Caledonian lead. Furthermore, the respective maximum ages for the basement rocks calculated from the Caledonian and Permian leads respectively (1340 ± 100 m.y. and 1110 ± 200 m.y.) just lie within the errors. It is reasonable to postulate that the rocks underlying at least parts of the Caledonides and of the Oslo igneous province (and its surroundings) have approximately the same geological age and geochemical character.

6. General Discussion

The thirty-five isotopic analyses of Norwegian leads and two analyses of Swedish leads fall into three distinct categories:
1) Thirteen "normal" leads which yield model ages in good agreement with the absolute age of mineralization.
2) Three "B-type" leads which give model ages greater than the time of emplacement.
3) Six leads which give variable model ages younger than the age of emplacement and fifteen leads with very variable isotopic composition which all yield negative (future) model ages. These twenty-one leads are characteristic "J-type" anomalies.

A brief, general discussion of each group of leads now follows, with particular reference to the Norwegian leads.

i) Normal leads.

Normal leads, interpreted as such by various models, have been reported in large numbers from all over the world by many workers. They may be of any geological age and occur in almost any type of sulphide deposit, ranging from typical vein deposits to 'concordant' ore-bodies in metamorphic terrains. In general, the mode of occurrence in the field cannot be correlated with any degree of reliance with the type of isotope composition. It is, however, significant that most
normal leads are from deposits which occur I) in or near the centre of orogenic belts, II) in or near the centre of other major structural lineaments within in earth's crust, III) in or near areas of plutonic igneous activity. Frequently, of course, these categories overlap. The Norwegian normal leads occur in one or more of these categories.

At the present state of knowledge there is, unfortunately, no agreement on the fundamental reason for the existence of normal leads. Some workers consider that normal leads are derived from a source region, homogeneous with respect to uranium, thorium and lead, which they equate with the upper part of the earth's mantle (see Russell and Farquhar, 1960b). This hypothesis forms the basis of the Russell-Cummings-Farquhar and Russell-Stanton-Farquhar models for the interpretation of lead isotope abundances.

On the other hand, Shaw (1957) postulated that continual recycling of the materials of the earth's crust from the earliest times, with repeated crustal homogenization, could equally well account for the existence of normal leads.

This paradox arises because average values of the geochemical ratios Pb/U and Th/U in acidic and intermediate igneous rocks (granites, granodiorites, etc.), as well as in certain sediments which probably represent a crustal average, do not appear to differ significantly from the ratios found in basic igneous rocks such as gabbros and basalts, which may represent the uppermost mantle. The average Pb/U value for acid and basic igneous rocks is in the region 6—7, whilst the average Th/U ratio is about 4. These Pb/U and Th/U values are in the same range as those calculated from the isotopic composition of normal leads from all over the world. A further discussion of this topic, with detailed references and a summary of published analytical data, has been given elsewhere (Moorbath, 1962). Further progress on this important problem will undoubtedly be made when much more analytical data on the uranium, thorium and lead content of rocks becomes available, and when an overall lead isotopic growth curve can be measured directly on basic igneous rocks of all geological ages. At the present time, therefore, the common lead method cannot be used to decide unambiguously between a crustal and a mantle origin for normal leads.

A self-consistent and plausible choice of model parameters quite often yields good agreement between the model ages of a given lead
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when calculated both from the Russell et al models and from the Holmes—Houtermans model (MOORBATH, 1962; RICHARDS, 1962). Nevertheless, with a given set of model parameters, the Holmes—Houtermans model does allow for slight, but significant regional differences in the Vp and Kp ratios of the source regions of normal leads. These differences can be calculated from the normal lead isotope data and there is little doubt of their reality on a regional scale. The average Vp value for the southern group of normal Caledonian leads (No. 4, 5, 6, 7) is 9.06, whilst for the northern group (No. 8, 9, 25) it is 9.53. The error in these values is ± 0.15 at the most. The average Vp values for the normal Permian leads (No. 18, 26, 27) is 9.17, possibly identical with the Caledonian value, within the limits of error. The average value for the Precambrian leads (No. 1, 2, 3) is 8.71. In addition to regional differences of this type, there may also be a superimposed correlation between Vp and model age (MARSHALL, 1957).

Any theory of lead ore genesis will have to take these regional variations into account. In the case of a crustal origin, the regional variation in Vp would imply that the overall Pb/U ratio for a given mountain belt or geochemical province could remain more or less constant or 'homogenised' throughout geological time (SHAW, 1957; MOORBATH, 1962). In the case of a mantle origin, the variations would point to the existence of slight regional geochemical differences.

The variations in the Kp values are not so well-marked or consistent, although small regional (and local) differences certainly exist. The mean value of Kp for all normal Norwegian leads in this paper is 3.88, which agrees well with the average value of 3.95 found in the British Isles.

ii) 'B-type' leads

Since B-type leads yield model ages greater than their age of emplacement it has been suggested that they represent older ore-lead, or rock-lead, which was subsequently remobilised, transported and emplaced elsewhere (CAHEN et al., 1958). Without further evidence it is not strictly correct to refer to all such leads as 'anomalous' and confusion has arisen in the literature because of this terminology. A clarification of existing terminology is proposed at this stage, consisting of a division of B-type leads into two principal groups.

a) Normal B-type leads, in which the model age represents the
true age of primary emplacement. Such leads have a normal isotopic composition and are considered to have been remobilised, transported and re-emplaced at a later date without change in isotopic composition. In other words such lead is not contaminated with lead of any other isotopic composition during transport to the site of secondary emplacement. It would be characterised by normal and homogeneous isotope compositions within a single deposit, or within a group of related deposits, and would give a plausible and self-consistent set of model ages and geochemical model parameters for the primary mineralization.

b) Anomalous B-type leads which show evidence of contamination with younger normal and/or radiogenic lead during transit from the primary to the secondary site of emplacement. Such leads will be expected to yield variable model ages and geochemical ratios from within a single deposit or within a series of genetically related deposits, provided that large-scale mixing has not occurred or is incomplete. The calculated model age will be less than the true age of primary emplacement and greater than the age of secondary emplacement. Leads of this group will, in general, bear the same relationship to normal B-type leads, as J-type leads do to ordinary normal leads. There is evidence from the fairly scanty literature on this particular topic that many B-type leads belong to the second group. This is in good accord with the assumption that the production of B-type leads is a supracrustal phenomenon.

Let us discuss the three Norwegian Caledonian B-type leads (No. 15, 16, 17) from the Ofoten area. They are considered to belong to the second group of B-type leads since the model ages and in particular the geochemical ratios exhibit some scatter. Nevertheless, several tentative deductions may be made from these leads:

1) Primary emplacement of these leads occurred at least 830 ± 90 m.y. ago (No. 17). Consequently this is also a minimum age for the rocks immediately underlying this part of the Caledonides, from which these leads were remobilised. It is quite possible that these basement rocks fall in the same general age range as those further east, for which a maximum age of 1340 ± 100 m.y. was calculated from the $^{207}/^{204}$ vs. $^{206}/^{204}$ plot of Caledonian leads (fig. 2).

2) These three B-type leads are probably related in some way to the three normal Caledonian leads of this northern region (No. 8, 9,
It was pointed out previously that the latter have a significantly higher average Vp ratio (9.53) than the Caledonian leads of the southern group (9.06). All six leads lie well above the main $^{207}/^{204}$ vs. $^{206}/^{204}$ line of fig. 2 and there is at least a hint of a crudely linear relationship between them. Despite the scatter and probable slight anomaly, the mean Vp value for the three B-type leads is 9.48, which agrees well with the mean Vp value of 9.53 for the normal leads of this northern province. The Kp values for the two groups of three leads are respectively 4.01 and 4.02, that is to say virtually identical.

It is tempting to postulate that in this comparatively restricted region of the Caledonian mountain belt we may actually be witnessing older leads in the process of being "made over" or "homogenised" into normal leads, but due to certain local geochemical and or structural peculiarities this was not achieved in this particular case. Hence the isotopic composition of leads 15, 16 and 17 remained partially "fossilised". If a complete and continuous transition between B-type leads and normal leads could be conclusively demonstrated in this, or other, areas, it would be strong evidence that normal leads could be produced, in at least some cases, within the crust. The abnormally high Vp ratio in this area might itself be an indication of a crustal origin.

3) In analogy with normal leads, a survey of published data indicates that B-type leads may be found in almost any type of ore deposit and in most types of geological or tectonic environment. The essential conditions for their production are that a) lead has been remobilised from an older crustal source and re-emplaced, b) the section of the basement complex through which the lead travels, or with whose lead it is mixed, has a lower mean U/Pb ratio than average crustal rocks, or is locally deficient in available radiogenic isotopes.

iii) 'J-type' leads.

The principal feature of interest that emerges from the present study and that of Wickman et al (1963) is the existence of a major province of J-type lead deposits in Norway and Sweden along the outer areas and border zones of the Caledonian mountain belt. This is the first such province yet described from Europe.

It was suggested earlier that normal Caledonian lead produced in the central parts of the Caledonides migrated east- and south-east-
wards, sometimes as much as 200 km, becoming progressively contaminated with different amount of a single radiogenic lead produced in rocks not older than 1340 ± 100 m.y. Lithological and tectonic factors determined the site of final deposition, producing major ore deposits in several cases. The relationship of regional geological structure to lead isotope composition is conclusively demonstrated in this case.

An analogous situation is found in the Oslo Permian graben, a major tectonic and igneous province. Normal Permian lead produced within the province (either by derivation from the upper mantle or by crustal homogenisation) has migrated outwards — even into the Precambrian rocks surrounding the graben — and become progressively enriched in radiogenic lead, produced in rocks whose maximum age was 1110 ± 200 m.y.

A similar close correlation between lead isotope composition and a major crustal lineament has been described by Slawson and Austin (1962) from the Western United States. Normal leads (as well as two B-type leads) are found along the axis of a lineament, which is bounded on both sides by J-type anomalous leads. The general interpretation of the above workers is very similar to that presented in this paper for the Norwegian occurrences.

Three J-type provinces have been described by Russell and Farquhar (1960b) from Canada and Australia, although the relationship between the normal and anomalous leads does not appear to be structurally so clear-cut, on a regional scale, as in the cases described by Slawson and Austin and in the present work.

The Mississippi Valley lead ores constitute by far the greatest J-type anomalous lead province yet described (Bate and Kulp, 1955). It is to be hoped that these results will soon be published in detail. As far as the present authors are aware the lead isotope anomalies have not yet been correlated with any major structural lineament. Nevertheless, Bate and Kulp point out that the Mississippi Valley ores are deep-seated and are not derived from the enclosing Palaeozoic sediments, since the variable excess radiogenic lead component was extracted from ancient Precambrian rocks.

It is interesting to note that Grip (1960) draws a close analogy between the Mississippi Valley deposits and those along the eastern border of the Caledonides. Nevertheless, he also makes comparisons with certain lead deposits in Germany and Britain which definitely
yield normal isotope compositions. Clearly, there need not necessarily be a direct connection between mode of field occurrence and type or degree of anomaly. In the present work, for example, J-type anomalies have been found in deposits as diverse as in some of the ‘concordant’ deposits of the Bleikvassli type near the central part of the Caledonides (although, admittedly, the anomalies here are very small), in the vein deposits near the western border of the Oslo Permian graben, and in the low temperature impregnation and dissemination deposits along the eastern border of the Caledonides. Evidently the production of J-type lead is more directly dependent upon certain tectonic, structural and geochemical criteria which permit lead-containing ore solutions to extract excess radiogenic lead from the country rocks which they traverse.

7. Acknowledgments

The present study arose out of discussions by the authors regarding the desirability of a survey of the lead isotope ratios in Norwegian galenas. Due to the limited number of analyses it was possible to carry out, the survey must be regarded as being in the nature of a detailed reconnaissance. It is believed, however, that the study has pointed towards certain solutions of the genetical problems connected with the emplacement of lead-bearing ores in Norway.

The contribution of the first author forms part of the programme of age and isotope studies in progress at the Department of Geology and Mineralogy, Oxford University under the general direction of Professor L. R. Wager.

The contribution of the second author forms part of a general programme of research on Norwegian minerals and mineral deposits, sponsored by Norges teknisk-naturvitenskapelige forskningsråd and carried out at the Mineralogisk-Geologisk Museum, University of Oslo.

The sincere thanks of both authors are due to Professor Wager for the provision of facilities at Oxford and for his help and encouragement; to Professor T. W. F. Barth and Dr. H. Neumann for permission to work on the problem at Oslo; to them and to other Norwegian colleagues for discussion of the geological problems arising from the isotopic results; and to Mrs. H. J. McArdle, Oxford, Miss. I. Lowzow, Oslo and Mr. R. W. Goodwin, Oxford, for technical assistance, draughting and typing.
8. Appendix

ADDITIONAL GEOLOGICAL DESCRIPTION OF THE DEPOSITS MENTIONED IN THE TEXT.

A. Precambrian deposits.

1. Espelands (Etterdals) deposit.

The deposit occurs in gneisses of the Kongsberg—Bamble region, close to the southern boundary of the Vegårdshei porphyric granite body. According to J. H. L. Vogt (1886, pp. 58—9) these gneisses are impregnated with sulphide minerals over a strike length of about 2 km, the main metallic mineral being argentiferous galena (0.25—0.65% Ag), as well as zincblende, pyrrhotite and arsenopyrite. The width of the mineralization is of the order of 1 metre. Vogt emphasizes that the mineralization appears to keep in the same horizon in the gneisses, at an almost constant distance from the granite border. It thus appears to be a deposit of the “fahlbånd” type, so very common in the southern Norwegian Precambrian region. Oftedal (1942, p. 64) describes what he regards as “exsolution” bodies within the galena crystals in certain parts of the Espeland deposit. Apart from pyrrhotite, sphalerite and chalcopyrite, there occur at least four or five other minerals, all of which Oftedal was not able to identify. Those he tentatively identifies are schapbachite (matildite), native Bi and pyrargirite. Analyses by this author show nearly 2 per cent Bi and 1.0 per cent Ag in the Espeland galena.

2. Nordre Bygstøl (Drithol) prospect.

The prospect lies towards the centre of the Telemark metalliferous district, on the north side of Lake Bandak, some 11 km NW of Kviteseid and about 80 km NNW of the Espeland deposit.

The area contains chiefly a series of copper deposits, but in addition there are a number of molybdenum deposits, and minor lead, bismuth and antimony ores, often somewhat silver-bearing, very rarely auriferous. The vast majority belong to a single geological type, ore-bearing quartz veins or granitic dykes occurring in a belt along the border of the Telemark granite-gneiss which forms the southern boundary to the Telemark suite of supracrustal rock (see Dons, 1963).

According to Dons (op. cit. p. 23) the deposit consists of several parallel quartz veins which carry galena, chalcopyrite, minor hematite and tetrahedrite-tennantite, together with traces of bornite. The veins strike NNW or N and dip steeply to the east. The main vein reaches a maximum width of up to 2 metres towards the southern end of the workings and is also richest in ore minerals at this end. The surrounding country rocks are mainly granitic gneisses, with in parts inclusions of amphibolite and some quartzite. The deposit was probably known in the early 1880s, and exploratory working took place in 1887, without any economically encouraging results.

Vogt, (1886a, p. 25) gives a figure of 0.03—0.04 percent for the silver content of the galena from Nordre Bygstøl.

The deposit forms one of a group of lead-zinc ores, which occur along the Arctic coast in both Norway and U.S.S.R. Hausen, (1926, pp. 96—97) has described the geology of the deposits occurring in the former Finnish Petsamo territory.

According to Hausen the deposits are younger than all the rock formations in the area and occur as numerous continuous, steeply dipping, sulphide-bearing fissure veins striking mainly NE. He links them structurally with Tertiary tectonic movements of the Varanger area.

The gangue minerals are mainly quartz and carbonate, as well as barite, while the sulphides are mainly galena and sphalerite with minor amounts of chalcopyrite and pyrite.

The exposed strike lengths of the veins can vary from a few tens of metres up to nearly 2 kilometres, while the widths vary from a centimetre or two up to over half a metre.

Various attempts were made to work these deposits prior to 1926, but were unsuccessful partly, according to Hausen, because the individual veins lay isolated from each other and partly because of the erratic and sparse occurrence of the ore minerals in the mainly siliceous vein-filling. The sulphides occur as veins, or as spots or lenses in the gangue minerals. The galena is partly quite fine-grained and partly coarsely crystallized. It is apparently very poor in silver.

B. Deposits in the Central zone of the Caledonian orogenic belt.

4. Lille Tromsdal prospect, Grong area, Nord Trøndelag.

The Lille Tromsdal prospect lies in greenstones and green-schists on the high ground west of the southernmost of the two large lakes of the Grong area, Tunnsjø. According to Oftedahl (1958, p. 39, No. 46) there is a zone of low grade banded iron ore, together with an irregular body of “blue quartz” in the greenstone in a small stream exposure. The banded iron ore is partly impregnated with pyrite, which also appears as an irregular dissemination in the quartz, in parts with notable chalcopyrite and locally, with galena and sphalerite. The strike length of the zone is about 350 m and it is of no economic importance.

Oftedahl considers that Lille Tromsdals prospect together with another small showing at Borvasselv (Nr. 15 in his list) northeast of lake Limingen, represent transitional types between the massive pyritic copper-zinc bearing ores of the Grong-Løkken type and the pyritic lead-zinc ore of the Nordland type1 (see below). A third representative of this type in the Grong area which may also be mentioned, is a small prospect known as Godejord’s (115 in Oftedahl’s description). Specimens from this prospect in the Geologisk Museum, Oslo, (collected by S. Foslie) show pyrite, chalcopyrite, galena and zinc blende in a gangue of calcite and barite.

1 It may also be remarked that these deposits show marked similarity to the Fløttum type described by C. W. Carstens (1935, pp. 20—21) from Fløttum mine between Trondheim and Røros.
5. Ravnåsen, Mosjøen district, Nordland.

The somewhat erratic and low grade sulphide mineralization at this prospect has been exposed in a series of trenches and pits over a length of nearly 3 kilometres. The width of mineralized rock in the best exposures can reach 2 metres, but in many places it is not more than a few centimetres (Torgersen, 1928, pp. 14–18).

The mineralization consists of mainly sphalerite, with lesser galena and minor chalcopyrite. Very occasionally individual grains of pyrrhotite may be observed. The dominant sphalerite occurs as strips, veins or irregular patches, very erratically distributed. As a whole the sulphide bearing zone lies parallel to the layering of the surrounding rocks and to their contact with the concordant granite gneiss mass to the east.

Calcsilicates are developed in the enclosing limestones, mainly green dipsoide a pale garnet and in places, tremolite. Calcite and some quartz are the other main gangue minerals.


The geology of Mofjell mine has been touched on by among others, Torgersen (1928, pp. 23–30) and Bugge (1948, pp. 114–115). The ore-bearing zone has an E–W extension of 2–3 km, but the horizontal width of workable ore usually does not exceed 100–200 metres. The sulphides occur at several different levels and were originally referred to as "lenses", there being three principal "lenses" lying one above the other. Recent work has indicated that in part at least there is a continuous connection between these lenses and that in effect the ores may be part of one originally continuous layer which was later folded to give the appearance of three separate ore-bodies.

Whatever the genesis of the ores, the sulphides occur as extremely elongated, narrow, thin bodies which lie perfectly parallel to the lineation in the surrounding gneisses (see Vogt, 1944). In the westerly part of the mine the plunge is eastwards at 5–10°, but to the east it flattens considerably and appears even to be reversed in direction.

The ore minerals at Mofjell are pyrite, sphalerite, galena and chalcopyrite and in parts pyrrhotite. Barite is quite abundant at times. The ore varies in character from massive to disseminated. In 1961 70,000 tons of ore were beneficiated, with an average grade of 0.35% Pb, 0.40% Cu, 4.50% Zn and 10.0% S.


The ore deposits of the Sulitjelma area, in Nordland County at about 67°10' N latitude, form one of the more important and famous mining fields of Norway. The ores yield copper, zinc and pyrite concentrates and occur as flat, plate- or lens-like forms concordant with the layering of the enclosing schists. The reader is referred to the publication of Th. Vogt (1927) for an account of the geology of the area.
Literature on the ore deposits is widespread, but no detailed descriptions of the orebodies have as yet been published. The question of their genesis has been discussed by, among others, J.H.L. Vogt (1894), Foslie (1926, pp. 109—114), Carstens (1935), Kautsky (1953) and Krause (1956).


Foslie (1926, pp. 114—117) describes briefly the geology of the main ore at Bjørkåsen. The ore lies in a thick series of garnetiferous mica schists, partly bituminous, belonging to the lowest group of the metamorphosed Cambro-Ordovician sediments of the area. These schists enclose important bodies both of gabbroic and of granitic rocks. These bodies as well as the ore have a concordant attitude to the schistosity. According to Foslie the ore occurs towards the margin of a rather thick lens of (now schistose) basic rock, and is apparently directly connected with this rock. The ore is regarded as being younger than the granitic rocks and is often accompanied by a marked sericitization of the enclosing schists and, in parts, of the granite.

Mineralogically the main ore is rather homogeneous, consisting of coarsely crystalline pyrite cubes in a quartz ground-mass. The wall-rock contacts are usually quite sharp. Chalcopyrite, pyrrhotite and zincblende occur in small amounts, especially where the ore zone wedges out, or where it thickens up. Since 1932 copper and zinc concentrates have been produced by differential flotation. Up to about 1940 about 250,000 tons of ore were broken yearly at Bjørkåsen, but more recently the amount has been about half this.

Lead is not an important component of the Bjørkåsen ore (Foslie quotes 0.12% Pb in “richest ore”), but in places galena, along with chalcopyrite, and zincblende occurs in megascopic amounts. Oftedal (1941, pp. 57—61) describes one such enrichment of galena from the border zone of a large quartz mass enclosed in the ore body. The galena contained 0.3% Ag and was accompanied by a lead-bismuth mineral (galenobismuth?). Similar enrichments are also stated to be usual where the main ore zones thin out. Oftedal interprets them as low-temperature parageneses, (cf. Ramdohr’s interpretation of the lead-antimony mineralization at Jakobsbakken).


According to Torgersen (1935, p. 44), this prospect was first staked in in 1933, but until recently little or no work had apparently been carried out on the deposit.

Very few details are available regarding the geology, but the deposit appears to be a steeply dipping breccia filling in crystalline limestone, the ore minerals comprising dominant sphalerite (iron-poor), galena and lesser pyrite, chalcopyrite and pyrrhotite.

The Geological Survey of Norway (NGU) recently conducted prospecting operations at Mosbergvik, including diamond drilling, with rather disappointing results.

The massive pyritic ore at this mine is at present supporting a yearly production of some 7,000 tons of zinc concentrate, 3,400 tons of lead concentrate and 25,000 tons of pyrite concentrate, making it the biggest producer of lead-zinc ore in Norway, at the present time. The medium-grained pyrite-zincblende-galena-pyrrhotite-chalcopyrite ore occurs as plates or thin lenses, varying in thickness from a few centimetres up to 15 metres, lying concordantly to the foliation of the surrounding crystalline schists and gneisses. The gangue minerals consist mainly of quartz and muscovite and constitute less than 30 wt per cent of the ore. In lesser, often trace, amounts occur arsenopyrite, lead-arsenic-antimony sulphosalts, tennantite, stannite and cassiterite.

In places a pyrrhotite-rich type of ore occurs along the foot-wall of the massive pyritic ore. This ore is enriched in copper over the pyritic ore.

The ore has obviously been involved in metamorphism and folding during the Caledonian orogeny and the ore texture appears to be a metablastic one. At present the ultimate origin of the ore remains unsolved.


This small deposit has been described by Torgersen (1928, pp. 30—33). The mineralization is exposed over a strike length of some few tens of metres and occurs in a zone of tightly folded garnet amphibolite and biotite-quartz schist. The sulphide zone lies apparently concordant to the layering of these schistose country rocks. The sulphides present are zincblende, chalcopyrite, galena and pyrrhotite in very variable amounts and they occur as irregular small veins, as "splashes" and as irregular disseminations in the schists along the zone. The geology of the surrounding area is not very well known, but the rocks consist mainly of micaceous schists and gneisses of the Nordland facies, often with considerable amounts of migmatitic pegmatites and other granitic bodies. Crystalline limestones occur in Bjerkadalen to the south of Rostafjell.


These deposits have been known since about 1897, and trial workings have taken place there at various periods in the past (see Torgersen 1928, pp. 42—51). The ores occur along a N—S striking zone over a length of 3 to 4 km, with the most important deposits occurring in the southern kilometre or so. The ore exposures seem to occur in a continuous zone following a band of crystalline limestone which reaches 40 to 50 metres in thickness. The ore lies partly in the limestone, and partly along the junction with the adjacent schists. Gneissose granite of the Nordland type occurs immediately to the west of the ore zone, the intervening country being composed of mica- and hornblende schists, with injections of porphyritic granite. The deposits occur as concordant bands following the strike and steep westerly dip of the limestone. The ore is generally medium- to coarse-grained, mainly zincblende and galena, with minor quantities of pyrrhotite, chalcopyrite and in places, arsenopyrite. The gangue minerals comprise quartz, mica, hornblende, garnet, calcite and epidote.
Torgersen calculated ore-reserves of the order 100,000 tons in the Husvik field, but from the work done up to date it does not appear that its economic prospects are very great.


Outcrops of a weak to moderate pyritic lead-zinc mineralization have been exposed by shallow trenching along a strike length of some 230 metres. The outcrops lie a short distance to the east of the small pyrite mine of Malmhaugen (see Foslie, 1926, pp. 105—107) and apparently on the same general line of strike. Diamond drilling from the surface has not revealed anything of economic interest.

The Malmhaugen lead-zinc zone strikes SE and dips at about 30—40° to the southwest. The wall rocks are crystalline limestones and micaceous schists, which are complexly and tightly folded. The sulphide zone appears to lie generally conformably with its country rocks and its very variable thickness seems to be dependent on the degree of folding in them.

The mineralization varies from disseminated to massive or compact, the latter type being indistinguishable in hand specimen from the massive Bleikvassli ore. As in the latter ore, pyrite is the dominant ore mineral, the others being zincblende, galena and pyrrhotite. As often at Bleikvassli, too, the compact ore bands at Malmhaugen, generally not exceeding 10—20 cms in thickness show a division into a dominantly pyritic ore in the hanging-wall and a pyrrhotite rich ore along the foot-wall.


These formerly productive silver-bearing deposits, which in the years 1870—1900 yielded about 20 tons of silver and 37 kg of gold, have been described in detail by J. H. L. Vogt (1886b, 1900, 1902).

The veins cut almost at right angles a N—S striking belt of crystalline limestones, schists and gneisses lying along the eastern flank of the large granite-gneiss massif of Reinfjell. This massif, typical of the Nordland type of concordant granitic gneisses has a N—S length of about 50 km and is up to 10 km wide at its widest, in its northern half. In the Svenningdal area, towards its southern termination, it is no more than two kilometres across from east to west. In this area the massif is composed of a medium- to coarse-grained white to grey plagioclase-microcline gneiss carrying both biotite and muscovite. Its junction with the enclosing metasedimentary rocks is quite concordant with the latters’ schistosity and with its own marked gneissose foliation.

The Svenningdal field has a N—S extent of about 1 km and contains between 15 and 20 separate veins, some of which have lengths of 200—400 metres. The veins vary considerably in width, from a few centimetres up to over 1 metre, but the most usual width is 0.1—0.25 m. The veins are mainly quartz-fillings, showing very little banding and drusy structure, but brecciated masses of the wall-rocks are occasionally important. They lie parallel to each
other, striking E—W and dipping to the north around 60°, thus cutting the metamorphic rocks almost at right angles.

The main ore minerals are galena (with a variable silver content — from, roughly, 0.2% to 0.8%) tennantite-tetrahedrite (very variable silver content, but usually around 3 to 4 per cent; sometimes up to 10—20 per cent) and proustite (rare). Other sulphides are zincblende, arsenopyrite, stibnite, chalcopyrite, pyrite and pyrrhotite.

**Deposits in the sedimentary succession of the Ofoten basin, Nordland and Troms.**

In the Ofotfjord area the sedimentary sequence of the eugeosynclinal Nordland facies has been folded into a wide basin-like structure (Ofotbekken) which closes in the Håfjell area south of the fjord, widening to the east and north in the vicinity of Bogen and probably closing again in the mountainous area of southern Troms further north (see Strand, in Holtedahl, 1960, pp. 163—5; Foslie, 1949; Vogt, 1941).

The sequence is apparently continuous, without important tectonic breaks and with very little granitization or granitic intrusions, except in the upper part. The sequence consists of a lower part with mainly mica schists and an upper part in which limestones are predominant. A Cambro-Silurian age has been assumed for these rocks, but this cannot be proved due to lack of fossils.

The lead-zinc deposits under consideration here occur in the upper part of the Ofotbekken sequence within the large NE-plunging, synclinal structure, Håfjellsmulden or Håfjell syncline. They appear to be related very intimately to the layering of the metamorphic rocks in which they occur, in that they are restricted to a few definite horizons within the sequence and occur always apparently parallel to this layering.


On the north side of the Ofotfjord; the crystalline schists of the Nüingen division, strongly interlayered, or injected, with rocks of acid, granitic composition, occur as the uppermost unit of the Bogen group. This group, the highest recognised in the Nordland sedimentary sequence in the Ofoten area, is composed of alternating micaschists quartzites and limestones. Sedimentary iron ores occur at two horizons, in the middle and upper parts of the group (see Vogt, 1941).

The Niingen schists in the area around lake Niingen are disposed in a shallow, basin-like structure, the centre of which lies near the southeast shore of the lake. Dips are everywhere fairly gentle, of the order of 20—30°.

The *Villdalsfjell* deposit lies at an altitude of between 500 and 600 metres in very wild country at the northeast end of lake Niingen, some 8 km north of the northern shore of Ofotfjord at Bogen (see Torgersen, 1935, pp. 25—29).

The ore zone outcrops along the steep, southwest ridge of Villdalsfjell and can be followed almost from the level of the lake for a distance of about 600 metres up this ridge, though not always continuously.
In general the mineralization appears to conform to the schistosity of the surrounding rocks, but at a point some 400 metres from the lake the ore cuts through its hanging wall rocks along a marked shear zone to a position some 20 metres stratigraphically higher, before resuming its apparently conformable course. This evidence indicates that the mineralization is probably localized by thrusting or shearing nearly parallel to the foliation of the crystalline schists.

The ore minerals are almost exclusively zincblende and galena, with, occasionally, trace amounts of chalcopyrite. Other sulphides cannot be recognized in hand specimen. The sulphides occur often as solid or massive concordant layers or strips in the schists, varying between 5 and 20 cm. In places, especially where blasting has taken place, the ore zone can be seen to reach a thickness of up to 3½ metres, although the average thickness appears to be considerably less. The zone as a whole strikes NE and dips 20° to 30° to the southeast.

The Niingen (Niingstoppen) deposit is similar to that at Villdalsfjell, though it has a much shorter outcrop and appears to lie in a different structural-stratigraphic position. It lies in a very exposed position on the shoulder of Niingen mountain, 1⅓ km west of the southern end of Lake Niingen, and at an altitude of about 600 metres. (Torgersen, 1935, p. 47).

17. Djupvik prospect, Ofoten district, Nordland.

This prospect lies to the south of the Ofotfjord on the northern side of the Ballangen peninsula. (Torgersen, 1935, pp. 23—25).

The deposit lies concordantly in garnetiferous quartz-mica schists, which strike NE and dip 15°—20° to the southeast. As in the case of the Villdalsfjell deposits, the ores at Djupvik occur some distance stratigraphically above a well-marked, thick layer of quartzite, though Torgersen is of the opinion that the Villdalsfjell deposits occur at a stratigraphically higher level than those at Djupvik.

The sulphide mineralization is confined, typically, to one horizon in the schists which here form part of the SE-dipping westerly limb of the Håfjell syncline, the axis of which lies some 1—2 km to the southeast of the deposits.

The exposed strike length of the Djupvik deposit is not more than 100 metres and the thickness of ore exposed in the surface trenches varies between 10 and 40 cm. Torgersen considered it one of the minor deposits of the area. The sulphide minerals are zincblende and galena in varying amounts.

C. Deposits along the Caledonian border zone.


This deposit has been described by Skjeseth and Vokes (1956). It lies on the mountain plateau of central Norway, at an altitude of some 1200 metres, 160 kilometres WNW of Oslo. The sulphides, zincblende, and galena, with minor chalcopyrite and pyrrhotite, occur as very irregular and economically insignificant coarse-grained disseminations in thin lenses of milky quartz and calcite. These lenses have been emplaced between the almost flat-lying bedding
planes of the Cambrian phyllites which overlie steeply dipping Precambrian gneisses having a N—S strike.

The mineralization has been localized in the phyllites along a N—S fault in the Precambrian basement. This fault, which shows a throw of not more than 5 metres, moved in post-Caledonian times, flexing, and in parts, breaking, the overlying Cambrian layers. This flexing opened up lenticular spaces between the bedding planes, in which spaces the quartz-calcite-sulphide mineralization was deposited.

From the geological relations it was concluded that the age of the mineralization at Krækkjaheia was most likely of Permian age. This conclusion is apparently confirmed by the lead isotope analysis.


The Bømarken deposit is now largely inaccessible due to recent highway construction, but galena from it in the collections of the Mineralogisk-Geologisk Museum was analysed in the present study.

According to Reusch (op. cit.) the Bømarken deposit, some 22 kilometres southwest of the centre of Oslo, was opened up in 1881—82, but since then no further working appears to have taken place. The country rocks are a white, porphyritic, mica-poor granite in which the mineral vein, dipping vertically, strikes NW. Its width is up to 20—30 cm, but often much less, at times almost disappearing and being represented by a fracture plane in the gneiss. The vein filling was mainly calcite and the sulphide minerals, galena (Ag-bearing), zincblende, chalcopyrite and pyrite, occurred in this and as impregnations in the wall rocks up to a distance of 50 cms on either side.

20. Tufsingdal deposit, Femund area.

At this locality trial working has taken place on a vein-like deposit. The mineralization occurs in a quartzite immediately above the Precambrian peneplane, which is exposed a short distance below the working.

The mineralization has most likely been localized along a faultzone and several more prospects are known along the same line of strike (S. Skjeseth, personal communication).


The Løvbekken deposit may be regarded as a direct continuation of the Vassbo deposit, although the details of stratigraphy are somewhat different. At Løvbekken the basal Cambrian sandstone shows a much reduced thickness. Galena impregnations occur in an outcrop of this sandstone, not more than 1 metre in thickness, which rests directly on the weathered Precambrian surface and is overlain by Cambrian shales (S. Skjeseth, pers. comm. and 1963).

1 Arkose according to Spjeldnæs (pers. comm.).
22. Bråstadelven occurrence, Vardal, Gjøvik district.

The mineralization at Bråstadelven occurs in upper Eocambrian sandstone ("Ringsaker quartzite") at its junction with overlying fossiliferous Lower Cambrian beds. The sequence belongs to the Quartz Sandstone nappe which is thrust southwards over autochthonous Cambrian alum shales. The mineralization occurs near the front of the nappe where the beds are repeated by mainly steeply-dipping imbricate thrusts. Galena impregnations occur over a considerable area around the margins of a marked synclinal structure, and the control of the mineralization by the overlying Cambrian shales is very marked. As at Laisvall zincblende, fluorite and calcite accompany the galena. (S. Skjeseth pers. comm.).

D. Deposits in the vicinity of the Precambrian peneplane in Northern Norway.

23. Nasafjell deposits, Norwegian—Swedish border, Saltfjell area, Nordland.

The Nasafjell deposit has been included in the recent investigation of Swedish lead isotopic compositions by Wickman et al. (196) and the reader is referred to this publication for further details.

Strand (in Holtedahl, 1960, p. 250) has discussed the latest views of the geology of the area from the Norwegian side. The main feature is the Lønsdal basal massif, composed mainly of granite gneisses, lying between about 66°30' N and 67° N latitude and extending on either side of the border. In the eastern, Swedish, part the rocks of the massif can be proved to be of Precambrian age, as sediments of probably lower Cambrian age overlie them with a primary unconformity.

In Norway along the southwestern margins of the massif intrusive contacts have been observed between granitic rocks apparently belonging to the massif and the overlying sediments.

The deposits worked in the past lie at the southern border of the massif, just inside Swedish territory.

The ore minerals, mainly pyrrhotite, zincblende and galena (silver-bearing) occur as coarsely crystalline, erratically distributed, patches and splashes, sometimes veins, in bodies of massive vein quartz. Boulangerite is a minor mineralogical component of the ore.

The quartz bodies, which have been described as "veins", lie parallel to the schistosity of the metamorphic rocks overlying the Nasafjell granite at this edge of the massif. These schists dip generally to the south or SSW, off the granite, and have been openly folded along WNW axes, which are flat or very gently plunging.

Zenzen's view was that the folding of the schists caused openings between the schistosity planes of the metamorphic rocks. These openings were then filled by the deposition of the sulphide-bearing quartz bodies. The mechanism resembles strongly that proposed by Skjeseth and Vokes for the Krækkjeheia deposit (see above).

The actual source of the proposed ore-bearing solutions is, in both cases, by no means obvious.
24. Katterattvann deposits, Ofoten area, Nordland.

Within the Precambrian Rombak window, to the east and southeast of Narvik (Vogt, 1941), occur a number of lead-zinc deposits (Torgersen, 1935), as well as deposits carrying auriferous arsenopyrite (Bugge and Foslie, 1922, pp. 10—16). The lead-zinc deposits occur as pyrrhotite-rich “fahlbånd”-like deposits in the gabbroic rocks, as vein deposits in the vicinity of these and as concordant layers in a quartz-rich biotite schist.

The galena analysed in this investigation came from the deposit at Katterattvann almost on the Swedish border and near the eastern edge of the Rombak window. (Torgersen, op. cit., pp. 9—13). The deposits here were first staked in about 1880, but very little work has been done on them.

The dominating rock in the vicinity of the deposits is a coarse-grained microcline granite (Rombak granite of Vogt, called Vassijavre granite in Torgersen). Within this granite there occur several NNW-striking zones of a dark, mica-rich feldspathic gneiss. These zones are in the form of larger and smaller lenses and in outcrop they show marked hands of rusting due to the weathering of a marked pyrrhotite content. Zincblende and galena also occur in these “fahlbånd” zones.

The ore deposits occur as a series of calcite veins, striking approximately N—S, with a steep dip to the west. They occur partly in the granite, partly along the junction between the granite and the dark schist and partly in the latter. The veins have comparatively small strike lengths and vary in width from a few centimeters to a few decimetres — exceptionally up to half a metre. They carry in parts coarse-grained galena with small amounts of zincblende, pyrite and chalcopyrite.

The gangue minerals comprise calcite with minor quartz and now and then fluorite and epidote.

Four main veins are known at Katterattvann, but they are all of comparatively short strike length and the values in them are highly erratic. Torgersen regarded them as being without economic interest.

25. Gurrogaissa deposit, Finnmark.

The mineralization occurs as small fracture fillings with vertical dips, which intersect the gneisses in all directions. Individual fractures can be up to 10—15 cm long and about 5 cm wide, but more usually they are much smaller than this. The fracture-fillings consist of quartz, calcite and galena. In two NW-striking zones the fractures form a close network in the country rocks, constituting a form of stockwork. The zones are of the order of 2 m wide and lie close together. According to Torgersen the more westerly zone has a length of 30 metres and can hold up to 10 per cent lead. The more easterly zone is longer, but shows very little galena. Reitan puts the total length of mineralized exposures at a couple of hundred metres.

The Gurrogaissa galena carries insignificant amounts of silver.
E. **Deposits in the Permian province of the Oslo area.**

26, 27. Deposits in the Grua area, Nordmarka.

In the Grua area contact deposits of sulphidic ores are situated along the border of the deep eruptives on both sides of the road and railway line north from Oslo. (Goldschmidt, 1911, pp. 50—53).

West of Grua the border of the eruptive rocks of the Nordmarka area runs for a considerable distance in an E—W direction, but a short distance to the east it swings to a more northerly course. The greater bulk of the eruptive rocks is composed of nordmarkite and pulaskite, but to the east of Grua there occurs an area of biotite granite. The pulaskite, too, shows a local quartz-rich facies in places.

At Grua the nordmarkite is in contact with Ordovician and Silurian sediments. The most important unit of these, as far as the ore deposits is concerned, is a thick bed of massive limestone. From the somewhat rare fossils in this limestone, it probably belongs to the Ordovician, stage 5a (the Gastropod limestone). The limestone is intercalated in a thick series of sandstones. Northwards from the sharp bend of the border of the eruptives east of Grua, lower Silurian and Cambrian beds are in contact with the nordmarkite. In this area, stage 3c, the Orthoceras limestone, is of importance as an ore bearing unit.

The contact metamorphism is very intense. The alum shales of the Cambrian have been altered to andalusite hornfelses, the shales of stage 4 give rise to biotite-rich hornfelses, while the sandy sediments of stages 5 and 6 have been altered to various sandstone-hornfelses.

The lime-rich sediments, the Orthoceras and Gastropod limestones, are often changed to marble. Near the contact deposits a quite different metamorphism is met with; the limestones are here changed to lime-iron-silicate assemblages. Andradite-felses, at times hedenbergite-felses, in large masses, occur as a result of the metasomatism, during which process the sulphidic ores have also been introduced.

The deposit of **Skjærpemyr** (26) 2 km west of Grua was worked as early as the beginning of the 17th century for its argentiferous galena. In the 19th century the zincblende content of the ore was recovered, but the deposit has not been worked since the beginning of this century and must be considered as of little economic interest.

At Skjærpemyr the limestone along its contact with a large dyke-like mass of nordmarkite is impregnated with zincblende and galena. The impregnations occur as several zones, lying one above the other, which thin out with increasing distance from the eruptive contact.

Garnet always accompanies the ores — a sulphur yellow andradite — while pyroxene, partly uralitised, is also common.

The nordmarkite dyke appears to be an apophysis from the pulaskitic nordmarkite lying immediately to the south, probably localized by a fault.

The Skjærpemyr deposit has apparently been metamorphosed again after the deposition of the sulphide ores. It is penetrated by quartz veins which have given rise to hemimorphite at the expense of the zincblende. In addition lievrite
has grown in the quartz. This second metamorphism is probably connected with the emplacement of the younger biotite-granite east of Grua.

At *Mutta* (27) half way between Grua and Skjærpmeyr, is a smaller deposit of galena and zincblende, also in limestone (stage 4-5). Formation of garnet is subordinate at this place. Sulphide mineralization is also found along a fissure dyke of nordmarkite. (Goldschmidt, 1911, pp. 52—53).

28, 29. Deposits in the area of Drammen.

Lead-zinc deposits are again important in the central area of the Oslo province around the town of Drammen. The following general account is taken from Goldschmidt (1911, pp. 66—86).

The area around Drammen offers excellent examples of the effect of contact metamorphism. On each side of the valley of the Drammen River there are to be found remnants of the sedimentary roof lying on the granite laccolith. To the north of the valley the remnants are limited to a few downsunken blocks. In the area north of Mjøndalen one or two larger remnants of Silurian rocks can be found. In the past a few zinc prospects were investigated in this area.

South of the Drammen valley the laccolith roof is excellently preserved and can be observed in numerous fine exposures. All in all there is an area about 10 km long from east to west and 5 km wide, north-south, underlain by high grade contact metamorphosed sediments. Imposed upon the normal contact metamorphic phenomena, occur the numerous ore deposits, cutting the altered sediments.

The roof rocks are composed of upper Silurian beds (Wenlock and Ludlow) overlain by Dowtonian sandstone, and lie in a shallow synclinal fold over the granite.

The ore deposits (which have not been worked for many years) lie mainly in two groups; those around Konnerudkollen, immediately south of the Drams valley, and those of the Aaserud area, further to the south, towards the Sande-valley.

The deposits of the Konnerud area, which were the more important, are intimately connected with lines of faulting. Two parallel north-south fault lines have caused a portion of the granite's roof to be depressed in the form of a graben bringing Dowtonian sandstone in contact with the underlying Silurian rocks. Granite is exposed to the north of the mine-area and a tongue of it projects southwards along the line of the more westerly fault zone, seemingly indicating a close connection between the faulting and the emplacement of the granite.

Mineral deposition, mainly zincblende with lesser galena and chalcopyrite occurs in the actual fault zones, partly in a gangue of calcite and quartz and partly as impregnations in Silurian limestone. No mineralization was observable in the Devonian sandstone.

The *Dalen* mine (28) lies towards the southern side of the mineralized area on Konnerudkollen (Goldschmidt, 1911, pp 79—82). The rocks around and to the south of the mine are Dowtonian sandstones which lie concordantly over the gently southwards dipping Ludlow beds exposed on Konnerudkollen. These
sedimentary beds form part of the roof of the underlying granite laccolith, as already mentioned. This sedimentary roof is cut by numerous quartz-porphyry dykes whose origin is in the underlying granite.

In places these quartz porphyry dykes are ore bearing, as at Dalen mine. At this locality a wide dyke which can be followed for several kilometres cuts the sandstone beds, which have been contact-metamorphosed to the usual amphibole rich sandstone-hornfels. The ore occurs almost exclusively in the quartz porphyry dyke, extremely rarely in the bordering sandstone. The dyke has been mined down to a depth of about 40 m, the ore minerals being argentiferous galena, zincblende, and lesser amounts of molybdenite and pyrite.

Fragments of garnet fels also occur as macroscopic and microscopic inclusions in the ore bearing porphyry and Goldschmidt interpreted these as having originated from a garnet rich bed in the underlying Ludlow limestone. The quartz porphyry dyke had broken through this bed and carried up the garnet bearing fragments to the level of the Devonian beds before consolidation. Goldschmidt carried this idea further in considering that the ore also came from an original contact metamorphic deposit in the Ludlow beds. Thus the ore as worked at the Dalen mine may be considered as a “rejuvenated” or “secondary” type.

The small deposit at Bø in the Lier area (29) is briefly mentioned by Goldschmidt (op. cit. p. 98). Further information is contained in an unpublished M.Sc. thesis by B. R. Playle (1960).

The workings on this deposit are almost entirely inaccessible at the present time and few details are obtainable. The mineralization, consisting of galena, hematite and a little pyrite, occurs in calcite veins which cut the sediments underlying the Permian lava RP1. These sediments were previously interpreted as Silurian by, among others, Goldschmidt, and consist of tectonically disturbed dark grey shales of a low metamorphic grade. Playle has discovered the basal Permian conglomerate grit nearby at a lower level than the working, which he takes as suggesting the shales themselves may be Permian.

F. Deposits in the Kongsberg—Bamble area.

For a description of the rocks of the Kongsberg—Bamble area, the reader is referred to Barth (in Holtedahl, 1960, pp. 23—24) and J. A. W. Bugge (1960).

In the Kongsberg area, the following rock limits have been recognised, (beginning with the oldest); 1. Banded gneisses and dioritic gneisses (grey Kongsberg gneiss), 2. Vinor amphibolites, 3. Granitic gneiss (Kongsberg granite). All these rocks are intersected by diabase dykes which strike EW and which are related to the Permian rocks of the Oslo area.

Characteristic for the area are the so-called “fahlbands” which are elongated narrow zones in which the rocks have been heavily metasomatized and impregnated with sulphides. They strike roughly N—S, almost parallel to the strike of the rocks as a whole. There are several fahlband zones, the most important of which are Underberget and Overberget. Most of the silver-bearing vein deposits are to be found in these two zones. In the Overberget zone the fahlbands reach a
thickness of from 180 to 900 metres and are over 10 km long. The sulphides of the fahlband are mainly pyrrhotite, pyrite, chalcopyrite and some zincblende. Less commonly occur arsenopyrite, cobaltite, galena, magnetite and ilmenite.

Two groups of veins are found in the Kongsberg area: the older quartz veins carrying sulphides of iron, copper, zinc and lead, and the younger calcite veins carrying arsenides of cobalt and nickel, together with native silver. C. Bugge (1917) called these two groups veins of the first and second generation, respectively. He also gave the name “sulphide-bearing quartz-breccia veins” to the first group.

Such quartz veins intersect the area in great numbers, not only in the neighbourhood of the old silver mines. They are especially common to the west of the Oslo area. Such veins are also found within the Oslo area, being in all probability identical with the sulphide bearing quartz veins of the Konnerudkollen area near Drammen (see above). Their usual strike is ENE in the Kongsberg area, though a few strike N—S.

The veins of the second generation (native silver-nickel and cobalt arsenide-calcite type) are found almost only within the fahlband zones, never extending for more than a few metres into the surrounding gneisses. These veins are usually very narrow, seldom more than 0.5 m wide (average 5—10 cm). The vein proper is often surrounded by parallel and crossing fissures, resulting in a complex mineralized zone or breccia, which may in places reach room size. The veins usually strike E—W and dip steeply towards the south. In addition, steep northerly dips are sometimes found, and dips of 45° S are common in the northerly part of the Overberget fahlband zone.

The Kongsberg veins are usually homogeneous from one wall to the other and only a small minority show banded structures. Vughs are comparatively frequent and in these the metallic and other minerals, especially the native silver, are found as crystals of unusual beauty (see Neumann, 1944).

As a representative of the veins of the first generation, a galena was selected from a specimen from Kronløkken (30) prospect east of Kjennerud lake, some 3 km NE of the centre of Kongsberg. (Bugge op. cit. pp. 113—132).

The prospect lies towards the east end of a vein which, after Bugge's description, has a total strike length of about 9 km and which cuts across all the main fahlband zones west of Kongsberg, crosses the valley of the Laagen river and can be followed to a point east of Kjennerudvann. The vein is a quartz breccia vein with often considerable amounts of calcite, the latter being especially abundant where the vein crosses the fahlbands. The ore minerals are abundant pyrite, much chalcopyrite and lesser amounts of sphalerite and galena. The vein has been staked in the past for copper at several localities, apart from Kronløkken prospect. However, the economic prospects of this type of deposit do not appear to be of any significance. According to Bugge (op. cit. p. 132), the galena of this type of vein is “exceptionally rich in silver”.

The old disused mine of Gottes Hülfe in der Not (31) lies in the Overberget fahlband zone, some 3 km from the centre of Kongsberg. It was in its time one of the larger silver mines of the area, and reached a depth of about
700 m below outcrop. The mine worked a north-plunging vein system consisting of a main vein and branching apophyses of calcite-veins (veins of the second generation). The main vein is that portion of a quartz breccia vein of the first generation where it crosses the fahlband zone and has been apparently affected by the solutions depositing the native silver-nickel cobalt arsenide-calcite veins of the second generation. These main veins, as a Gottes Hülfe, were often very rich in silver, in particular they appear to have carried more argentite than other veins. Vughs with fine crystals were particularly abundant in such veins. The “normal” calcite veins which appeared to branch out from the main vein at this mine were often of considerable length both along strike and down dip, up to a maximum of about 200 metres. They normally occurred with about 50 m between adjacent veins.

The second sample of galena from a vein of the second generation was taken from the small working of Bratteskjærpet (32) in the valley of the Kongsberg river, some few kilometres west of the town. This working is somewhat west of the main zones of Underberget and Overberget.

The now disued zinc mine at Tråk (33) in Bamble lies on the western side of Skiensfjord, a few kilometres from the border of the Oslo province. The geology of the deposits has been described by J. H. L. Vogt (1907), while Th. Vogt (1908, p. 4 – 17) has given a detailed account of the mineralogy of the barite occurring there. According to the first of these authorities, a significant number of quartz-breccia veins carrying zincblende, galena, and lesser pyrite and chalcopyrite occur in a reddish gneissose Precambrian granite. In one of the veins barite appears in quantity. The veins strike parallel to the Silurian border, which lies a few kilometres to the east, (i.e. N – S). The vein fractures are faults connected with the graben structure of the neighbouring Oslo province. J. H. L. Vogt gives the following sequence of events: the vein fractures were first opened up and then filled with quartz and sulphides. Later several of the veins were reopened and there followed an intrusion of diabase: Yet later, the original veins were, in a few places, opened up once more and a late generation of barite was deposited.

Vogt’s account of the sequence of events implies a Permian origin for the Tråk veins, which thus both in geological characters and in age of deposition are almost identical with Bugge’s veins of the first generation in the Kongsberg area. The similarities in the lead isotopic composition of the two galenas (30 and 33) reinforces the geological evidence.

9. REFERENCES


LEAD ISOTOPES IN NORWEGIAN GALENAS

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Accepted for publication February 1963.
Printed September 1963.