Silver mineralization in the ancient Akersberg mine, Oslo

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Recent archaeological excavations have uncovered parts of the ancient silver workings of the Akersberg mine in the city of Oslo. Pb–Zn mineralization is confined to a partially brecciated Permian diabase intrusion which intersects the Ordovician slate/limestone sequence of the area. The sulphides occur as steeply dipping veins – partly within the diabase and partly at the diabase contact. The main ore minerals are pyrite, sphalerite, galena and chalcopyrite, argentite, sternbergite, hessite and covellite are accessory constituents. Brecciation with 'crack-and-seal' structures are common and reflect several episodes of mineralization. Supergene alteration processes have led to the silver enrichment in secondary silver minerals that coat the primary sulphide minerals. The diabase dyke follows the NW–SE-trending fracture pattern of the Oslo district, and subsequent development of cross-cutting fissures in the diabase may have allowed the introduction of ore-bearing fluids. Lead isotope analyses of galenas from Akersberg reveal a pattern comparable to that of other Pb–Zn vein deposits within the Oslo Graben and point to a granitic source of the metals.

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The geology of the Oslo district is characterized by the lithological units and structural features associated with the development of the Permo-Carboniferous rift system of SE Norway, commonly referred to as the Oslo Graben or the Oslo Paleorift (Ramberg 1976). The main geological features of the Oslo Graben have been extensively studied and documented for more than a century (Dons 1978), and have been summarized by Dons & Larsen (1978) and Neumann & Ramberg (1978).

The Oslo district belongs to the southern part of a northern (Akershus) graben segment, and consists largely of Cambro-Silurian rocks and Permian plutonic and volcanic rocks which have subsided into the surrounding Precambrian gneisses of the Fennoscandian shield along major N–S to NNE–SSW-trending fault lines. The Cambro-Silurian sequence of the Oslo district consists predominantly of marine shales and limestones, and lesser arenaceous and conglomeratic beds. The succession was folded along NE–SW-trending horizontal axes during the Caledonian orogeny, and has an overall NE–SW strike and a moderate to steep NW dip. The Cambro-Silurian sequence has been intruded by Permian granites, syenites and monzonites, which occupy the northern part of the Oslo district and comprise the southern part of the Nordmarka–Hurdalen batholith complex of the Akershus graben segment. Swarms of Permian dykes, which comprise a variety of igneous lithologies, intersect the Cambro-Silurian metasedimentary rocks within the area of the city. Diabases constitute the majority of the dykes in question, although syenitic and monzonitic varieties are also common. The major dykes are featured on the key map (Fig. 1) and their tectono-magmatic relationships in the Oslo district will be discussed later.

Reports of and remnants from ancient mining activities in the city of Oslo are scanty. An overall account on the metallogeny of the entire Oslo Paleorift has been given by Olerud & Ihlen (1986), and brief accounts of the ore deposits in the vicinity of the city and their history have been given by Falck-Muus (1935) and Segalstad & Dons (1977). These deposits comprise a number of small, skarn-type Fe-oxide and Cu–Zn sulphide deposits at the contact between the Permian intrusives and hornfelsed meta-limestones in the Sognsvatn area (Fig. 1), and they constitute some of the oldest recorded iron ore deposits in Norway, having been worked from the beginning of the 16th century.

At the foothill of Akersberg, beneath Gamle Aker church in the central part of the city, old silver mine workings have been known for centuries, but little is known about the nature and setting of the ores, as no material remains from the working periods. According to the Latin document *Historia Norvegiae*, from the late 12th century, the mine might have been exploited and abandoned even before that century. The mine was eventually reopened for two short periods during the 16th century and may at that time have caught the attention of Agricola (1546), who refers to the deposit in his *De veteribus et novis metallis* (Falck-Muus 1935; Thuesen 1979). The mining operations at Akersberg were in all probability finally closed down some time between 1580 and 1612.

The urban development since that time has brought about infilling of the old mine shafts and adits, and quarrying by the municipality of Oslo during the years 1908–1910 left a partially infilled adit (Fig. 2) of the old mine, which was protected by law by the Central Office of Historic Monuments in 1975 (Madsen 1975). The site

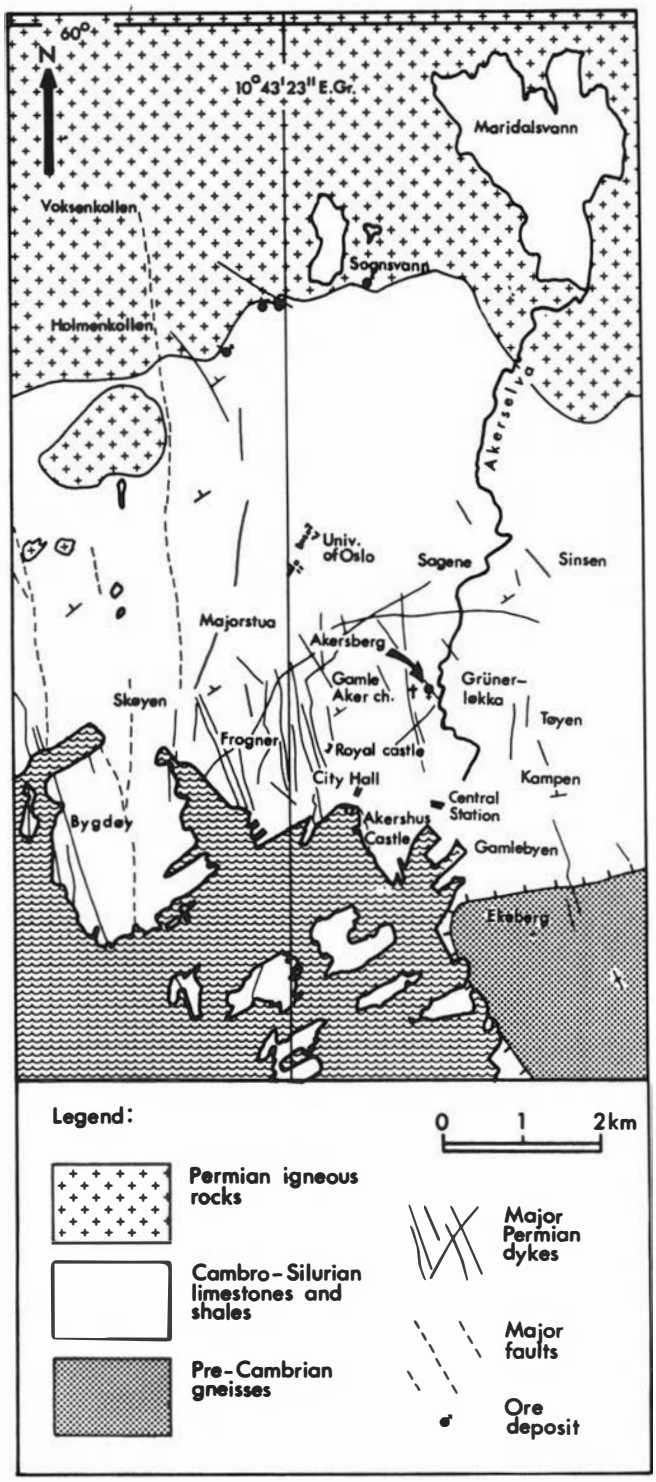

Fig. 1. Key map of the central Oslo district showing the main geological units (modified from K. O. Bjørlykke 1898, Holtedahl & Dons 1952 and Naterstad et al. 1990).

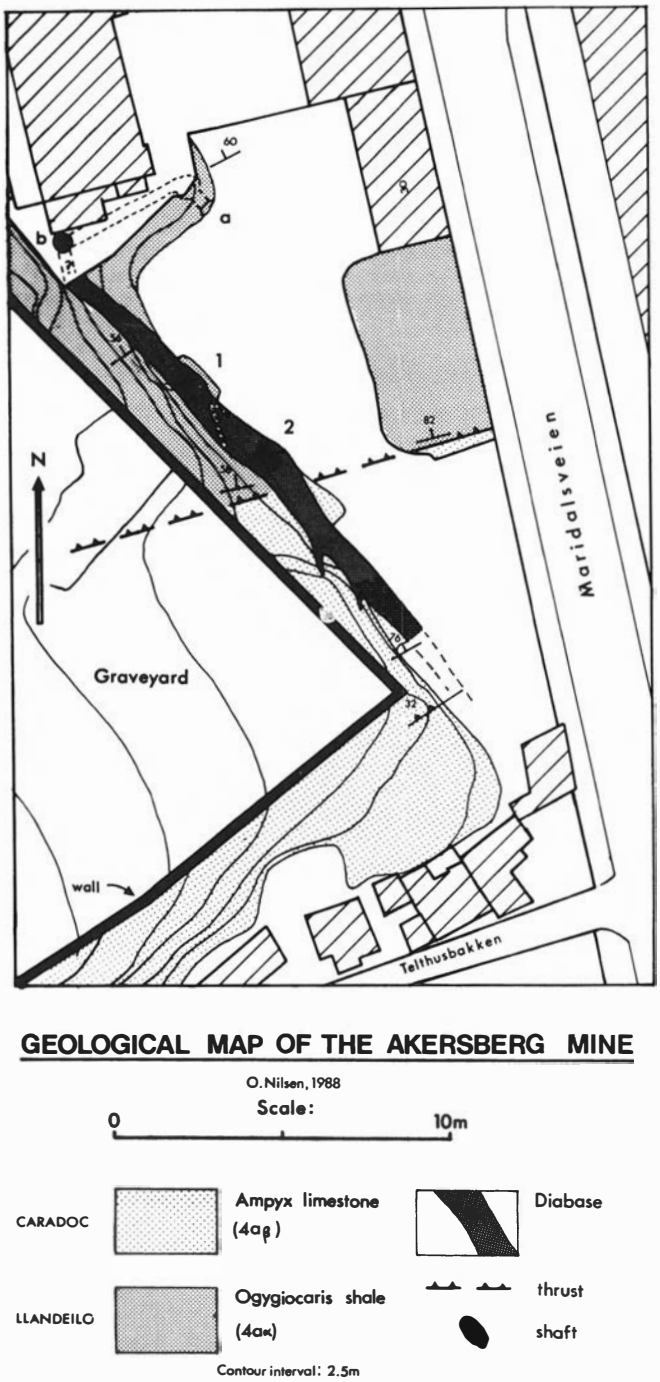

Fig. 2. Geological map of the Akersberg mine.

of the old quarry was occupied by a soap factory by the time of World War I, and this was demolished early in 1988. The site was then made ready for the construction of a new office building. This situation provided an excellent opportunity for a re-examination of the reported old workings by a supervised excavation to recover possible ore material and artifacts. This was carried out in late August 1988 by the University Museum of National Antiquities in Oslo in cooperation with the contractor.

Previous work

The excavations revealed and confirmed that the ore mineralization is closely associated with a diabase dyke which intersects the Cambro-Silurian strata of the area. This particular affiliation was pointed out by Keilhau as early as 1823. The presence of sphalerite, chalcopyrite and galena in the ores was later noted by Keilhau (1838),

Kjerulf (1865, 1879) and Schetelig (1917). Scheerer (1845, 1848) presented three analyses of the black sphalerite from the specimens available at that time. However, since the turn of the century no further information has become available regarding the local setting and mineralogy of the (presumed) silver-bearing ores at Akersberg. A preliminary account of the Akersberg mine, based on recent information, has been given by Nilsen (1988).

Geological setting

The bedrock of the investigated area of Akersberg (Maridalsveien 26 and 28) (Fig. 2) consists of a sequence of Middle Ordovician slates and nodular limestones with a NE–SW strike and a steep NW dip (N56–60E/60–80NW). The site of the old quarry is bordered to the SW by a nearly vertical jointed wall, 15–20 m in height, which displays a good geological section through the strata (Figs. 2 and 3).

Grey, fossiliferous marls and carbonaceous slates with pyrite concretions and with sparsely distributed disc-shaped limestone nodules occupy the NW part of the section. A member of the Llandeilian Elnes formation (or *Ogygiocaris series* (4aα)) Owen et al. 1990) has been thrust towards the SE (Telthusbakken) above the Caradocian Vollen formation (or *Ampyx limestone* (4aβ)). Towards the reverse fault, the Ogygiocaris shale becomes strongly crenulated and contorted; it has been partly brecciated and intersected by numerous NE-dipping, calcite filled strike-slip veins (Fig. 3).

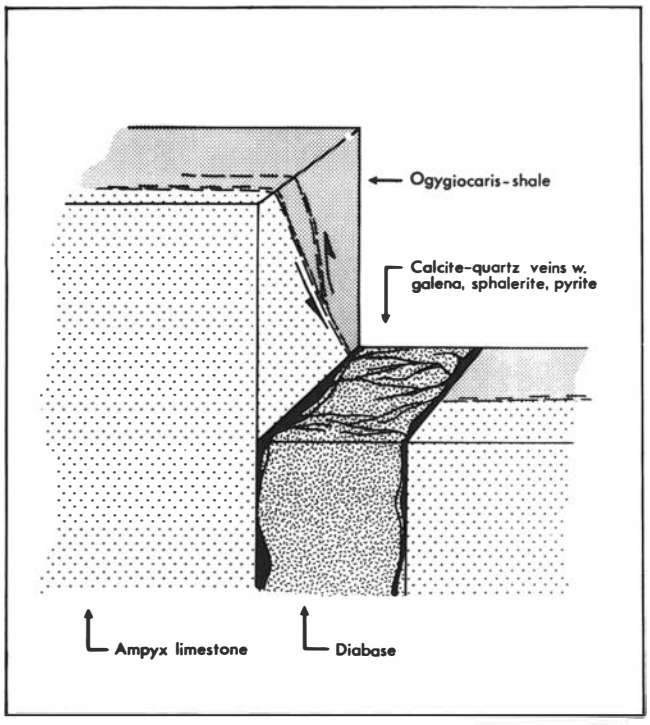

Fig. 3. Schematic block diagram of the Akersberg mine.

The Permian diabase dyke cut nearly vertically through the strata, following a prominent set of vertical NNW–SSE-striking (N140–160E) master joints, which form the surface of the steep wall of the quarry. The dyke has been mapped along its strike for more than 1 km (K. O. Bjørlykke 1898). The diabase crops out in the NW corner of the quarry where it is 3 m thick.

Recent excavation included a trench dug along the strike of the diabase from NW to SE to try to confirm the presence of at least two vertical shafts reported by Falck-Muus (1935) from the old mine workings. The diabase was uncovered for 70 m along the trench beneath a shallow (0.2–0.5 m) cover of urban debris. The two vertical shafts (or winzes) into the diabase were exposed (Shafts 1 and 2, Fig. 2), filled with rock and ore waste as well as prepared timber (props). The filled-in shafts were excavated to a depth of approximately 3.5 m and revealed the openings of a drift running parallel to the dyke – 1–1.5 m below the present surface – linking the two shafts (Fig. 2).

The mineralization

Shaft 1 with its waste material provided the best opportunity to study the *in situ* ore, as well as ore and gangue material from the inaccessible parts of the mine. The NW and SE part of the shaft opening reveals a cross-section of the diabase dyke, which is intersected by a linked system of sulphide-bearing quartz-calcite veins.

The central part of the diabase is a massive, fine-grained, greenish grey rock with darker, chilled margins against an altered, pastel-green marl of the Ogygiocaris shale. The latter is intersected by a set of closely spaced, barren calcite veins along the master joint set of the area, which runs parallel to the diabase walls. In the central part of the diabase, angular xenoliths, 1–10 cm across, occur. They consist of Permian syenite and grey granite from the Precambrian basement, as earlier noted by Keilhau (1823) and K. O. Bjørlykke (1898).

The diabase has a porphyritic texture and carries phenocrysts of sericitized plagioclase and chloritized Ti-augite in a fine-grained matrix of plagioclase, clinopyroxene, chlorite and magnetite. Serpentine, biotite, apatite, rutile and sphene are accessory constituents. Amygdules, several millimetres across, occur frequently in the central part of the diabase and are filled with chlorite, calcite, quartz crystals and chalcopyrite.

Petrographically, the mafic dyke at Akersberg does not differ significantly from the numerous amphibole-free, pyroxene-bearing diabase dykes of the Oslo Region, and the earlier term 'proterobas' applied by K. O. Bjørlykke (1898) for the dyke in question is inappropriate.

Near the sulphide veins, silicification of the diabase has taken place, as its plagioclase has been replaced by fine, granular quartz pseudomorphs. A 1–2 cm thick chlorite selvage in most cases borders the sulphide veins.

The sulphide mineralization occurs as a steeply-

dipping, linked vein system which cross-cuts the dyke in its central parts, being deflected into parallelism towards the dyke walls and along the master joint set within the wallrocks (Fig. 3). Here small-scale faulting and brecciation of the veined diabase has occurred and in places the veins swell out into massive nests of quartz, calcite and sulphides. The mineralization within the brecciated diabase contact cuts across the barren veins that parallel the strike of the wallrocks (Fig. 3). Here, vugs composed of spectacular coarse-grained euhedral crystals of quartz, calcite, black sphalerite and pyrite are found. The quartz breccia occurs as a comb-structured system of 'crack-and-seal' veins between fragments of shattered diabase that have been highly argillitized and silicified. This indicates multiple fracturing and resealing events during mineralization. Weak argillization and decarbonization (bleaching) have affected the immediate contact (±10 cm) of the Ogygiocaris shale and have obliterated the possible effects of contact metamorphism by the diabase. Galena, which was probably the target of the ancient exploitation, and pyrite are chiefly confined to the thin (2–10 mm) crustified veins within the central part of the diabase.

Mineralogy

The ore of the Akersberg mine consists of hypogene and supergene ore assemblages which are restricted to the thin (2–20 mm) crustified veins within the diabase (Table 1). The vein crustification is in general symmetrical, with similar crusts on both sides of the vein, but more complex relationships are found in some places, e.g. at the junctions of cross-cutting veins.

Sphalerite and pyrite (I) are the chief ore minerals and have a grain size of 0.5–5 mm. The primary sulphide assemblages are intersected by fissures which are commonly healed by the secondary minerals. The sphalerite is brownish black and is characterized by a 'chalcopyrite disease' texture which points to a hypogene replacement of the sphalerite (Barton & Bethke 1987; Eldridge et al. 1988). Microprobe analyses reveal high iron contents within the sphalerites (10–12% Fe), in accordance with the old analyses published by Scheerer (1845, 1848) and Oftedal (1941).

Pyrite (I) occurs as subhedral and euhedral grains, 0.5–5 mm across, and contains abundant inclusions of sphalerite, pyrrhotite and galena. It often shows myrmekitic and atoll-textured intergrowths with galena. Galena and chalcopyrite form an intergranular matrix between sphalerite and pyrite. In some places galena is seen as tiny veinlets that have invaded the other matrix minerals along fractures. Less commonly, hessite occurs as small, wedge-shaped inclusions in galena. Molybdenite is occasionally found as small, flaky inclusions in pyrite.

The supergene minerals constitute, in general, very minor components of the ore and are commonly found in the waste-ore material from the excavations. They are characteristically restricted to mere stain along fissures and cracks in the primary ore assemblages. An exception is covellite, which in places has replaced small grains of galena along grain boundaries (Fig. 4). The supergene silver mineralization is generally confined to fissures in sphalerite. Here, sternbergite ($AgFe_2S_3$) is a minor accessory constituent of the waste-ore material. It occurs as granular fissure fillings and has developed with a radial, sheaf-like intragranular texture. The mineral has commonly been replaced by argentite (Ag_2S) and fine globular pyrite (II) (Fig. 5). Argentite occurs mostly as fissure

Table 1. Ore mineral assemblages of the Akersberg mine (in decreasing order of abundance).

Hypogene	Supergene
Sphalerite	Limonite
Pyrite (I)	Anglesite
Chalcopyrite	Covellite
Galena	Pyrite (II)
Pyrrhotite	Argentite
Hessite	Sternbergite
Molybdenite	

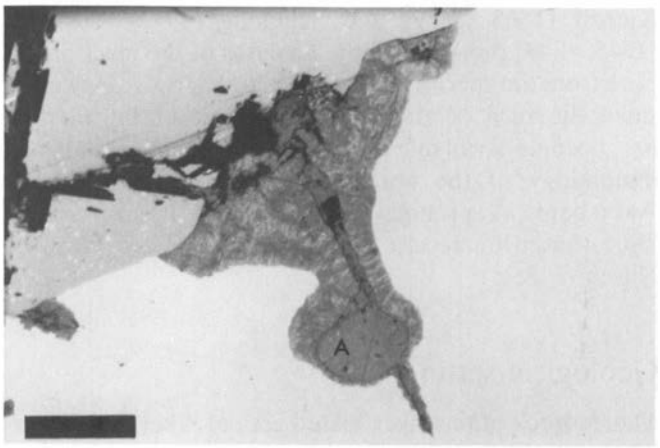

Fig. 4. Sooty covellite (grey) and anglesite (A) replacing galena (white) in contact with sphalerite (light grey). Reflected light. Scale bar: 0.05 mm.

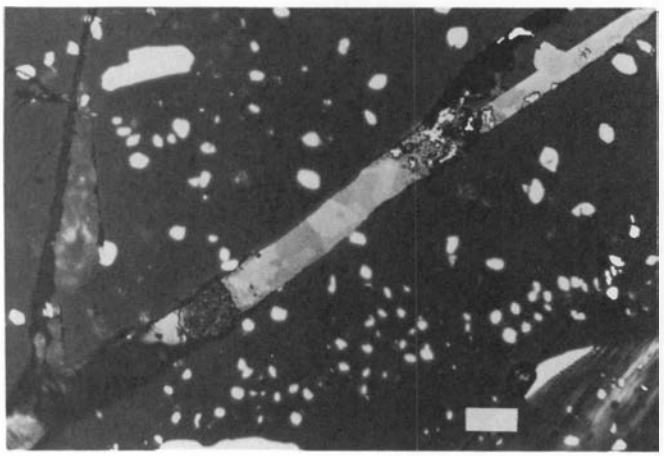

Fig. 5. Fissure filling of sternbergite (grey), partially replaced by pyrite (II) and argentite, in sphalerite (dark grey) that contains blebs of chalcopyrite. Reflected light, oil immersion. Scale bar: 0.01 mm.

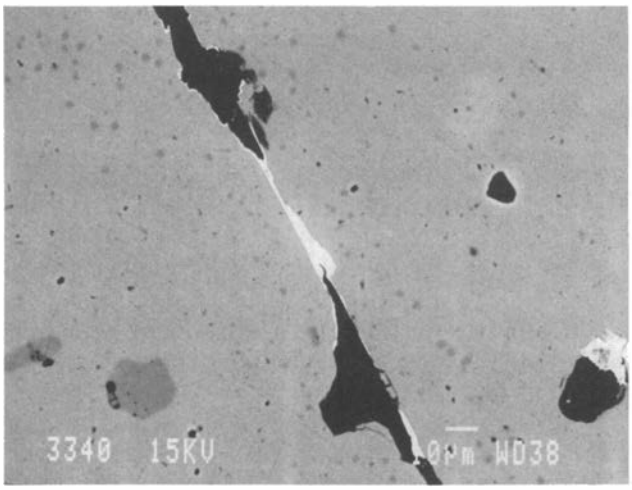

Fig. 6. SEM back-scatter image of argentite (white) in fissure in sphalerite (grey) with blebs of chalcopyrite (dark grey). Scale bar: 0.01 mm.

coatings (Fig. 6). Pyrite (II) also forms a thin (±0.005 mm) coating along the grain boundaries and fissures within the primary sulphides and as filigree-textured fissure fillings within the gangue minerals. Anglesite and limonite, however, are the most common minerals along the healed fissures.

Of the ancient production of the mine, it is difficult to state the proportion between the silver produced from the hypogene and from the supergene mineral assemblages. The secondary minerals (argentite, sternbergite), though richer in silver than the primary minerals (except for hessite), appear to be only erratically distributed and present in relatively meagre amounts in the altered ores. Oxidation of the vein material, though extending to the maximum depth attained in mining (40 m below natural surface according to Falck-Muus (1935)) has not been thorough, and the silver minerals are characteristically restricted to supergene stains along fractures in the cobbed ore. The major part of the silver content of the veins, even close to the surface, is preferably confined to the primary galena and hessite.

Complex supergene processes have evidently brought about the silver enrichment at Akersberg, but certain lines in the development of the supergene assemblages can be considered. Silver enrichment apparently necessitates ferric sulphate as an active solvent, and this may be furnished by the supergene decomposition of pyrite. Descending solutions of ferric sulphate may cause the deposition of anglesite at the expense of galena in an acid and oxidizing environment (Takahashi 1960) and promote the deposition of covellite at the expense of chalcopyrite. The paragenetic relationships of the argentiferous (sternbergite–argentite–pyrite (II)) assemblages are more ambiguous. Sternbergite constitutes a member of the German 'Silberkies-gruppe', which apparently belong to the youngest members of argentiferous hypogene vein assemblages (Ramdohr 1980). Heating experiments show that sternbergite is stable at low temperatures (Czamanske 1969; Taylor 1967) and its maximal thermal stability in the presence of vapour lies below 145°C but possibly above 100°C (Clark & Taylor 1970), where it breaks down to monoclinic pyrrhotite and pyrite. However, the textural relationships suggest that the secondary argentite + pyrite (II) assemblages were formed through the supergene breakdown of sternbergite, possibly with the aid of excess sulphur liberated by the reaction between chalcopyrite and ferric sulphate.

Tectonomagmatic aspects

The rift segments of the Oslo region are arranged in an én echelon pattern, giving the Oslo Paleorift a NNE–SSW trend (Ramberg & Larsen 1978). Many of the lineaments within the Oslo Paleorift were probably established by earlier Late Precambrian and Early Paleozoic events. A large number of these tectonic lines were reactivated during the Permo-Carboniferous extensional tectonic events and have controlled the structural setting of the Permian epigenetic hydrothermal ore deposits of the Oslo Paleorift (Vokes 1973).

A prominent, vertical fracture system within the central Oslo Graben has a general N–S trend and corresponds with the direction of the Permo-Carboniferous dykes of the region. Although much less frequent, NW–SE and NE–SW trends are also found, as shown by Ramberg et al. (1977) and Ygre (1988). In the Akersberg district, the diabase dyke runs parallel to this NW–SE-trending fracture system, which is developed as a closely spaced joint set that intersects the older (Caledonian) system of more irregular trending and barren calcite-filled strike veins and strike-slip faults within the Cambro-Silurian metasedimentary rocks (Fig. 3). A subsequent development of extensional fissures that cross-cut the diabase may have allowed the introduction of ore-bearing fluids along the most permeable conduits. Evidence for small-scale fault displacements along the fracture system is revealed by the late stage brecciation and recrystallization of the ore at the diabase walls at Akersberg.

A great number of similar diabase-hosted, argentiferous Pb–Zn deposits confined to the Permian faults and fracture zones have been described from the Oslo Paleorift and adjacent areas and were classified by Vogt as early as 1884. One class of deposits occurs peripherally to the exposed igneous complex of the Oslo Paleorift and is confined to the reactivated Precambrian structures in the Kongsberg–Bamble segments of the Western Rift margin (Fig. 7) and classified as *Rift margin deposits* by Ihlen (1986a) and Bjørlykke et al. (1990). They extend from the Arendal region at the Skagerrak coast (Vogt 1886) to the Fiskum area near Kongsberg (Ihlen et al. 1984). The relatively few age determinations for diabases of the Oslo Paleorift and adjacent areas reveal a wide range in ages – the youngest being at 219 Ma (Dons 1977).

Vein-type sulphide deposits of another class are confined to the (southern) Vestfold- and Akershus Graben

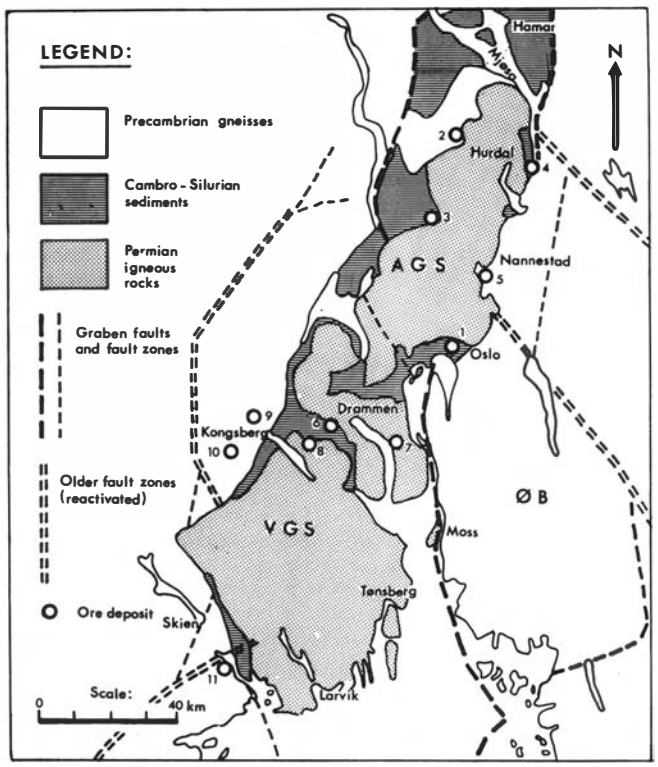

Fig. 7. Simplified geological map of the Oslo Graben and adjacent areas (modified from Sundvoll et al. 1990 and Bjørlykke et al. 1990). AGS = Akershus Graben Segment; VGS = Vestfold Graben Segment; ØB = Østfold Block. AGS deposits: 1: Akersberg, 2: Skrukkelia, 3: Grua, 4: Mistberget, 5: Abbortjern. VGS deposits: 6: Konnerudkollen, 7: Rørvik, Drammen, 8: Blygruben, Eikern. Western Rift Margin deposits: 9: Fiskum, 10: Saggrenda, Kongsberg, 11: Tråk.

segments of the Oslo Paleorift (VGS resp. AGS) (Fig. 7). The polymetallic deposits are spatially associated with biotite granites and peralkaline granites (Ihlen 1978; Bjørlykke et al. 1990). The majority of the Zn–Pb deposits are situated in brecciated skarns adjacent to the plutons, and are often associated with diabase dyke intrusions, e.g. at Konnerudkollen (Ihlen 1986b).

Geochemistry

Two galena concentrates from the Akersberg mine were obtained by hand-picking grains from specimens collected *in situ* from Shaft 1 and from the waste-ore material. The concentrates were analysed for Ag, Sb and Bi by atomic absorption spectrophotometry using the method recommended by Rubeska et al. (1967). The analyses (Table 2) fall well within the range of values published by Oftedal (1941) for galenas from the contact-metasomatic Pb–Zn deposits within the Oslo Graben.

Table 2. Ag, Sb and Bi contents (in ppm) of galena concentrates from the Akersberg mine.

	Ag	Sb	Bi
Galena, Shaft 1	551	450	61
Galena, waste ore	471	316	82

Table 3. Lead isotope compositions of galenas from the Akersberg mine.

	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Galena, Shaft 1 (north)	18.590	15.612	38.604
Galena, Shaft 1 (south)	18.583	15.597	38.569
Galena, waste ore	18.580	15.602	38.591

They are, in general, characterized by relatively low Ag-contents (10–1000 ppm Ag), in contrast to the Rift Margin vein deposits, which are characterized by more argentiferous galenas (0.1–1% Ag). They have a Sb/Bi ratio >1.

In the light of the recent plumbotectonic investigations in the Oslo Paleorift, it was pertinent to consider the lead-isotope signatures of the galenas from the Akersberg mine in order to characterize the primary source for the metals. Three galena concentrates were obtained by hand-picking grains from specimens from the veins exposed in the northern and southern faces of Shaft 1 and from the waste ore material. The Pb isotope analyses (Table 3) were performed at the Mineralogical-Geological Museum in Oslo.

The galena concentrates were dissolved in 8 ml 2N HCl and slowly evaporated to dryness. About 1 μg Pb was loaded on a Re filament using the silicon gel-phosphoric acid technique and analysed on a VG 354 mass spectrometer. The 2σ error limits for the Pb isotope ratios, as determined by repeated analyses of the US National Bureau of Standards SRM 981 and 982 common lead standards, are approximately $\pm 0.1\%$.

The variation between samples is within the field of analytical uncertainty, indicating that the supergene alteration (e.g. of the waste-ore material) had little effect on the lead isotope composition. This is in agreement with the observations of Lawrence & Rafter (1962) and Richards (1971), who showed that lead isotope signatures from primary lead-ore assemblages are transferred to the secondary lead-ore assemblages formed during supergene processes.

In a $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ diagram (Fig. 8) the lead isotope compositions of the galenas from Akersberg

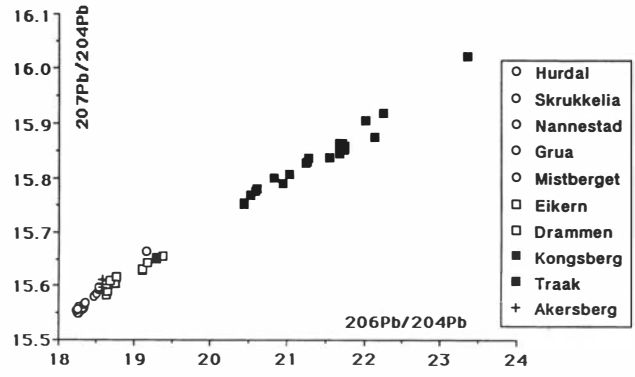

Fig. 8. $^{206}Pb/^{204}Pb$ – $^{207}Pb/^{204}Pb$ ratios of Permian lead ore deposits in the Oslo Paleorift. Filled symbols: Western Rift Margin deposits; open symbols: Within-graben deposits.

are plotted together with those for other Permian deposits in the Oslo Paleorift (Bjørlykke et al. 1990). The data form two distinct groups. Group 1 consists of deposits within the Oslo Graben, including the Akersberg mine and the Saggrenda rift-margin deposit near Kongsberg. They are characterized by $^{206}Pb/^{204}Pb$ ratios between 18.2 and 19.5. Group 2 consists of Permian vein deposits in Precambrian gneisses along the Western Rift margin and are more radiogenic with $^{206}Pb/^{204}Pb$ ratios greater than 20. The Akersberg galenas (Fig. 9) are more radiogenic than most of those from deposits in the Akershus Graben segment (AGS), but are less radiogenic than those from the deposits of the Vestfold Graben segment (VGS) (Fig. 7).

The Akersberg mine is spatially related to diabase intrusions in an Ordovician shale and carbonate sequence within the Akershus Graben segment. However, its spatial relation to diabase dykes is similar to many of the rift margin deposits of the Oslo Paleorift. Lead isotope data from the hydrothermal deposits in the Oslo Paleorift show that the rift-margin deposits are very radiogenic in general, reflecting an upper crustal source for the metals (Moorbath & Vokes 1963; Bjørlykke et al. 1990), whereas the lead isotope ratios from the graben segments are less radiogenic and reflect a deeper (crustal or mantle) source for the metals. The lead isotope composition of the Akersberg mine is, in this respect, very different from those for the rift-margin deposits, but similar to the within-graben deposits of the Oslo Paleorift.

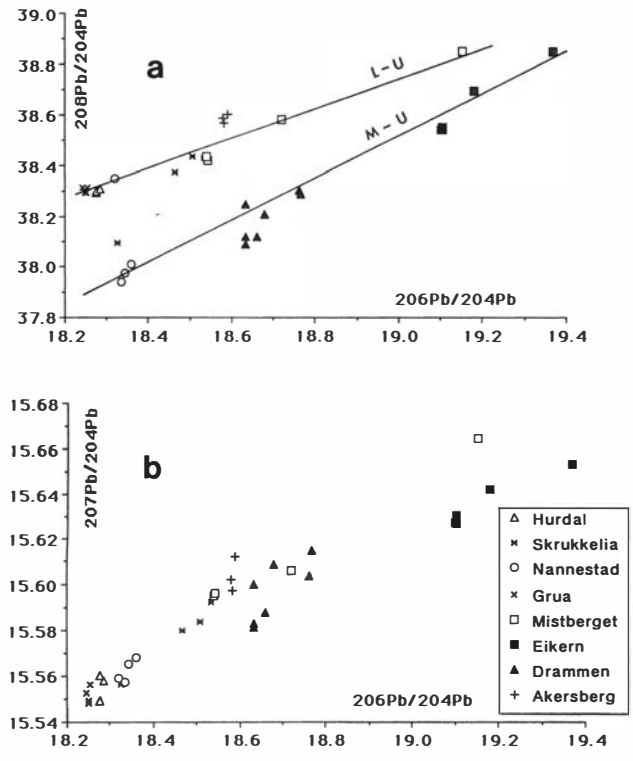

Fig. 9. (a) $^{206}Pb/^{204}Pb$ – $^{208}Pb/^{204}Pb$ ratios of Permian lead ore deposits in the Oslo Paleorift. (b) $^{206}Pb/^{204}Pb$ – $^{207}Pb/^{204}Pb$ ratios of Permian lead ore deposits in the Oslo Paleorift (enlarged from Fig. 8). Filled symbols: Vestfold Graben Segment deposits; open symbols: Akershus Graben Segment deposits.

The lead isotope composition of the Akersberg mine plots within the range of deposits in the Akershus Graben segment, both in a $^{206}Pb/^{204}Pb$ – $^{207}Pb/^{204}Pb$ diagram and a $^{206}Pb/^{204}Pb$ – $^{208}Pb/^{204}Pb$ diagram (Figs. 9 and 10). This points to the existence of a granitic intrusion at depth which may be the source of the metals.

In the $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ diagram (Fig. 9a) deposits from the AGS, including the Akersberg mine, have a higher $^{208}Pb/^{206}Pb$ ratio and plot along the L–U line. The exceptions to this trend are three samples from Nannestad (Abbortjern) and one from Skrukkelia – all situated in Precambrian gneisses (Fig. 7), and these plot together with the samples from the VGS along the M–U line. Galenas plotting along the L–U line have higher 208/204 ratios, and are interpreted to represent mixing of lead from lower and upper crustal sources. Galenas plotting along the M–U line are interpreted to represent mixing of lead from mantle and upper crustal sources. The intersection between these two lines would then be the upper crustal end member. A hydrothermal system in which the associated intrusion only acted as a heat source would give an upper crustal signature of the lead isotopes – similar to the rift-margin deposits.

For most areas within the Oslo Paleorift there is a limited spread in the lead isotope compositions of deposits spatially related to a single granitic intrusion, indicating a common magmatic source with some contribution of lead from the upper crust, either by contamination of the magma and/or by mixing between magmatic and meteoric hydrothermal fluids. The primary magmatic lead isotope compositions (non-radiogenic end members) would then reflect partial melting of either mantle or lower crustal rocks.

None of the exposed rocks in the Akersberg area can account for the lower crustal end member in the lead isotope compositions from Akersberg. Some of the lead must have been derived from water from underlying magmas that were formed by partial melting of lower crustal rocks or from water circulated by deep hydrothermal convection. More samples should be analysed in order to determine the spread in isotopic compositions of galenas from Akersberg, which is important in distinguishing between these alternatives.

Discussion and conclusions

Secondary ore assemblages formed by supergene enrichment processes are very uncommon in Norwegian ore deposits. The nature and extent of the apparent (secondary) copper enrichment revealed in some Norwegian sulphide ores have been discussed by H. Bjørlykke (1960) and Vokes (1961). From the few reports on evident supergene assemblages (e.g. covellite and anglesite as cited by Neumann (1985)), one must conclude that post-Pliocene processes have played a quantitatively insignificant role in the alteration of Norwegian ore assemblages. However, particularly well jointed bedrock may

provide suitable drainage conditions for leaching and redeposition of ore-bearing material, as revealed in the secondary ore assemblages of the Akersberg mine. The secondary silver enrichment, as revealed by the mineralogy of the mine waste, has evidently affected only the uppermost (worked-out) parts of the mineralized veins and may have encouraged the ancient silver exploitation at Akersberg. At deeper levels, the low-grade primary vein assemblages may, in addition to the constant drainage problems due to the jointed wallrocks, have led to the final closure of the mine by the end of the 17th century. The Akersberg mine provides in this respect a puzzling example of how the tectonic and topographic settings have not only provided the silver ore potential, but have also controlled its commercial development.

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