Geological Survey of Finland

Bulletin 316

The lead isotopic composition of some Finnish galenas

by Matti Vaasjoki

Geologinen tutkimuslaitos
Espoo 1981

Geological Survey of Finland, Bulletin 316

THE LEAD ISOTOPIC COMPOSITION OF SOME FINNISH GALENAS

by

MATTI VAASJOKI

with 6 figures and one table in the text and one appendix

GEOLOGINEN TUTKIMUSLAITOS
ESPOO 1981

Vaasjoki, Matti 1981. The lead isotopic composition of some Finnish galenas. *Geological Survey of Finland, Bulletin 316.* 25 pages, 6 figures, one table and one appendix.

New high-precision lead isotopic analyses of 85 galenas from 54 localities in Finland are reported. The leads from both the Archean basement area and the Karelides exhibit a large scatter, suggesting that remobilization of lead formed in the upper crust during the Lower Proterozoic occurred during the Middle Proterozoic Svecokarelian orogeny. Lead isotopic compositions of galenas from the Svecofennian area exhibit a marked correlation with their respective geological environments and form a sublinear trend on all diagrams employed. This is interpreted as a result of mixing of various amounts of mantle and crustal leads in the course of the Svecokarelian orogeny and this group of mineralizations is therefore thought to represent Svecokarelian orogenic leads. It is concluded that the present results suggest a close relationship between orogeny and lead evolution, which is to be expected in any orogenic environment. Based on the new data, application of lead isotopic determinations to mineral exploration in Finland is more plausible than ever.

Key words: lead, isotopes, galena, Archean, Proterozoic, Svekokarelides, Finland.

Matti Vaasjoki, CSIRO Division of Mineralogy,
P.O. Box 136, North Ryde, NSW
Australia 2113

ISBN 951-690-146-8
ISSN 0367-522X

Vammala 1981, Vammalan Kirjapaino Oy

CONTENTS

INTRODUCTION

The first comprehensive study of lead isotopic compositions of Finnish galenas from a wide variety of geological environments was published by Olavi Kouvo and Laurence Kulp in 1961. Although the data suffered from uncertainties in the determination of the $^{206}Pb/^{204}Pb$-ratio, and some of the interpretations were hampered by an insufficient number of existing radiometric dates from adjoining rocks, they demonstrated that there was a distinct difference between the leads of the Svecofennian and Karelian orogenic subunits. The Svecofennian leads yielded model ages consistently around 1800 Ma, whereas the Karelian leads formed a cluster on the $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ diagram with model ages ranging from 2050 up to 2300 Ma. The reason for the abnormal behaviour of the Karelian leads was thought to be either an earlier history of the lead or its evolution in an unusual crustal environment.

A large number of new lead isotopic analyses, generally supporting the point made by Kouvo & Kulp (1961), were published in the Annual Reports of the Geological Survey of Finland (hereafter referred to as GSF) in 1965 and 1966.

In the course of an interlaboratory comparison of samples G16, G25 and G30 (GSF 1973, p. 16) it was found that the results differed significantly from those obtained by Kouvo and Kulp (1961). Moreover, the introduction of the new decay constants for uranium (Jaffey *et al.* 1971) and thorium (LeRoux & Glendenin 1963), the redetermination of the meteorite isochron and especially of the lead isotopic composition of the Canyon Diablo troilite lead (Tatsumoto *et al.* 1973) rendered any single stage lead evolution model obsolete. All these factors contributed to the decision to reanalyze the Finnish galena material employing rigorous isotopic fractionation control and frequent standardization during the investigation. The data were to be interpreted on the basis of the latest lead evolution models and with the help of geochronologic data accumulated since the early 1960s.

ANALYTICAL PROCEDURES

As a rule, the galenas were chipped off handspecimens or fragments of diamond drill cores. They were cleaned of silicates and other sulfides by handpicking under a stereoscopic microscope. In some rare cases, when galena occurred as fine-grained disseminations, the samples were ground and the galenas were handpicked from heavy ($d > 4.2\ g/cm^3$), nonmagnetic separates.

The chemical treatment was as reported by Vaasjoki (1977, p. 12).

Each sample was prepared in duplicate.

Two mass spectrometer analyses (runs) were performed on one, and one run on the other batch. If the difference between the batches seemed significant, i.e the standard deviations did not overlap, the second batch was analyzed again. If the results of three runs coincided, the deviating fourth was rejected. In the sole case where there seemed to be a significant difference between the duplicates, a third analysis of a new mineral separate demonstrated the isotopic homogeneity of the sample.

The samples from the rapakivi granites (Vaasjoki 1977) were run on the older mass-spectrometer of the laboratory of the Geological Survey of Finland, in which fractionation was controlled by maintaining the power on the filaments as constant as possible. Since the dimensions of the filaments vary, this involved the measurement of both the voltage and the current and the calculation of their product. All other analyses were carried out on the newer instrument, which is a z-focusing single filament mass-spectrometer built at the Geological Survey according to the design of the Department of Terrestrial Magnetism of the Carnegie Institution, Washington D.C. In this version, it is possible to measure the filament temperature directly by means of an optical pyrometer. The filament temperature was first kept at 1150°C, but as experience was gained on the new instrument, the running temperature was raised to 1200°C. The manufacturers report the accuracy of the pyrometer used as ± 5°C in this temperature range. Tests involving three staff members of the laboratory indicated and average »personal» difference of ± 3°C. Thus there are grounds for assuming that the temperature differences between runs never exceeded ± 10°C.

The results were normalized by comparison with the CIT standard lead, which was run 2—3 times after every 60—80 runs. The values reported by Catanzaro (1967) were assumed to be correct. The average correction was + 0.08 % per mass-unit. The reliability of the standardization is demonstrated by the interlaboratory comparison of samples G25, G30 and G16 (GSF 1973, p. 16) carried out by Drs Olavi Kouvo (Geological Survey, Finland) and Bruce Doe (United States Geological Survey, Denver). The precision of the reported ratios is on average ± 0.07 %.

GRAPHICAL PRESENTATION OF DATA

The ^{206}Pb/^{204}Pb vs. ^{207}Pb/^{204}Pb diagram

This presentation involves the uranogenic lead isotopes ^{206}Pb and ^{207}Pb and the non-radiogenic ^{204}Pb. It thus reflects the changes which have occurred in the U,Pb systematics of the material analyzed. For galenas, this essentially represents the history of their leads before their final crystallization.

The drawback of the diagram is its sensitivity to errors in the measurements of the ^{204}Pb and the correlated error arising from this (e.g., Kanasewich 1968, Fig. 7). On the other hand, it is particularly attractive, because it involves only the U,Pb system, and the isotopic fractionation of uranium in nature has been demonstrated only in one unusual case, the Oklo natural reactor in Gabon (IAEA 1975). Thus on this diagram each point is defined by a unique pair of parameters consisting of the ^{238}U/^{204}Pb ratio (μ) and the model age. Moreover, since geological processes are not known to cause any isotopic fractionation of lead, and the nonradiogenic

^{204}Pb provides a natural reference isotope, the diagram is eminently suited for the calculation of higher order isochron ages.

The ^{204}Pb/^{206}Pb vs. ^{207}Pb/^{206}Pb diagram

This diagram contains essentially the same information as the previous one but, as the ordinate is based on the more precise ^{207}Pb/^{206}Pb ratio, it does not suffer from the correlated error. The main difference to the previous diagram is that the age of a higher order isochron is given by the intersection of the ^{207}Pb/^{206}Pb axis. The slope of a straight line on this diagram has no simple geological meaning.

A drawback of this diagram is that it is practically impossible to present common lead data at a sufficiently large scale together with the complete ^{207}Pb/^{206}Pb axis, and thus the visual comparison of isochron data is difficult.

The ^{206}Pb/^{204}Pb vs. ^{208}Pb/^{204}Pb diagram

This diagram is also sensitive to errors in the measurement of the ^{206}Pb/^{204}Pb ratio and the correlated error arising from it. Since it involves the thorogenic ^{208}Pb, it is particularly useful for the detection of changes in the U, Th systematics of the geochemical environment studied. Its dependence on both U, Pb and Th, Pb pairs gives it one degree of freedom, which makes both model and isochron ages doubtful.

The trilinear ^{206}Pb—^{207}Pb—^{208}Pb diagram

On the ^{206}Pb—^{207}Pb—^{208}Pb diagram the molar abundances of the three radiogenic lead isotopes are reduced to percentages yielding a sum of 100, and are presented on a conventional trilinear plot well known from petrology. Thus, e.g. the ^{206}Pb coordinate of a given analysis is:

$$^{206}\mathrm{Pb} = \frac{^{206}\mathrm{Pb}}{^{206}\mathrm{Pb} + {}^{207}\mathrm{Pb} + {}^{208}\mathrm{Pb}} \times 100$$

which by dividing the right side by ^{206}Pb becomes:

$$^{206}\mathrm{Pb} = \frac{1}{1 + {}^{207}\mathrm{Pb}/{}^{206}\mathrm{Pb} + {}^{208}\mathrm{Pb}/{}^{206}\mathrm{Pb}} \times 100$$

By the same procedure, the other two coordinates become:

$$^{207}\mathrm{Pb} = \frac{^{207}\mathrm{Pb}/{}^{206}\mathrm{Pb}}{1 + {}^{207}\mathrm{Pb}/{}^{206}\mathrm{Pb} + {}^{208}\mathrm{Pb}/{}^{206}\mathrm{Pb}} \times 100$$

and

$$^{208}\mathrm{Pb} = \frac{^{208}\mathrm{Pb}/{}^{206}\mathrm{Pb}}{1 + {}^{207}\mathrm{Pb}/{}^{206}\mathrm{Pb} + {}^{208}\mathrm{Pb}/{}^{206}\mathrm{Pb}} \times 100.$$

It is evident that the effect of the ^{206}Pb/^{204}Pb ratio is not expressed on the trilinear plot. From a theoretical point of view this should therefore be the ideal way to present lead isotopic results, because the main source of unreliability is eliminated (e.g. Richards 1962). However, it should be kept in mind that this presentation involves all the three elements affecting the geochemical history of lead. Therefore, for samples with similar U, Pb-, but different Th, Pb-histories (or vice versa), the distribution of the data on the diagram becomes inconclusive.

It is easily shown that for samples defining a straight line on this diagram the change in the ^{208}Pb coordinate is proportional to the change of the ^{206}Pb coordinate. This can be interpreted as a development from the same initial lead with closely related subsequent changes in the U,Th-Pb system. In geological terms, samples defining a straight line on the trilinear lead diagram probably belong to the same geochemical system.

SAMPLING AND GROUPING THE SAMPLE MATERIAL

The sampling was determined to a great extent by the need to reanalyze already existing material. The work was restricted to samples collected from outcrops, and no results from ore-containing boulders are presented. Leads exhibiting future or modern model ages were rejected, because they have all probably experienced multistage histories. No other application of the »accepted age» principle was made.

Towards the end of the study, when the general picture of the data had already emerged, a special effort was made to extend the geographical coverage and to assess the differences and similarities between the various lead groups established. In all, 85 samples from 54 different localities, ranging from the 40 million ton Outokumpu ore deposit to subordinate sulfide disseminations and inconspicuous veins a few millimeters in width, were analyzed.

The initial division of the sample material into seven groups was based on the geologic environment alone in the following manner:

A. *The Archean basement leads* are found in rocks belonging to the socalled Presvecokarelian basement. Radiometric ages for zircons of these areas range from 2600 to 2800 Ma (e.g. Kouvo 1958, 1976; Wetherill *et al.* 1962; Kouvo & Tilton 1966).

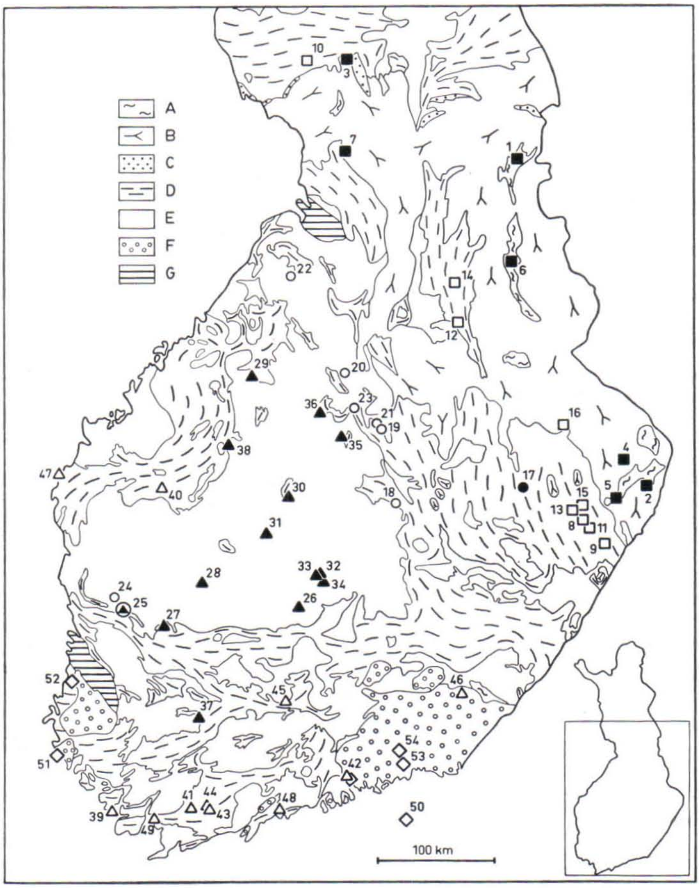

Fig. 1. Location of the sampling sites. For symbols of the localities, consult Fig. 2. Geological background simplified from Simonen (1962). A. Archean supracrustal formations. B. Archean gneissose granites. C. Layered gabbro intrusions. D. Svecokarelian supracrustal formations. E. Svecokarelian intrusive rocks, mainly granitoids. F. Rapakivi granites. G. Jotnian unmetamorphosed sediments.

B. *Deposits in the Karelian schists* are usually epigenetic mineralizations. In order to be classified into this category, the mineralization had to lie relatively close to the Archean basement in rocks of established Karelian nature. Thus, for example, the occurrences in the main sulfide ore belt as defined by Kahma (1973), which were reported by Kouvo and Kulp (1961) as Karelian leads, are not considered in this group.

C. *The Outokumpu mine.* Both the geological environment and the lead isotopic composition of the Outokumpu copper ore deposit and some other associated deposits (e.g. Luikonlahti and Vuonos, Kahma 1973) are unique in Finland. The Outokumpu ore complex (see Appendix 1) is situated in the Kalevian micaschists and phyllites, which are thought to present the flysch-facies of the Karelian sedimentation. It should be noted, that the »ages» of the Outokumpu ores referred to in the literature (e.g. Kahma 1973 and 1978) are based on lead model age calculations from data obtained for galenas, and may therefore not be related to the true age of the deposit.

D. *Leads from the main sulfide ore belt.* All sampled ores are situated in schists of probable volcanic origin (Nikander 1976; Rauhamäki *et al.* 1978; Helovuori 1979; Huhtala 1979). Usually there are two types of ores within each deposit: pyritic Cu-Fe-S ores and sphaleritic Zn-Pb-Cu ores. Comparisons have been drawn between these ores and the yellow and black Kuroko ores in Japan, and the origin of the ores is ascribed to synsedimentational volcanic activity in a marine environment (Rauhamäki *et al.* 1978; Rehtijärvi *et al.* 1979). For descriptions of the individual deposits and further references see Appendix 1.

Two galena occurrences from the Kankaanpää area, SW-Finland (no:s 24 and 25 in Fig. 1) were included in this group of deposits on the basis of their lead isotopic composition.

E. *Leads from the Central Finnish batholith area* come from mineralizations situated in small supracrustal zones surrounded by granites, granodiorites and gabbros. The supracrustal series consist mostly of metavolcanic rocks. No mineralization in this area is, by present standards, of any economic importance.

F. *Leads from the Svecofennian supracrustal rocks* represent a multitude of geologic environments ranging from skarn formations (e.g. Orijärvi) to quartzitic veins in shear zones (e.g. Koskenkylä, Pernaja) and Svecofennian roof pendants in the rapakivi granites (Hyvärilä, Lemi).

G. *Leads from the rapakivi granite massifs* consist mainly of greisen lodes around the youngest intrusive phases of each massif and epigenetic quartz—epidote—galena veins. They have recently been dealt with in detail (Vaasjoki 1977) and are included in this study for the sake of completeness only.

Short descriptions of the sampled deposits are given in Appendix 1, and their locations in relation of the main geologic units of Finland are given in Fig. 1.

RESULTS

The analytical data obtained are summarized in Table 1 together with the milieu indices μ and W and the model ages for both the two-stage model of Stacey and Kramers

Table 1. Lead isotopic data from Finnish galenas

Sample locality	Lead isotopic Ratios			Stacey and Kramers			Cumming and Richards		
	206/204	207/204	208/204	Model age Ma	μ	W	Model age Ma	μ	W
A. Archean basement leads									
G 33 Saarikylä, Suomussalmi	13.600	14.863	33.440	3020	13.78	55.65	2825	11.388	45.931
G 305 Saarikylä, Suomussalmi	13.606	14.879	33.494	3036	14.14	58.40	2831	11.447	46.743
G 306 Saarikylä, Suomussalmi	14.030	15.003	33.829	2766	12.021	47.93	2603	11.182	44.592
G 168 Viitaranta, Ilomantsi	14.686	15.158	34.715	2367	10.660	45.49	2249	10.922	45.346
G 145 Suhanko, Ranua	14.716	15.192	34.556	2389	10.913	44.11	2254	11.005	44.060
G 31 Huhus, Ilomantsi	14.828	15.227	34.936	2341	10.897	47.47	2204	11.012	46.326
G 54 Hevoskumpu, Tuupovaara	15.099	15.239	34.682	2124	10.256	38.34	2028	10.821	41.067
G 149 Tapaninkylä, Hyrynsalmi	15.139	15.325	34.969	2217	10.93	44.01	2069	11.057	44.048
G 128 Pahkakoski, Yli-Ii	15.155	15.422	35.049	2336	11.827	48.74	2131	11.348	45.862
B. Deposits in Karelian schists									
G 183 Hammaslahti Mine	14.744	15.120	34.800	2257	10.091	43.16	2179	10.742	44.705
G 75 Mosku, Tohmajärvi	14.958	15.182	34.813	2160	10.091	40.67	2079	10.754	42.976
G 289 Runkaus, Tervola	14.986	15.337	35.468	2360	11.511	55.04	2180	11.225	50.336
G 82 Tikkala, Tohmajärvi	15.030	15.240	34.937	2185	10.43	42.75	2075	10.877	43.917
G 303 Kolmisoppi, Sotkamo	15.077	15.241	34.815	2145	10.322	40.33	2044	10.843	42.388
G 153 Runkaus, Tervola	15.147	15.371	35.285	2274	11.341	49.57	2098	11.194	47.152
G 41 Niittylahti, Pyhäselkä	15.249	15.286	34.934	2067	10.318	39.76	1963	10.853	41.981
G 152 Mieslahti, Paltamo	15.258	15.360	35.144	2168	10.936	44.66	2016	11.071	44.501
G 304 Suoranta, Pyhäselkä	15.310	15.281	34.935	2009	10.155	38.45	1919	10.797	41.265
G 296 Suoranta, Pyhäselkä	15.341	15.313	35.041	2031	10.350	40.06	1923	10.870	42.146
G 302 Koli, Lieksa	15.675	15.458	35.273	1977	10.863	41.20	1820	11.084	42.231
C. The Outokumpu mine									
G 170 Outokumpu mine	14.716	15.015	34.471	2113	9.200	35.75	2114	10.426	40.808
G 30 Outokumpu mine	14.731	15.016	34.476	2100	9.174	35.52	2104	10.416	40.673
G 40 Outokumpu mine	14.873	15.056	34.533	2034	9.206	34.77	2036	10.428	40.019

D. Leads from the main sulfide ore belt										
G 295	Pukkiharju, Rautalampi	15.091	15.125	34.765	1950	9.335	35.49	1940	10.478	40.304
G 17	Säviä, Pielavesi	15.102	15.115	34.771	1924	9.243	35.06	1924	10.443	40.113
G 25	Pyhäsalmi mine	15.111	15.147	34.835	1969	9.470	36.57	1944	10.531	40.911
G 26	Vihanti mine	15.125	15.128	34.870	1925	9.303	36.07	1918	10.4	40.778
G 106	Jylhä, Pielavesi	15.128	15.145	34.805	1950	9.426	35.91	1931	10.514	40.474
G 89	Vihanti mine	15.131	15.131	34.878	1925	9.313	36.14	1917	10.47	40.820
G 57	Kumpuselkä, Keitele	15.134	15.107	34.709	1881	9.128	33.68	1895	10.397	39.206
G 93	Vihanti mine	15.137	15.137	34.886	1930	9.352	36.32	1919	10.485	40.894
G 92	Vihanti mine	15.138	15.136	34.890	1927	9.338	36.29	1917	10.48	40.893
G 90	Vihanti mine	15.144	15.130	34.870	1913	9.288	35.82	1908	10.460	40.611
G 87	Vihanti mine	15.144	15.146	34.869	1938	9.404	36.30	1920	10.506	40.795
G 126	Vihanti mine	15.15	15.146	34.896	1934	9.398	36.49	1917	10.503	40.95
G 91	Vihanti mine	15.150	15.158	34.941	1952	9.487	37.32	1927	10.538	41.438
G 86	Vihanti mine	15.151	15.153	34.873	1943	9.445	36.44	1921	10.521	40.839
G 88	Vihanti mine	15.153	15.156	34.942	1945	9.462	37.18	1922	10.528	41.378
G 74	Heittola, Kankaanpää	15.155	15.172	34.929	1971	9.588	37.57	1935	10.577	41.474
G 58	Kumpuselkä, Keitele	15.162	15.186	34.963	1987	9.685	38.27	1942	10.614	41.847
G 286	Vihanti mine	15.173	15.170	34.955	1951	9.538	37.44	1920	10.558	41.450
G 292	Verttuunjärvi, Kankaanpää	15.230	15.167	34.916	1898	9.420	35.99	1879	10.512	40.514
E. Leads from the central Finnish batholith area										
G 70	Verttuunjärvi, Kankaanpää	15.383	15.234	35.024	1875	9.668	36.60	1831	10.613	40.582
G 100	Kaipola, Jämsä	15.389	15.225	35.010	1853	9.586	36.06	1818	10.581	40.289
G 293	Verttuunjärvi, Kankaanpää	15.409	15.267	35.263	1904	9.866	39.51	1840	10.691	42.472
G 118	Lepomäki, Hämeenkyrö	15.416	15.223	35.026	1827	9.531	35.73	1798	10.559	40.111
G 45	Visuvesi, Kuru	15.450	15.224	35.019	1801	9.491	35.19	1776	10.543	39.747
G 95	Sykäräinen, Toholampi	15.451	15.198	35.006	1756	9.305	34.29	1753	10.468	39.318
G 96	Sykäräinen, Toholampi	15.470	15.224	35.092	1783	9.460	35.55	1762	10.531	40.065
G 84	Muittari, Saarijärvi	15.518	15.266	35.055	1811	9.687	35.71	1766	10.624	39.850
G 85	Muittari, Saarijärvi	15.528	15.293	35.120	1846	9.866	36.97	1782	10.695	40.545
G 122	Tarhapää, Keuruu	15.529	15.280	35.131	1824	9.77	36.66	1770	10.657	40.451
G 294	Muurame	15.552	15.300	35.183	1837	9.878	37.39	1771	10.701	40.846
G 98	Korpilahti	15.552	15.304	35.178	1843	9.905	37.45	1774	10.711	40.850
G 83	Muittari, Saarijärvi	15.557	15.310	35.166	1849	9.946	37.46	1777	10.727	40.797
G 15	Karna, Viitasaari	15.561	15.278	35.147	1795	9.712	36.28	1747	10.634	40.236
G 307	Koijärvi, Forssa	15.569	15.234	35.066	1716	9.396	34.18	1704	10.505	39.058
G 16	Ritovuori, Pihtipudas	15.577	15.287	35.164	1796	9.748	36.44	1744	10.649	40.303
G 173	Alajärvi	15.595	15.281	35.157	1771	9.682	35.93	1726	10.623	40.006
G 99	Tahkonsaari, Korpilahti	15.510	15.276	35.113	1832	9.765	36.66	1779	10.65	40.45

Table 1. cont.

F. Leads from Svecofennian supracrustal rocks											
G 11	Attu, Parainen	15.66	15.327	35.192	1792	9.912	36.63	1722	10.717	40.194
G 284	Tervasmäki, Nurmo	15.673	15.340	35.228	1801	9.984	37.13	1724	10.746	40.473
G 283	Marttalanniemi, Nurmo	15.685	15.343	35.237	1797	9.991	37.13	1719	10.75	40.465
G 282	Ylimysjärvi, Nurmo	15.688	15.341	35.214	1791	9.971	36.81	1715	10.742	40.248
G 12	Orijärvi, Kisko	15.699	15.356	35.261	1805	10.061	37.52	1720	10.778	40.649
G 263	Koskenkylä, Pernaja	15.705	15.336	35.250	1769	9.910	36.74	1700	10.718	40.277
G 169	Karkalinniemi	15.710	15.347	35.195	1782	9.982	36.49	1705	10.747	39.979
G 52	Lammi	15.712	15.327	35.325	1749	9.840	37.07	1687	10.69	40.624
G 7	Hyvärilä, Lemi	15.719	15.373	35.280	1815	10.150	37.88	1721	10.814	40.798
G 288	Lohjansaari	15.720	15.337	35.210	1757	9.890	36.16	1690	10.711	41.703
G 9	Korsnäs mine	15.721	15.330	35.277	1747	9.849	36.59	1684	10.694	40.246
G 13	Pakila, Helsinki	15.725	15.366	35.275	1800	10.092	37.54	1711	10.791	40.622
G 48	Hästö, Perniö	15.745	15.371	35.324	1792	10.100	37.85	1702	10.795	40.836
G 266	Koskenkylä, Pernaja	15.802	15.388	35.360	1772	10.136	37.81	1679	10.812	40.751
G. Leads from the rapakivi granite areas											
G 272	Hogland, USSR	15.908	15.367	35.380	1655	9.857	35.91	1592	10.702	39.678
G 63	Taivassalo	15.968	15.388	35.540	1641	9.924	37.06	1570	10.731	40.458
G 274	Eurajoki	16.037	15.381	35.764	1575	9.801	37.84	1519	10.682	41.243
G 260	Eurajoki	16.067	15.403	35.724	1587	9.908	37.70	1518	10.727	40.972
G 259	Eurajoki	16.071	15.417	35.856	1606	9.993	39.15	1528	10.763	41.967
G 261	Peippola, Kymi	16.073	15.420	35.760	1609	10.010	38.39	1529	10.770	41.354
G 151	Peippola, Kymi	16.094	15.429	35.660	1607	10.044	37.51	1523	10.785	40.616
G 141	Anjalankoski	16.251	15.441	35.740	1505	9.954	36.49	1431	10.752	39.933
G 277	Koskenkylä, Pernaja	16.273	15.464	35.740	1525	10.074	36.81	1437	10.803	40.007
G 62	Anjalankoski	16.334	15.471	35.840	1490	10.057	37.06	1404	10.798	40.216
G 258	Finnström	16.470	15.458	35.924	1365	9.858	35.82	1304	10.714	39.498

All data normalized against the CIT-standard lead (Catanzaro 1967)

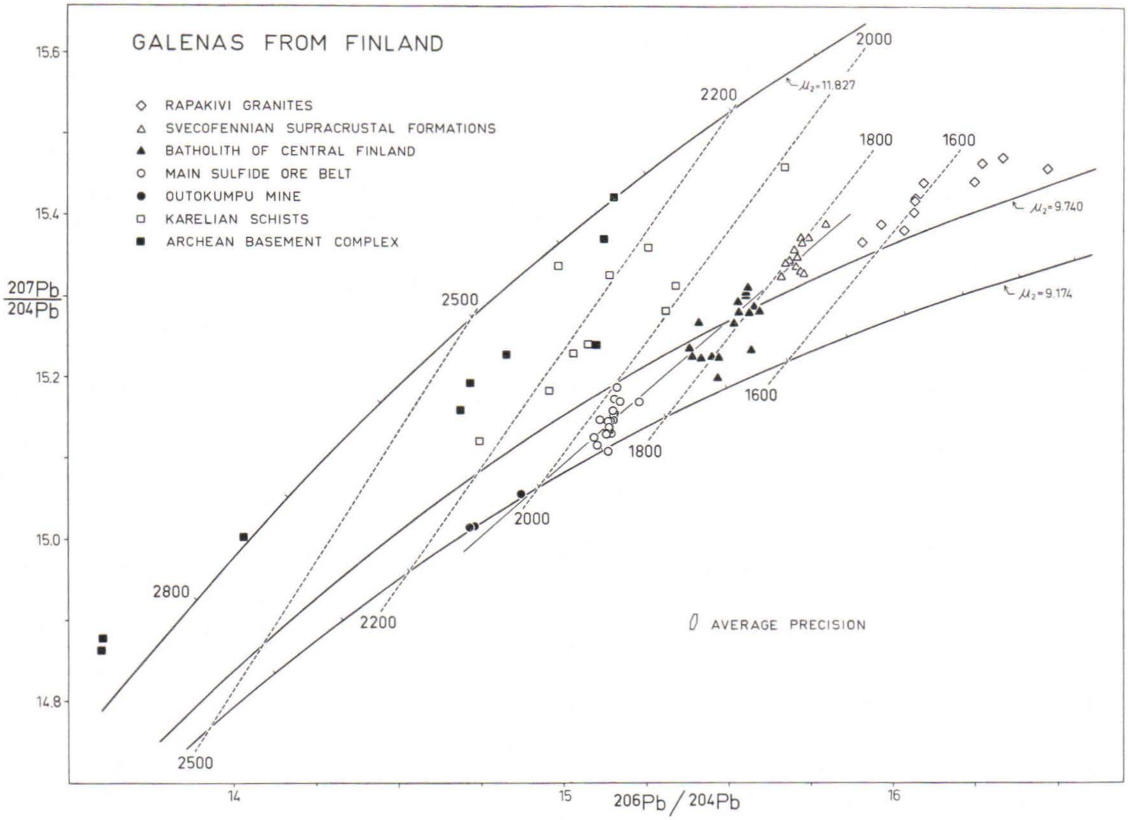

Fig. 2. The $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ diagram. Growth curves according to the two-stage model of Stacey and Kramers (1975). The middle curve is their average global lead growth curve. The trend of the Svecokarelian orogenic leads is indicated by a solid line.

(1975, hereafter referred to as the SK-model) and the linear uranium accretion model of Cumming and Richards (1975, hereafter referred to as the CR-model). The data are plotted on the diagrams discussed on pp. 6—7 in Figures 2—5. The following features are evident:

A. The samples from the Archean basement are widely scattered on all diagrams. Their model ages range from 3000—2000 Ma for the SK- and from 2800—2000 Ma for the CR-model. A characteristic feature of these leads is the high values of both μ and W, irrespective of the model employed. On the trilinear diagram (Fig. 4), samples with younger model ages tend to plot towards the uranogenic lead field.

B. Samples from the Karelian schists exhibit lead isotopic patterns and μ and W relationships similar to those of the Archean group, though the range of their model ages is considerably smaller, being 2360—1970 Ma for the SK- and 2180—1820 Ma for the CR-model.

C. The large Outokumpu copper ore deposit has a lead isotopic composition which is unique in Finland. The μ and W values are the lowest encountered during this study. The ages yielded by the two models are in excellent agreement around 2100

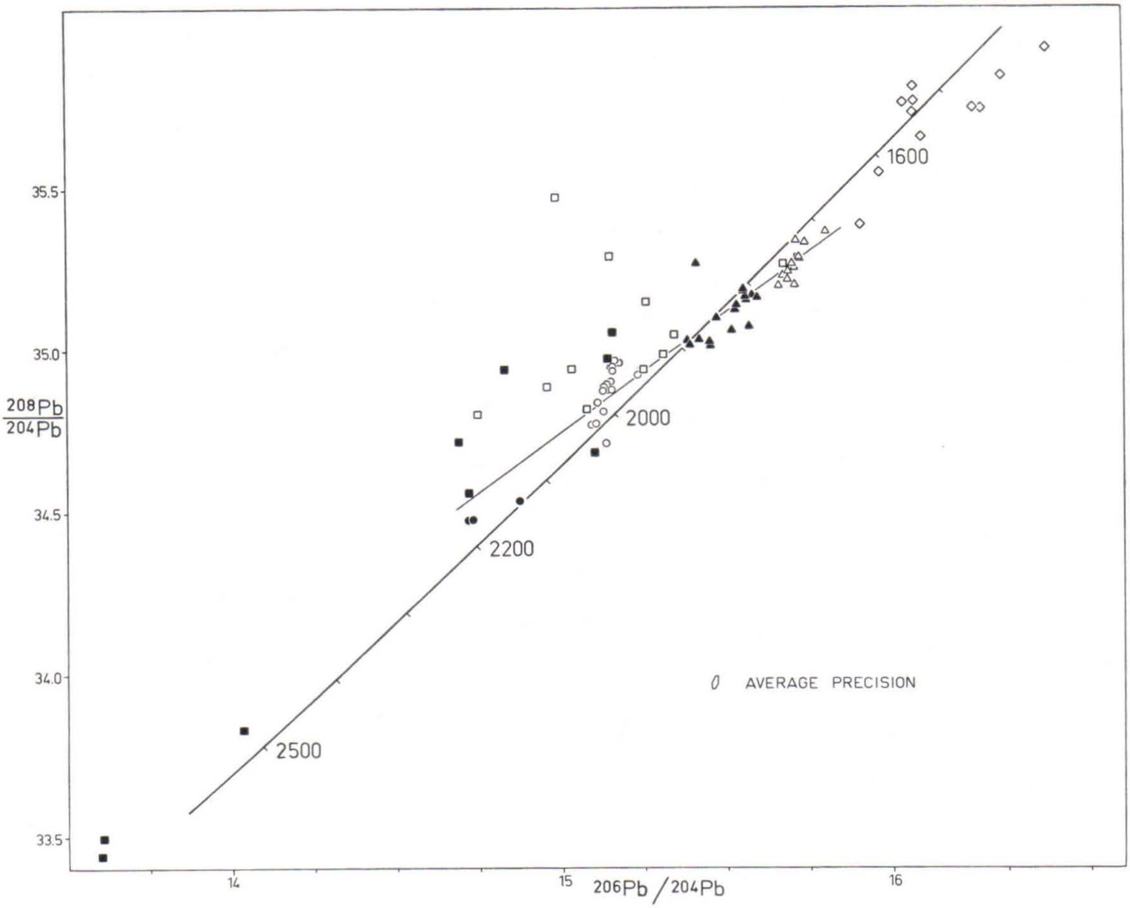

Fig. 3. The $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ diagram. The growth curve is the average global growth curve as calculated by Stacey and Kramers (1975). The trend of the Svecokarelian orogenic leads is indicated. Symbols as in Fig. 2.

Ma. Sample G40 represents a skarn zone within the deposit, and its lead isotopic composition is probably due to reactions during the Svecokarelian regional metamorphism.

D. The group of samples from the main sulfide ore belt is the most coherent encountered during this study. The model ages are mostly of the order 2000—1900 Ma, and for each sample the results of both models agree quite well. The values of μ and W for both models are definitely lower than those for the conformable lead growth curves of either of the models employed.

E. The leads from the Central Finnish batholith area exhibit a fairly large range of lead isotopic compositions with $^{206}Pb/^{204}Pb$ ratios from 15.38 to 15.6. The model ages range from 1900 to 1700 Ma for the SK- and from 1850 to 1700 Ma for the CR-model. Both μ and W tend to increase as the leads become more radiogenic, and the samples plot quite close to the conformable lead growth curve of both models.

F. The leads from the strongly migmatized Svecofennian supracrustal formations form a surprisingly coherent group when the wide variety of their genetic environments is considered. The analytical data plot slightly above the conformable lead growth curves on the ^{206}Pb/^{204}Pb vs. ^{207}Pb/^{204}Pb diagram, which also is reflected in the values for both μ and W. The model ages are 1800—1750 Ma for the SK- and 1725—1680 Ma for the CR-model.

G. The lead isotopic composition from the galena mineralizations of the rapakivi granites are variable. Vaasjoki (1977, pp. 42—51) suggested on the basis of combined isotopic and mineralogic observations, that the leads in these mineralizations become more radiogenic as the temperature and pressure of their formation decrease.

Perhaps the most striking feature of the data presented is that the leads from the Outokumpu mine, the main sulfide ore belt, the Central Finnish batholith area and the Svecofennian supracrustal belt define a sublinear trend on all diagrams. It is worth noting that two of the samples from Outokumpu (G30, G170) fall slightly off the general trend in Figs. 2 and 3, but are in perfect concert with it on the trilinear lead diagram (Fig. 4) where the total effects of the U,Th-Pb systematics become evident.

The data warrant the conclusion that groups C, D, E and F form a sample popula-

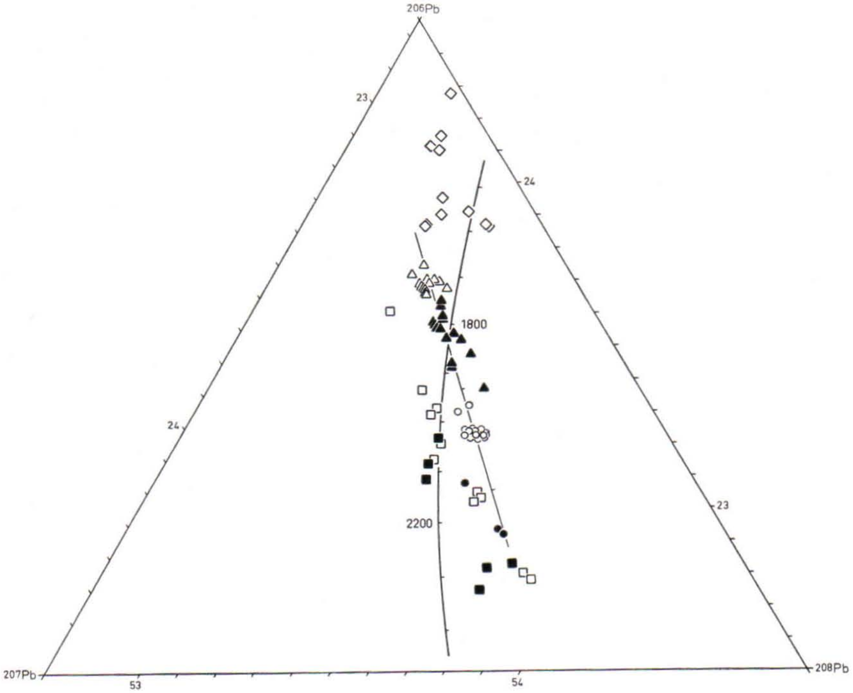

Fig. 4. The trilinear ^{206}Pb-^{207}Pb-^{208}Pb diagram. Samples from Saarikylä, Suomussalmi are omitted. The growth curve from Stacey and Kramers (1975). The trend of the Svecokarelian orogenic leads is indicated. Symbols as in Fig. 2.

tion intimately associated with the Svecokarelian orogeny, and can therefore be referred to collectively as the Svecokarelian orogenic leads. Besides the increasing $^{206}Pb/^{204}Pb$ ratio, the main characteristics of this group are:

1) a continuous decrease in the lead model age, especially evident in Fig. 2,
2) an increase of the U/Pb ratio, and
3) a decrease of the Th/U ratio in the source material of these galenas.

DISCUSSION

Leads from the Archean basement and from the Karelides

Radiometric U, Pb ages of zircons from the Archean basement complex range from 2600 to 2800 Ma (Kouvo 1958, 1976; Wetherill *et al.* 1962; Kouvo & Tilton 1966). The basement is unconformably overlain by the Jatulian quartzites, which are intruded by mafic volcanic rocks and diabases yielding zircon U,Pb ages from 2000 to 2200 Ma (Sakko 1971; Simonen *et al.* 1978). In southern Lapland the Jatulian overlies layered mafic intrusions (Fig. 1), which have been dated at 2450 Ma (Kouvo 1976). The middle succession of the Karelides, the so-called Marine Jatulian, consists of dolomites, black schists and banded iron formations. One of the banded iron formations has yielded a whole rock lead isochron age of 2080 Ma (Sakko & Laajoki 1975). The uppermost part of the Karelides, the Kalevian mica-schist—dolomite formation, is cut by the 1880 Ma old Svecokarelidic orogenic granitoids.

It is obvious that the lead model ages for the galenas from the Archean and Karelian mineralizations bear no relation to their true ages. Rather the wide variation of the lead isotopic compositions within both groups suggests that these mineralizations have undergone several phases of development. The high milieu indices point towards environments unusually rich in uranium and thorium as compared to lead. According to the plumbotectonics model (Doe & Zartman 1979), this would correspond to lead evolution in the upper crust.

The most surprising result is that the least radiogenic leads of the Archean basement complex, the samples from Saarikylä, Suomussalmi, have the highest μ values encountered in this study. Considering that the model ages of the samples are in good agreement with radiometric U,Pb dates of 2600—3000 Ma obtained from zircons from the Kuhmo-Suomussalmi greenstone belt (Kouvo, personal communication), it may well be that the high μ values implied by samples G33 and G305 reflect a primary feature of the Saarikylä ore. In order to generate a high μ lead, there should have been repeated fractionation of uranium, thorium and lead between the mantle and the crust before the formation of the deposit. Thus the lead isotopic composition of the Saarikylä ore suggest that at least parts of the Archean basement area may be considerably older than is indicated by the radiometric ages obtained so far.

The variations in the isotopic compositions of the leads in the Archean basement complex can be explained in the following manner: during the last Archean orogeny, some 3000—2600 Ma ago, there occurred one or more ore forming events, which resulted in the formation of a number of sulfide mineralizations with a variety of lead isotopic compositions. In the course of the Svecokarelian orog-

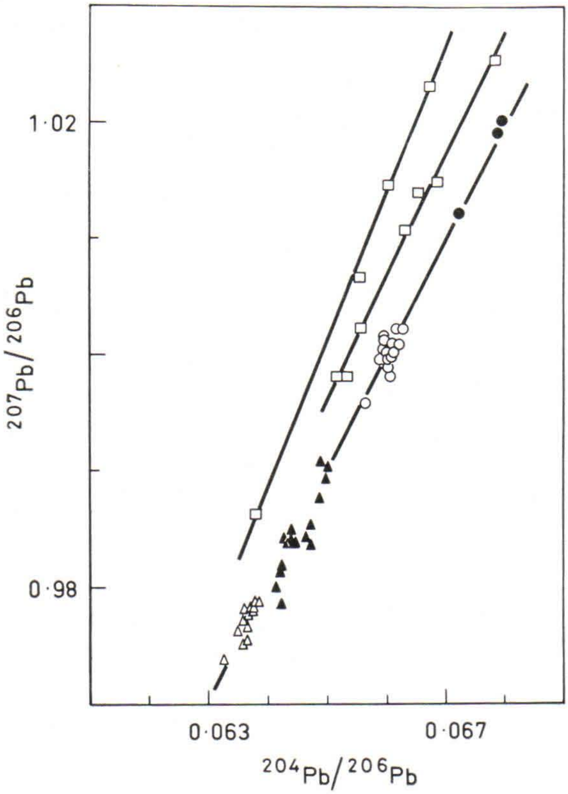

Fig. 5. The ^{204}Pb/^{206}Pb vs. ^{207}Pb/^{206}Pb diagram. The Archean basement samples and the galenas from the rapakivi granites are omitted. Note that the Karelian leads can be divided into two groups on this diagram. Symbols as in Fig. 2.

eny, about 2200—1800 Ma ago, these mineralizations were remobilized and radiogenic lead that had evolved in a crustal environment, characterized by high U/Pb and Th/Pb ratios, was incorporated into them. The scatter of the Archean basement leads on the trilinear plot (Fig. 4) indicates that the mixing was of a local nature, and that no regional homogenization of the lead isotopes occurred.

The higher resolution of the ^{204}Pb/^{206}Pb vs. ^{207}Pb/^{206}Pb plot (Fig. 5) reveals that the Karelian leads can be divided isotopically into two subgroups. Galenas situated in the Jatulian volcanic rock close to the Archean basement have higher U/Pb ratios in their source material than the other Karelian samples, which are situated mostly in the Kalevian formations. It is also worth noting, that the only mineable ore in this group, Hammaslahti, is the least radiogenic lead of the group and plots closest to the average growth curve.

The epigenetic nature of the mineralizations in the Karelian schists in general and of the Hammaslahti ore in particular (Hyvärinen *et al.* 1977), as well as the proximity of the Archean basement to the more radiogenic mineralizations suggests that these occurrences were formed during the Svecokarelian orogeny by hypogene material, which penetrated both the basement and the sediments of the continental margin. While passing through the rocks with high U/Pb ratios, the hypogene material scavenged from them lead evolved in a crustal environment. The sublinear trend of the Karelian leads on the trilinear plot (Fig. 4) suggests that the mixing of lead isotopes from a variety of sources was on a regional scale.

The Svecokarelian orogenic leads

The Outokumpu ore complex is situated in the Kalevian mica-schists and phyllites, which are thought to represent the flysch-facies of the Karelian sedimentation. A lower age limit to this phase of sedimentation is set by the Pb-Pb whole rock isochron age (2080 ± 45 Ma) of a Marine Jatulian iron formation (Sakko & Laajoki 1975). A detrital zircon from the Vuonos mine has an apparent age of 2285 Ma (GSF 1976), which indicates the minimum age of the source material of the Kalevian rocks. A uraninite from the remobilized part of the Outokumpu ore has a U,Pb age of 1895 Ma (Kouvo & Tilton 1966). Whole rock Pb-Pb and U-Pb isochrons (Asa, unpublished data) indicate ages of 1896 and 1875 Ma, respectively. Because the galena data (G30, G170) plot below the isochrons, the ages yielded by the latter are thought to reflect the remobilization rather than the emplacement of the ore. The ore is cut by pegmatite dikes dated by Rb-Sr studies of muscovites at 1790 Ma (Kouvo 1958, Kouvo & Tilton 1966). Likewise, phlogopite from a shear zone has yielded a Rb-Sr age of 1780 Ma (λ^{87}Rb $= 1.42 \times 10^{-11}/$ a).

A noteworthy feature is that the isotopic composition of the lead in the Outokumpu galenas is unique in the Karelides. The Outokumpu mineralization is most likely volcanic exhalative in origin (Mäkelä 1974). If formed at its present site, immediately next to the Archean basement and enveloped in sediments whose source material is at least 2285 Ma old, it is surprising that the ore has not scavenged any significant amount of crustal lead, though mineralizations of much lesser extent and often emplaced under less severe conditions have done so in the same geological environment. The ophiolitic nature of the Outokumpu complex, its high chromium and cobalt contents, and its paucity of lead point towards an origin from a basic or ultrabasic source. Geochemically, it resembles in many ways the pyritic copper ore deposits of the Troodos complex on Cyprus, which are popularly regarded as having been formed by volcanic activity at an ocean rise (e.g. Sillitoe 1972). However, the Outokumpu complex lacks signs of a submarine emplacement such as e.g. pillow lavas. In addition, it should be noted that the Troodos massif has also been interpreted as being due to a caldera collapse and subsequent fumarolic activity (Constantinou & Govett 1973).

The interpretation of the Outokumpu ore complex as a remnant of an ancient piece of oceanic crust, thrust by a nappe-forming movement (the F_1 phase of Gaál *et al.* 1975) into the flysch sediments accumulating at an active continental margin (e.g. Väyrynen 1939), could explain both the singular character of the ore as well as the lead isotopic composition of its galenas, which deviates so much from the other leads encountered within the Karelian formations.

Recently much new geochronologic data has been outlined from the *main sulfide ore belt*. The oldest age registered is a U,Pb date from zircons of granitic gneiss of 1932 ± 2 Ma (Helovuori 1979). A whole rock Pb-Pb isochron from the metavolcanic rocks in the Pyhäsalmi area yields an apparent age of 1909 ± 27 Ma (op. cit.). The isochron passes within analytical error through the data point for the Pyhäsalmi ore lead (G25). Titanites from the rocks of the Pyhäsalmi area generally yield ages around 1860 Ma. In the Vihanti area, an early orogenic dioritic gabbro has been dated by U,Pb analyses from zircons to be 1900 ± 10 Ma old. Synorogenic granitoids yield an age of 1875 ± 15 Ma, and a titanite from a diabase dike cross-cutting the ore gives a U,Pb age of 1860 ± 15 Ma (Vaasjoki, unpublished data). Whole rock Pb-Pb isochron and U,Pb data from the uraniferous phosphatic horizon suggest a complete resetting of this U,Pb system at 1876 ± 2 Ma (Vaasjoki *et al.* 1980). Thus the ores of the main sulfide ore belt have been emplaced before 1860 Ma. The fact that the whole rock lead isochron from the Pyhäsalmi metavolcanic sequence passes through the lead isotopic composition point of the galena from this deposit strongly supports the concept of a genetic link between the volcanic activity and the emplacement of the ores. From this point of view, the most likely age of deposition of the ores of the main sulfide ore belt is 1880—1940 Ma.

From the *Central Finnish batholith area,* a radiometric age survey was recently published by Aho (1979) for the area surrounding the small Ritovuori mineralization at Pihtipudas (no. 36, Fig. 1). Zircons from both the metavolcanic rocks and the surrounding granitoids give a U,Pb age of 1883 ± 20 Ma, and titanites as well as monazites from the granitoids yield

1800 Ma. A whole rock Pb-Pb isochron of the metavolcanic rock suite yields an age of 1898 ± 26 Ma, which may possibly indicate the time of ore formation, since the isochron passes through the point defined by the Pihtipudas galena (G16). Thus, though different in their lead isotopic compositions, the Pyhäsalmi and Pihtipudas ores are essentially coeval.

There is abundant geochronologic data from the plutonic rocks of the *Svecofennian supracrustal belt.* Radiometric U,Pb and Rb,Sr dates from a variety of minerals (e.g., Kouvo 1958, 1976; GSF 1975, 1976 and 1977) indicate that in southern Finland the intrusion of the early orogenic gabbros occurred about 1890 ± 10 Ma ago. Synorogenic granodiorites were emplaced during the interval from 1890 to 1860 Ma. Late orogenic granites and pegmatites, many of them migmatite forming, intruded the area about 1835 ± 15 Ma ago (Vaasjoki *et al.*). The orogenic period was followed by the emplacement of the post-orogenic granites around 1815 Ma in the Åland area and by the intrusion of the vast rapakivi massifs during the period from 1700 to 1540 Ma (Vaasjoki 1977). Most of the lead mineralizations in the Svecofennian supracrustal rocks occur either in quartzose veins cross-cutting the migmatites or in skarns formed during the migmatization. Thus, the most likely age for these deposits is from 1850 to 1820 Ma.

In summary, it is evident that the ore mineralizations exhibiting Svecokarelian orogenic leads have been formed during a time interval with a lower limit at 1835 ± 15 Ma and an upper limit ranging from 1880 to 2080 Ma. The lower limit is dependent only on the error limits of U,Pb mineral analyses from the late orogenic granites. The upper limit, however, depends to a large degree on the genetic interpretation of the Outokumpu ore deposit, and must be considered an open question at the present time. Obviously, any interpretation of the lead isotopic data from the Svecokarelian orogenic mineralizations must recognise this uncertainty.

The application of the shortest possible time span of Svecokarelian ore formation, about 30 Ma, would render the event practically instantaneous as far as lead model applications are considered. This means in effect that it might be permissible to interpret the Svecokarelian ore leads as mixtures of two discrete leads, one formed at the closing phases of the Archean, about 2800—2600 Ma ago, and the other during the Middle Proterozoic, about 1900—1800 Ma ago, with both leads plotting close to an average global growth curve. Such interpretations have been offered for a number of Scandinavian leads on various occasions (e.g. Kanasewich 1968; Rickard 1978). The data accumulated during this study indicate that the Svecofennian supracrustal leads, which should represent the other end member of the mixture, imply for their sources μ-values 10.0 ± 0.15 and 10.8 ± 0.1 for the SK- and CR-models, respectively. The μ-values implied by the least radiogenic Archean lead (Saarikylä, Suomussalmi) are much higher, thus ruling it out as the other end member of the mixture. Moreover, no leads have been detected between the Outokumpu ore lead and a hypothetical Archean end member. The present data therefore do not indicate a mixture of two discrete leads, though the possibility cannot be completely ruled out. It should also be pointed out that, if the Outokumpu deposit can be proven to have been formed more than 2000 Ma ago, the initial requirement of the lead mixing model, a short time span of emplacement of the Svecokarelian orogenic leads, would be obviated.

The Svecokarelian orogenic leads are plotted in Fig. 6 on a $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ diagram together with the mantle and orogene growth curves from the plumbotectonics model of Doe and Zartman (1979). This model

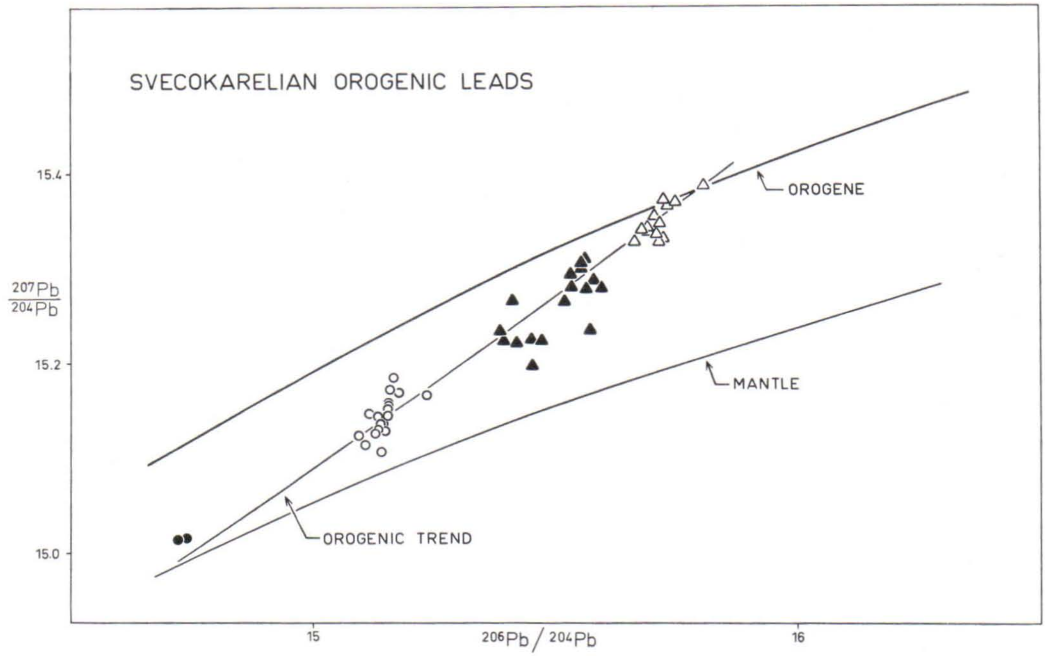

Fig. 6. The relationship of the Svecokarelian orogenic leads to the mantle and orogene curves of the plumbotectonics model (Doe & Zartman 1976) on the $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ diagram. Symbols as in Fig. 2. The sample G40 from a skarn in the Outokumpu deposit has been omitted.

presupposes that uranium, thorium and lead are initially divided between three sources, i.e. the upper and lower crust and the mantle. During an orogeny, which in the model is depicted as an instant event, fixed portions from the sources are mixed in the orogene and subsequently partially redistributed between the newly formed upper and lower crusts. The remainder is returned to the mantle. The redistribution concentrates mainly uranium, but also thorium and lead in the upper crust, while the mantle is depleted in these elements. Thus the orogene curve of the plumbotectonics model reflects the average evolution of lead in the lithosphere, while the mantle, the upper, and the lower crust curves depict the lead evolution in their various parts. It should be emphasized that, though orogenies are modelled as instant events, this has an impact on the interpretation of data only if the curves are used for dating purposes.

From Fig. 6 it becomes evident that the Svecokarelian orogenic leads can be interpreted as recording a steady evolution of lead from almost a mantle composition (Outokumpu, also noted by Stacey *et al.* 1978) to the final composition of an orogenic lead (leads of the Svecofennian supracrustal formation). It is worth studying the implications of such an interpretation in some detail.

The mantle origin of the Outokumpu ore can be supported by the intimate association of the ore with serpentinites, which, as indicated by olivine and pyroxene pseudomorphs, are at least partly metamorphosed peridotites (e.g. Huhma 1975). As indicated earlier, there is no reason why the Outokumpu complex could not be interpreted as an ophiolite derived from oceanic crust, which would explain its mantle-like characteristics.

Stacey *et al.* (1978) have concluded that the lead isotopic composition of the galena from the Pyhäsalmi mine (G25) indicated a mantle-derived lead. The data now available from the main sulfide ore belt (17 samples from 6 localities, excluding G74 and G292 from SW-Finland) suggest that significant amounts of crustal lead were incorporated into these ores. It seems plausible that lavas responsible for the mineralizations were generated through the melting of thoroughly homogenized crustal material under the influence of magmas derived from the mantle.

Though essentially coeval with the deposits of the main sulfide ore belt, the mineralizations of the Central Finnish batholith area contain more crustal lead. This may indicate either a passage of the mantle-derived material through a thicker pile of geosynclinal sediments or a lesser amount of lead in the mantle-derived component. The fact that all true lead ores are situated in the main sulfide ore belt, and no mineable ores of any kind are known from the Central Finnish Batholith area, favours the latter alternative.

Svecofennian supracrustal formation contains the youngest mineralizations within the Svecokarelian orogenic leads. These formed, as suggested by the wide-spread migmatization, at the peak of the regional metamorphism during the orogeny. Therefore, they should contain the largest and best mixed crustal component both in terms of rocks and lead. That the analytical data presented exhibit only a small scatter in the lead isotopic ratios, despite the variation in types and sizes of mineralization and the large geographic distances involved, is in the author's view strong evidence in favour of a plumbotectonic interpretation for the Svecokarelian orogenic leads.

From other areas, there are only few lead isotopic studies of galenas that encompass material on a large regional scale from a single orogenic domain. Data from Bohemia and Mexico indicate that the plumbotectonic interpretation may be generally applicable to orogenic regions.

Though Legierski and Sattran (1967) do not present individual analytical data, it is evident from their Fig. 3 that averages of their group I, II, III and IV deposits of the Hercynian of Bohemia form a sublinear array much resembling that of the Svecokarelian orogenic leads.

In a more recent paper, Cumming *et al.* (1979) have demonstrated that the Cenozoic Pb-Zn deposits of northern Mexico yield lead isotopic data conforming to a sublinear trend similar to that observed in the Finnish deposits. The relatively large scatter in the Mexican data is probably due to the combined effects of younger (and consequently more heterogeneous) starting material of lower metamorphic grade (and consequently less well mixed) than in Finland.

Exploration applications

The application of lead isotopic studies to mineral exploration has been long considered (e.g. Cannon *et al.* 1961). Doe and Stacey (1975) suggested that ores could be »fingerprinted» by their lead isotopic composition, and Gulson and Mizon (1979) have demonstrated that the lead isotopic composition of massive lead-zinc deposits such as Broken Hill is reflected in their weathered surface expressions as well.

The results of the present work provide accurate information on the lead isotopic compositions of the galenas of various types of base metal mineralizations in Finland. Especially in Central Finland, where it is possible to encounter in Pleistocene formations ore boulders derived from either the Archean basement, the main sulfide ore belt, the

Central Finnish batholith area or the Svecofennian supracrustal formation, the lead isotopic composition of galena is the easiest and most accurate way of determining the original geologic environment of the sample. Moreover, bearing in mind the constancy of the lead isotopic composition of galenas within the main sulfide ore belt as a whole and also within its individual deposits, lead isotopic determinations can make an important contribution to the assessment of mineral prospects within that region.

Another interesting aspect is that leads similar to those of the main sulphide ore belt occur in the Kankaanpää area in SW-Finland. The actual differences between the lead isotopic compositions of these two areas is of the same order as that observed between the Captain's Flat (Ostic *et al.* 1967) and Woodlawn (Gulson 1979) deposits in the Lachlan Fold belt in Australia. Though the paucity of the lead isotopic analyses does not allow to single out the Kankaanpää area as a major exploration target, it is evident that any future indication of base metal mineralization from the area should be given serious consideration and the material analyzed for its lead isotopic composition.

CONCLUSIONS

1) The leads from galenas from the Archean basement area demonstrate that remobilization of lead formed in the upper crust during the Lower Proterozoic occurred in the course of the Middle Proterozoic Svecokarelian orogeny. The least radiogenic lead of this group suggests that some parts of the basement area may be considerably older than is indicated by the radiometric data obtained so far.
2) Leads from mineralizations in the Karelian metasediments most likely represent material scavenged from the basement and underlying sediments of the Proterozoic continental margin.
3) The Svecokarelian orogenic leads suggest the formation of a mature orogenic lead by adding successively more homogenized crustal material into a mantle-derived lead component. The linear array formed by these leads is a typical feature to be expected in any orogenic environment.
4) Especially in Central Finland, the lead isotopic composition of galenas may be useful in assessing the value of new ore prospects and the origin of ore-containing boulders.

ACKNOWLEDGEMENTS

Throughout this study I was assisted technically by various members of the staff of the Geological Survey of Finland. Any help I needed was willingly given, and I am most grateful for this.

The encouragement of Dr. Olavi Kouvo was essential in initiating the work, and his keen interest at all its phases, as well as his appraisal of the first draft of the manuscript, was of great help. Constructive criticism by Drs. Atso Vorma and Brian Gulson (CSIRO) also served to improve the paper by way of curbing some of my wilder ideas.

The linguistic correction of the manuscript by Miss Judy Thomson of IER Editorial (CSIRO) as well as the final typing of the manuscript by CSIRO staff at North Ryde are gratefully acknowledged.

rived from oceanic crust, which would explain its mantle-like characteristics.

Stacey *et al.* (1978) have concluded that the lead isotopic composition of the galena from the Pyhäsalmi mine (G25) indicated a mantle-derived lead. The data now available from the main sulfide ore belt (17 samples from 6 localities, excluding G74 and G292 from SW-Finland) suggest that significant amounts of crustal lead were incorporated into these ores. It seems plausible that lavas responsible for the mineralizations were generated through the melting of thoroughly homogenized crustal material under the influence of magmas derived from the mantle.

Though essentially coeval with the deposits of the main sulfide ore belt, the mineralizations of the Central Finnish batholith area contain more crustal lead. This may indicate either a passage of the mantle-derived material through a thicker pile of geosynclinal sediments or a lesser amount of lead in the mantle-derived component. The fact that all true lead ores are situated in the main sulfide ore belt, and no mineable ores of any kind are known from the Central Finnish Batholith area, favours the latter alternative.

Svecofennian supracrustal formation contains the youngest mineralizations within the Svecokarelian orogenic leads. These formed, as suggested by the wide-spread migmatization, at the peak of the regional metamorphism during the orogeny. Therefore, they should contain the largest and best mixed crustal component both in terms of rocks and lead. That the analytical data presented exhibit only a small scatter in the lead isotopic ratios, despite the variation in types and sizes of mineralization and the large geographic distances involved, is in the author's view strong evidence in favour of a plumbotectonic interpretation for the Svecokarelian orogenic leads.

From other areas, there are only few lead isotopic studies of galenas that encompass material on a large regional scale from a single orogenic domain. Data from Bohemia and Mexico indicate that the plumbotectonic interpretation may be generally applicable to orogenic regions.

Though Legierski and Sattran (1967) do not present individual analytical data, it is evident from their Fig. 3 that averages of their group I, II, III and IV deposits of the Hercynian of Bohemia form a sublinear array much resembling that of the Svecokarelian orogenic leads.

In a more recent paper, Cumming *et al.* (1979) have demonstrated that the Cenozoic Pb-Zn deposits of northern Mexico yield lead isotopic data conforming to a sublinear trend similar to that observed in the Finnish deposits. The relatively large scatter in the Mexican data is probably due to the combined effects of younger (and consequently more heterogeneous) starting material of lower metamorphic grade (and consequently less well mixed) than in Finland.

Exploration applications

The application of lead isotopic studies to mineral exploration has been long considered (e.g. Cannon *et al.* 1961). Doe and Stacey (1975) suggested that ores could be »fingerprinted» by their lead isotopic composition, and Gulson and Mizon (1979) have demonstrated that the lead isotopic composition of massive lead-zinc deposits such as Broken Hill is reflected in their weathered surface expressions as well.

The results of the present work provide accurate information on the lead isotopic compositions of the galenas of various types of base metal mineralizations in Finland. Especially in Central Finland, where it is possible to encounter in Pleistocene formations ore boulders derived from either the Archean basement, the main sulfide ore belt, the

Central Finnish batholith area or the Svecofennian supracrustal formation, the lead isotopic composition of galena is the easiest and most accurate way of determining the original geologic environment of the sample. Moreover, bearing in mind the constancy of the lead isotopic composition of galenas within the main sulfide ore belt as a whole and also within its individual deposits, lead isotopic determinations can make an important contribution to the assessment of mineral prospects within that region.

Another interesting aspect is that leads similar to those of the main sulphide ore belt occur in the Kankaanpää area in SW-Finland. The actual differences between the lead isotopic compositions of these two areas is of the same order as that observed between the Captain's Flat (Ostic *et al.* 1967) and Woodlawn (Gulson 1979) deposits in the Lachlan Fold belt in Australia. Though the paucity of the lead isotopic analyses does not allow to single out the Kankaanpää area as a major exploration target, it is evident that any future indication of base metal mineralization from the area should be given serious consideration and the material analyzed for its lead isotopic composition.

CONCLUSIONS

1) The leads from galenas from the Archean basement area demonstrate that remobilization of lead formed in the upper crust during the Lower Proterozoic occurred in the course of the Middle Proterozoic Svecokarelian orogeny. The least radiogenic lead of this group suggests that some parts of the basement area may be considerably older than is indicated by the radiometric data obtained so far.
2) Leads from mineralizations in the Karelian metasediments most likely represent material scavenged from the basement and underlying sediments of the Proterozoic continental margin.
3) The Svecokarelian orogenic leads suggest the formation of a mature orogenic lead by adding successively more homogenized crustal material into a mantle-derived lead component. The linear array formed by these leads is a typical feature to be expected in any orogenic environment.
4) Especially in Central Finland, the lead isotopic composition of galenas may be useful in assessing the value of new ore prospects and the origin of ore-containing boulders.

ACKNOWLEDGEMENTS

Throughout this study I was assisted technically by various members of the staff of the Geological Survey of Finland. Any help I needed was willingly given, and I am most grateful for this.

The encouragement of Dr. Olavi Kouvo was essential in initiating the work, and his keen interest at all its phases, as well as his appraisal of the first draft of the manuscript, was of great help. Constructive criticism by Drs. Atso Vorma and Brian Gulson (CSIRO) also served to improve the paper by way of curbing some of my wilder ideas.

The linguistic correction of the manuscript by Miss Judy Thomson of IER Editorial (CSIRO) as well as the final typing of the manuscript by CSIRO staff at North Ryde are gratefully acknowledged.

REFERENCES

Aho, L., 1975. Ore mineralizations at Ritovuori, Pihtipudas, Central Finland. Geol. Surv. Finland Bull. 275. 20 p.

— , **1979.** Petrogenetic and geochronological studies of metavolcanic rocks and associated granitoids in the Pihtipudas area, Central Finland. Geol. Surv. Finland Bull. 300. 22 p.

Aurola, E. & Vähätalo, V., 1939. The pyrite deposits of Hevoskumpu in Tuupovaara. Bull. Comm. géol. Finlande 125, 87—95.

Borchert, H., 1954. Kritische Anmerkungen zu zwei neuen Arbeiten über Outokumpu, Finnland. Chemie der Erde 17, 1—5.

Cannon, R. R., Pierce, A. P., Antweiler, J. C. & Buck, K. L., 1961. The data of lead isotopes geology related to problems of ore genesis. Econ. Geol. 56, 1—38.

Catanzaro, E. J., 1967. Absolute isotopic abundance ratios of three common lead reference samples. Earth Plan. Sci. Letters 3, 343—346.

Constantinou, G. & Govett, J. S., 1973. Geology, geochemistry and genesis of Cyprus sulfide deposits. Econ. Geol. 68, 843—858.

Cumming, G. L. & Richards, J. R., 1975. Ore lead isotope ratios in a continuously changing Earth. Earth Plan. Sci. Letters 28, 155—171.

Cumming, G. L., Kesler, S. E. & Krstic, D., 1979. Isotopic composition of lead in Mexican mineral deposits. Econ. Geol. 74, 1395—1407.

Disler, J., 1953. Die Kupferkieslagerstätte von Outokumpu, Finnland. Bull. Comm. géol. Finlande 161. 108 p.

Doe, B. R. & Stacey, J. S., 1974. The application of lead isotopes to the problems of ore genesis and ore prospect evaluation; a review. Econ. Geol. 69, 757—776.

Doe, B. R. & Zartman, R. E., 1979. Plumbotectonics, The Phanerozoic. Pp. 22—70 *in* Barnes, H. L. (ed.) Geochemistry of hydrothermal ore deposits. 2nd ed., John Wiley & Sons, New York. 798 p.

Gaál, G., Koistinen, T. & Mattila, E., 1975. Tectonics and stratigraphy of the vicinity of Outokumpu, North Karelia, Finland. Geol. Surv. Finland Bull. 271. 67 p.

Geological Survey of Finland, Annual report on the activities for the year 1965, 42 p.; ... 1966, 43 p.; ... 1973, 62 p.; ... 1975, 69 p.; ... 1976, 75 p.; ... 1977, 76 p.

Gulson, B. L., 1979. A lead-isotope study of the Pb-Zn-Cu deposit at Woodlawn, New South Wales. J. Geol. Soc. Aust. 26, 203—208.

Gulson, B. L. & Mizon, K. M., 1979. Lead isotopes as a tool for gossan assessment in base metal exploration. J. Geochem. Expl. 11, 299—320.

Huhtala, T., 1979. The geology and zinc-copper deposits of the Pyhäsalmi-Pielavesi district, Finland. Econ. Geol. 74, 1069—1083.

Helovuori, O., 1979. Geology of the Pyhäsalmi ore deposit, Finland. Econ. Geol. 74, 1084—1101.

Huhma, A., 1975. New aspects to the geology of the Outokumpu region. Bull. Geol. Soc. Finland 48, 5—24.

Huhma, A. & Huhma, M., 1970. Contribution to the geology and geochemistry of the Outokumpu region. Bull. Geol. Soc. Finland 42, 56—88.

Hyvärinen, L., Kinnunen, K. & Mäkelä, M., 1977. The geochemistry, fluid inclusions, sulfur isotopes and origin of the Hammaslahti copper ore deposit, Finland. Geol. Surv. Finland Bull. 293. 23 p.

International Atomic Energy Agency, 1975. Le phenomene d'Oklo. Vienna, 649 p.

Isokangas, P., 1954. The Vihanti zinc deposit. Geol. tutkimusl., Geotekn. julk. 55, 29—32.

Jaffey, A. H., Flynn, K. F., Glendenin, L. E., Bentley, W. C. & Essling, A. M., 1971. Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U. Phys. Rev. C 4, 1889—1906.

Kahma, A., 1973. The main metallogenic features of Finland. Geol. Surv. Finland Bull. 265. 28 p.

— , 1978. The main sulfide ore belt of Finland between Lake Ladoga and the Bothnian Bay. Bull. Geol. Soc. Finland 50, 39—43.

Kanasewich, E. R., 1968. The interpretation of lead isotopes and their geological significance. Pp. 147—223 *in* Hamilton & Farquhar (eds.) Radiometric dating for geologists. Interscience, New York.

Kouvo, O., 1958. Radioactive age of some Finnish pre-Cambrian minerals. Bull. Comm. géol. Finlande 182. 70 p.

— , 1976. Kallioperämme kronostratigrafiasta. Pp. 1—13 *in* Stratigrafia-symposio 08. 09. 1976. Suomen Geologinen Seura, Geologiliitto, Koulutusmoniste n:o 2, Espoo. 111 p.

Kouvo, O. & Kulp, J. L., 1961. Isotopic composition of Finnish galenas. Ann. N.Y. Acad. Sci. 91, 476—491.

Kouvo, O. & Tilton, G., 1966. Mineral ages from the Finnish Precambrian, J. Geol. 74, 421—442.

Latvalahti, U., 1979. Cu-Zn-Pb ores in the Aijala —Orijärvi area, Southwest Finland. Econ. Geol. 74, 1035—1059.

Legierski, J. & Sattran, V., 1967. Blei-Isotope in Galeniten des Böhmischen Massivs. Freiberg. Forschungshefte C 209, 73—85.

LeRoux, L. J. & Glendenin, L. L., 1963. Half-life of thorium 232. Proc. Natl. Conf. Nuclear Energy, Pretoria, 83—94.

Mikkola, A., 1963. On the sulphide mineralization in the Vihanti zinc deposit, Finland. Bull. Comm. géol. Finlande 205. 44 p.

Mikkola, A. & Väisänen, S., 1972. Remobilization of sulfides in the Outokumpu and Vihanti ore deposits, Finland. 24th IGC, Canada, Section 4, 488—494.

Mäkelä, M., 1974. A study of sulfur isotopes in the Outokumpu ore deposit, Finland. Geol. Surv. Finland Bull. 267. 45 p.

Nikander, J., 1976. Pielaveden—Koivujärven jakson karsi- ja karbonaattikivien ja vulkaaniittien stratigrafiasta. [Master's thesis]. Unpubl. manuscript. Dept. Geology, Univ. Turku, Finland. 88 p.

Nykänen, O., 1971. The Karelides in the Tohmajärvi area, Eastern Finland. Bull. Geol. Soc. Finland 43, 93—108.

Ostic, R. G., Russell, R. D. & Stanton, R. L., 1967. Additional measurements of the isotopic composition of lead from stratiform deposits. Can. J. Earth Sci. 4, 245—269.

Rauhamäki, E., Mäkelä, T. & Isomäki, O-P., 1978. Geology of the Vihanti mine. Pp. 35—56 *in* Metallogeny of the Baltic Shield. Helsinki symposium 1978, June 12—21, Finland. Excursion guide. The Academy of Finland.

Rehtijärvi, P., Äikäs, O. & Mäkelä, M., 1979. A Middle Precambrian uranium- and apatite-bearing horizon associated with the Vihanti zinc ore deposit, Western Finland. Econ. Geol. 74, 1102—1117.

Richards, J. R., 1962. Isotopic composition of Australian leads. J. Geophys. Res. 67, 869—884.

Rickard, D. T., 1978. The Svecofennian anomalous ore lead line. Geol. Fören. i Stockholm, Förh. 100, 19—29.

Rouhunkoski, P., 1968. On the geology and geochemistry of the Vihanti zinc ore deposit, Finland. Bull. Comm. géol. Finlande 236. 121 p.

Sakko, M., 1971. Varhais-karjalaisten metadiabaasien radiometrisiä zirkoni-ikiä. Summary: Radiometric zircon ages of the Early-Karelian metadiabases. Geologi 23, 117—118.

Sakko, M. & Laajoki, K., 1975. Whole rock Pb-Pb isochron age for the Pääkkö iron formation in Väyrylänkylä, South Puolanka area, Finland. Bull. Geol. Soc. Finland 47, 113—116.

Saksela, M., 1957. Die Entstehung der Outokumpu-Erze im Lichte der tektonisch-metamorphen Stoffmobilisierung. N. Jb. Miner. Abh. 91, 278—302.

Sillitoe, R. H., 1972. Formation of certain massive sulphide deposits at sites of sea-flood spreading. Inst. Mining Metall. Trans. Sect. B, Vol. 81, No. 789 B141—B148.

Simonen, A., 1962. Alter und allgemeine Charakteristik des finnischen Grundgebirges. Geol. Rundschau 52, 250—260.

Simonen, A., Helovuori, O. & Kouvo, O., 1978. Laatokan—Perämeren vyöhykkeen kallioperän erikoispiirteistä ja iästä. Pp. 10—18 *in* Laatokan—Perämeren malmivyöhyke. Vuorimiesyhdistys, Espoo. 167 p.

Stacey, J. S. & Kramers, J. D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth Plan. Sci. Letters 26, 207—221.

Stacey, J. S., Doe, B. R., Silver, L. T. & Zartman, R. E., 1977. Plumbotectonics II A, Precambrian massive sulfide deposits. *In:* Geochronology and problems of the metallogeny, 93—106. »Nauka», Moscow. (In Russian).

Tatsumoto, M., Knight, R. J. & Allégre, C. J., 1973. Time differences in the formation of meteorites as determined from the ratio of lead-207 to lead-206. Science 180, 1279—1283.

Vaasjoki, M., 1977. Rapakivi granites and other post-orogenic rocks in Finland: their age and the lead isotopic composition of certain associated galena mineralizations. Geol. Surv. Finland Bull. 294. 64 p.

Vaasjoki, M., Äikäs, O. & Rehtijärvi, P., 1980 a. The age of Mid-Proterozoic phosphatic metasediments in Finland as indicated by radiometric U-Pb dates. Lithos 13, 257—262.

Vaasjoki, M., Appelqvist, H. & Kinnunen, K., in prep. On the genesis of some uranium deposits in the East-Uusimaa area, Southern Finland, in the light of mineralogic, fluid inclusion and geochronologic studies.

Vaasjoki, O., 1956. A comparison of the minor base metal contents of some Finnish galenas. Bull. Comm. géol. Finlande 172, 47—53.

Vähätalo, V., 1953. On the geology of the Outokumpu ore deposit in Finland. Bull. Comm. géol. Finlande 164, 98 p.

Varma, A., 1954. The copper–lead–zinc ore deposit of Orijärvi. Geol.tutkl. Geotekn. julk. 55, 17—19.

Väyrynen, H., 1939. On the geology and tectonics of the Outokumpu ore field and region. Bull. Comm. géol. Finlande 124. 91 p.

Wennervirta, P. & Rouhunkoski, P., 1970. Lithogeochemical aspects of the Vihanti zinc ore deposit, Finland. Econ. geol. 65, 564—578.

Wetherill, G. W., Kouvo, O., Tilton, G. R. & Gast, P. W., 1962. Age measurements of rocks from the Finnish Precambrian. J. Geol. 70, 74—88.

Yletyinen, V., 1978. Om antimonförekomsten i Seinäjoki—Nurmo. P. 38 *in* XIII Nord. Geol. Vintermöde. Abstracts, 98 p.

Descriptions of the mineralizations sampled

A. Mineralizations from Archean basement areas

1. Saarikylä, Suomussalmi (G33, G305, G306). An ore mineralization containing iron sulfides, galena and sphalerite. The host rocks are Archean metasediments, possibly of a volcanic origin, and belong to the Kuhmo—Suomussalmi greenstone belt.
2. Viitaranta, Ilomantsi (G168). A small galena mineralization in a mica schist.
3. Suhanko, Ranua (G145). A galena–iron sulfide mineralization in a drill-core sample. The host rock is a quartz diorite.
4. Huhus, Ilomantsi (G31). A disseminated galena–sphalerite–ilmenite mineralization in the basement gneiss.
5. Hevoskumpu, Tuupovaara (G54). A pyrite–galena–sphalerite ore in the Kiihtelysvaara—Ilomantsi amphibolite zone. The immediate host rocks are epidote and sericite quartzites, which probably were metasomatically formed during the emplacement of the ore (Aurola & Vähätalo 1939).
6. Tapaninkylä, Hyrynsalmi (G149). A few cm thick chalcopyrite–sphalerite–galena-bearing, sheared chlorite layers in a greenschist containing minor amounts of disseminated iron sulfides. Part of the Kuhmo—Suomussalmi greenstone belt.
7. Pahkakoski, Yli-Ii (G128). A dark, galena-bearing veinlet in a drill-core sample. The dominant rocks in the area are greenstones occurring together with acidic porphyries.

B. Deposits in Karelian schist

8. Hammaslahti mine (G183). The Hammaslahti copper ore is situated in a shear zone. The immediate host rock is an impure arkose containing fragments of phyllite. The ore is mainly of breccia type, but in places disseminated sulfides predominate. Chalcopyrite and pyrite are the principal ore minerals. Sphalerite and galena are scarce. Hyvärinen *et al.* (1977) consider the ore deposit to be epigenetic and that the ore-forming material was remobilized from the country rocks.
9. Mosku, Tohmajärvi (G75). Chalcopyrite–galena–bearing quartz veins cut a metadiabase belonging to the group that is known to penetrate both the Archean basement and the Jatulian quartzites (cf. Nykänen 1971).
10. Runkausvaara, Tervola (G153, G289). The samples are from two slightly different localities. G153 represents a 1 m thick mineralized quartz vein intersecting an albite diabase intercalation in a Karelian quartzite about 500 m from the contact against the basement gneiss. G289 is a drill-core sample, and represents a differentiated albite diabase beneath the Karelian quartzite. It contains a mineralized quartzose part, possibly a vein.
11. Tikkala, Tohmajärvi (G82). A set of 10—20 cm thick quartz veins containing galena, sphalerite, chalcopyrite and iron sulfides cut a dolomite belonging to the Marine Jatulian formation.
12. Kolmisoppi, Sotkamo (G303). Galena-bearing quartz vein cutting a Karelian black schist in a drill-core sample.
13. Niittylahti, Pyhäselkä (G41). Galena mineralization in mica schist.
14. Mieslahti, Paltamo (G152). Galena mineralization in Karelian quartzite close to the contact of the Archean basement.
15. Suoranta, Pyhäselkä (G296, G304). A quartz vein cutting Kalevian mica schists containing sporadic galena and chalcopyrite mineralizations.
16. Koli, Lieksa (G302). A schist in the lowest Karelian formation containing finely disseminated galena.

C. Outokumpu mine

17. Outokumpu mine (G30, G40, G170). The Outokumpu copper ore deposit is connected with the so-called Outokumpu complex composed of black schists, quartzites and serpentinites, which can be traced over a distance of 30 km. The rocks surrounding it are originally pelitic sediments metamorphosed to mica schists in the conditions of amphibolite facies (Gaál *et al.* 1975). The outermost units of the Outokumpu complex are black schists. Almost monomineralic quartzites, generally in connection with large serpentinite bodies (Huhma & Huhma 1970), constitute the immediate host rock of the ore. At times, dolomites and skarns occur between the quartzite and the serpentinite. The dimensions of the serpentinite lenses may reach several hundreds of metres in width and several kilometres in length. The Outokumpu ore body lies concordantly in one of the quartzite layers. Texturally, the ore can be divided into banded pyritic and massive pyrrhotitic types. The average thickness of the ore body is 7—9, its width 200—400 m and it is about 4 km long. Opinions of the genesis of the ore have ranged from epigenetic hydrothermal to syngenetic sedimentary. Currently, the ore is considered to be syngenetic volcanic–exhalative in origin (Mäkelä 1974).

    Very little galena has been found in the deposit. G30 is from the contact between the ore and the serpentinite, G40 from a diopside skarn, and G170 from the ore proper.

    The deposit has also been dealt with by Vähätalo (1953), Disler (1953), Väyrynen (1939), Borchert (1954), Saksela (1957) and Huhma (1975).

D. Leads from the main sulfide belt

18. Pukkiharju, Rautalampi (G295). A number of small ore showings, containing iron sulfides, sphalerite and galena occur in a schist zone consisting of gneisses, amphibolites, quartz–feldspar schists leptites and cordierite rocks. A number of skarns also occur in the area.
19. Säviä, Pielavesi (G17). The ore is situated in the cordierite-antophyllite gneiss formation of Säviä. Pyrite and chalcopyrite are the major ore minerals, with minor sphalerite and galena. See Huhtala (1979).
20. Pyhäsalmi mine (G25). The Pyhäsalmi ore deposit lies in a strongly metamorphosed schist belt of volcanic–sedimentary affiliation. The deposition of the compact pyrite ores seems to have preceded the folding. The formation of the ore was initially syngenetic, but later tectonic movements during the Svecokarelian orogenic culmination have brought about structures typical of epigenetic ores (Helovuori 1979).
21. Jylhä, Pielavesi (G106). Galena mineralization in a drill-core sample. The country rock is a cordierite gneiss belonging to the Säviä schist formation.
22. Vihanti mine (G26, G89, G93, G92, G90, G87, G126, G91, G86, G88, G286). This ore deposit is part of the Lampinsaari complex, which is enveloped by mica gneisses, usually interpreted as metagreywackes. The Lampinsaari complex comprises acid volcanic rocks, skarns, dolomites, graphite tuff and quartz porphyry. Most of the volcanic rocks are dacitic in composition. Pyrite and lead–zinc ores occur as separate bodies (Rauhamäki *et al.* 1978). The formation of the deposit has been attributed to various geologic processes ranging from epigenetic–igneous to syngenetic–volcanic. Currently, the latter interpretation is the prevailing one. The deposit has also been dealt with by Isokangas (1954), Mikkola (1963), Rouhunkoski (1968), Wennervirta and Rouhunkoski (1970) and Mikkola and Väisänen (1972).
23. Kumpuselkä, Keitele (G57, G58). A number of small iron sulfide–chalcopyrite–galena mineralizations in plagioclase porphyrites, amphibolites, arkosites and cordierite–sillimanite gneisses. G57 is from an outcrop, G58 from a drill-core sample.
24. Heittola, Kankaanpää (G74). A galena–sphalerite dissemination in skarn-bearing amphibolite in the NW-end of the Kankaanpää schist-zone, close to the contact of a gneissose diorite.
25. Verttuunjärvi, Kankaanpää (G70, G292, G293). Fine-grained sphalerite and galena are disseminated in an amphibolite (G292). The country rock is pierced by an EW-trending fracture zone, quartz and massive sphalerite, locally also galena and iron sulfides (G70, G293). The leads from this locality have been classified by isotopic grounds only.

E. Leads from the Central Finnish batholith area

25. Verttuunjärvi, Kankaanpää. See above.
26. Kaipola, Jämsä (G100). The Kaipola schist zone is surrounded by the typical rocks of the Central Finnish batholith area: potassium granites, diorites and hornblende gabbros. The supracrustal formation consists of mica schists, leptite gneisses, greywackes, conglomerates, amphibolites and uralite porphyrites, which all exhibit signs of granitization. In the hornblende–mica schists there are numerous small skarns, one of which contains a galena–chalcopyrite–sphalerite–iron sulfide mineralization. Field reports M/17/Jä 57/1 and M/17/Jä 59/2 by Paunu Oivanen (GSF).
27. Lepomäki, Hämeenkyrö (G118). Galena-bearing sulfide accumulations on schistosity plains in an acidic schist.
28. Visuvesi, Kuru (G45). An acidic–intermediate volcanic rock containing disseminated chalcopyrite, galena and sphalerite.
29. Sykäräinen, Toholampi (G95, G96). A volcanogenic schist formation, where amphibolite grades into quartz–feldspar schist. In the latter rock there occur narrow galena veins.
30. Muittari, Saarijärvi (G83, G84, G85). The supracrustal formation of Saarijärvi consists of quartz porphyry and plagioclase porphyry. In the marginal parts of the formation, close to the contact against potassium granites, galena and sphalerite occur both as dissemination and veins. The ore paragenesis also includes chalcopyrite, bornite, chalcocite, magnetite and fluorite.
31. Tarhapää, Keuruu (G122). A galena mineralization in a pegmatite vein crosscutting a veined gneiss possibly of supracrustal origin.
32. Muurame (G294). A galena-bearing quartzose vein in a granodiorite.
33. Korpilahti (G98). A galena-bearing quartzose vein in a foliated granodiorite.
34. Tahkonsaari, Korpilahti (G99). Similar to the previous two.
35. Kolima, Viitasaari (G15). The Kolima schist formation consists of partly migmatized amphibolites, leptites, agglomerates and garnet-bearing paragneisses. The sample, containing sphalerite, galena and iron sulfides stems from the last mentioned rock.
36. Ritovuori, Pihtipudas (G16). The mineralized rocks lie within the Pihtipudas schist zone, which comprises mostly acidic and basic metavolcanic rocks and a subordinate amount of metasediments. The ore mineralization occur in a brecciated zone rich in tourmaline, and can be divided into separate galena–quartz and arsenopyrite–quartz veins. The area has been studied in detail by Aho (1975, 1979).
37. Koijärvi, Forssa (G307). A sphalerite–pyrite–galena–chalcopyrite mineralization in an amphibolite, probably associated with a fracture zone.
38. Leppämäki, Alajärvi (G173). A galena–sphalerite–chalcopyrite–arsenopyrite mineralization in a migmatitic gneiss.

E. Leads from Svecofennian supracrustal rocks

39. Attu, Parainen (G11). A galena–sphalerite deposit associated with calcareous rocks (O. Vaasjoki 1956).
40. Seinäjoki—Nurmo (G282, G283, G284). The samples are from three slightly different localities, all belonging to the Seinäjoki—Nurmo antimony occurrences. The mineralizations are situated in Svecofennian schists close to the contact of the Central Finnish batholith. The main rock types are mica schists, probably both sedimentary and volcanic in origin, and intermediary and acid volcanic rocks. The antimony mineralizations occur partly as impregnations in sheared parts of the intermediary and acid volcanic rocks. The most important ore minerals are metallic antimony, arsenopyrite, loellingite, stibnite, gudmundite and pyrrhotite. Lesser amounts of pyrite, chalcopyrite, bethierite, breithauptite, metallic gold, galena and aurostibite occur (Yletyinen 1978).
41. Orijärvi, Kisko (G12). The Orijärvi mine, as well as the nearby Aijala and Metsämonttu mines, belong to the Kemiö—Kisko schist zone. The area is dominated by amphibolites and cordierite–antophyllite rocks. Limestones and tremolite–actinolite skarns occur as intercalates. The ores are partly disseminated and partly breccialike sphalerite–galena–chalcopyrite–iron sulfide mineralizations (Varma 1954; Latvalahti 1979).
42. Koskenkylä, Pernaja (G263, G266). See Vaasjoki (1977), Appendix 2.
43. Karkalinniemi, Lohja (G169). Small sulfide mineralization associated with skarns.
44. Lohjansaari, Lohja (G288). As G169.
45. Lammi (G52). Small galena mineralization in a quartz vein.

46. Hyvärilä, Lemi (G7). See Vaasjoki (1977), Appendix 2.
47. Korsnäs mine (G9). The Korsnäs lead ore deposit is situated in a tectonically brecciated zone cutting the surrounding gneisses. The immediate host rocks of the ore are skarns and calcite. A lead mine, with lanthanoids as an important by-product.
48. Pakila, Helsinki (G13). A galena-bearing quartz-vein intersecting the Svecofennian migmatites.
49. Hästö, Perniö (G48). A marcasite–galena–arsenopyrite–loellingite mineralization in Svecofennian migmatitic rock.

G. Leads from the rapakivi granite massifs

50—54. See Vaasjoki (1977), Appendix 2.

Tätä julkaisua myy

VALTION PAINATUSKESKUS
MARKKINOINTIOSASTO

Postimyynti
PL 516
00101 HELSINKI 10
Puh. 90-539 011

Kirjakauppa
Annankatu 44
00100 HELSINKI 10
Puh. 90-17341

Denna publikation säljes av

STATENS TRYCKERICENTRAL
MARKNADSFÖRENINGSAVDELNINGEN

Postförsäljning
PB 516
00101 HELSINGFORS 10
Tel. 90-539 011

Bokhandel
Annegatan 44
00100 HELSINGFORS 10
Tel. 90-17341

This publication can be obtained from

GOVERNMENT PRINTING CENTRE
MARKETING DEPARTMENT

Bookshop
Annankatu 44
00100 HELSINKI 10
Phone 90-17341

Orders from abroad:
AKATEEMINEN KIRJAKAUPPA
Keskuskatu 1
SF-00100 Helsinki 10

ISBN 951-690-146-8
ISSN 0367-522X