Sulphur Isotope Composition of the Sandstone–lead Deposits in Southern Norway

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Samples of galena, pyrite and barite from the Norwegian sandstone–lead occurences in the Gjøvik area and at Osen and Galåa have been analyzed for their sulphur isotope composition. Samples from the Vassbo and Laisvall deposits in Sweden were also analyzed. The galena samples are characterized by a large variation in the sulphur isotopic composition (+10 to +26 ‰) and they have an average $d^{34}S$ composition of +18.56 ‰. The sulphur source has earlier been interpreted to be oil-field waters, and these data are not inconsistent with this interpretation. However, the data also permit, as an alternative source for the sulphur, sea-water sulphate locally reduced by bacteria.

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Introduction

Several deposits and occurrences of lead are known in Late Precambrian to Early Cambrian sandstones of the Baltic Shield. They occur mainly along the eastern and southeastern frontal zone of the Scandinavian Caledonides, over a distance of approximately 2000 km (Fig. 1). Galena is the main base-metal sulphide in the deposits and the Pb/Zn ratio varies from 5–15, but locally within each deposit Zn may be the dominant base metal.

Laisvall is the largest deposit with 80 million metric tons of ore at an average grade of 4% Pb (Rickard et al. 1979). Two different genetic models for these deposits have recently been published. Rickard et al. (1979) proposed a basinal brine model, where dewatering of sediments is envisaged as the process during which lead was complexed and moved towards the basin margins. Precipitation took place when the metal-bearing brine mixed with a sulphide-bearing brine contained in the Laisvall sandstone aquifer. Bjørlykke & Sangster (1981), on the othe hand, suggested that the lead was released during weathering from the underlying granitic basement either directly or via formation of continental arkoses. Groundwater may then have carried the lead (and zinc) towards the basin and sulphides were precipitated when the groundwater met reducing conditions. Bjørlykke & Sangster (1981) also showed that the sulphur isotope composition is dependent upon the depositional environment: galena in continental sediments has a light sulphur isotope composition whereas in marine sediments the sulphur is heavy. On the Baltic Shield the sulphur isotope composition has earlier been analyzed from Laisvall (Rickard et al. 1979) and from Vassbo (Wallin 1980). Both studies showed a heavy sulphur isotope composition in galena.

Fig. 1. Stylized paleographic map of the Baltic Shield in Early to Middle Cambrian showing the position of sandstone lead deposits (modified from K. Bjørlykke 1974).

This study compares the sulphur isotope compositions in the Norwegian deposits with those from Laisvall and Vassbo in Sweden, and samples from Norwegian occurrences were therefore analyzed together with a few samples from Laisvall and Vassbo.

GEOLOGICAL SETTING

The Late Precambrian sediments of Scandinavia were deposited along the continental margin and in fault-controlled basins (Sparagmite Basin, Fig. 2).
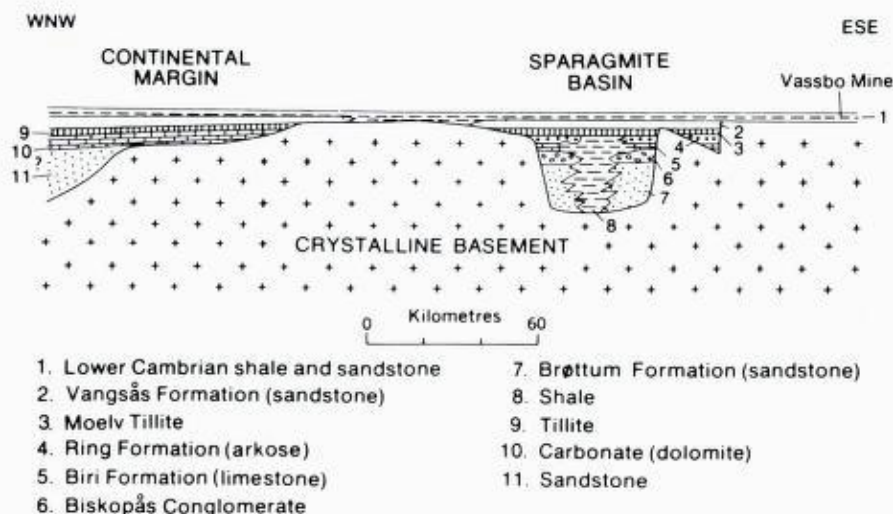
1. Lower Cambrian shale and sandstone
2. Vangsås Formation (sandstone)
3. Moelv Tillite
4. Ring Formation (arkose)
5. Biri Formation (limestone)
6. Biskopås Conglomerate
7. Brøttum Formation (sandstone)
8. Shale
9. Tillite
10. Carbonate (dolomite)
11. Sandstone

Fig. 2: Reconstructed cross-section through the Baltic Shield in early Paleozoic time showing a rift valley basin (sparagmite basin) and an onlapping continental margin sequence (modified from K. Bjørlykke 1978).

The sediments on the continental margins are widespread and consist mainly of sandstones and dolomites. The Sparagmite Basins contain turbidites (Brøttum Formation), limestones and shales (Biri Formation), and coarse arkoses and conglomerates (Biskopås and Ring Formations).

Deposition of Late Precambrian glacial sediments (Moelv Tillite) was followed by fluvial and/or deltaic sedimentation (lower part of Vangsås Formation). The lowermost Lower Cambrian (Tommotian; Cowie & Cribb 1978) contains quartzites deposited in a tidal or beach environment, and containing *Scolithus* burrows (Skjeseth 1963) (upper part of Vangsås Formation). In most areas fossiliferous Lower Cambrian strata begin with sandstones fining upwards to green shales. During Middle and Late Cambrian times most of the Baltic Shield was covered by a shallow and stagnant epicontinental sea in which mainly black shales were deposited (K. Bjørlykke 1974).

The Caledonian nappe movements occurred in an early Finnmarkian phase (Upper Cambrian–Lower Ordovician; Sturt 1978) and in a Silurian to lowermost Devonian phase. During the later phase, sediments deposited on the crystalline basement or along the continental margin were thrust eastward or southeastward. In the study area the Caledonides are divided into three major tectonostratigraphic units (Gee 1975, K. Bjørlykke 1978):
– Autochthonous sediments lying upon Precambrian basement;
– Lower nappe units with epicontinental, Late Precambrian to Ordovician sediments of low metamorphic grade and moderate deformation;
– Upper nappe units, long-distance transported and strongly deformed and generally comprising fragments of basement (e.g. anorthosites, augen gneisses) and sediments (sandstones and dolomites) deposited along the continental margin.

Lead mineralization occurs in the autochthonous sequences and in the lower-most nappes along the eastern and southeastern border of the Caledonides, suggesting that the lead was restricted to sediments deposited in topographic lows along the marginal areas of the Early Cambrian epicontinental sea (Fig. 1).

Outline of the Geology of the Sampled Areas

In this study sandstone lead occurrences in the Gjøvik area and at Galåa and Osen in Southern Norway were sampled and analyzed together with a few samples from Laisvall and Vassbo in Sweden (fig. 1).

GJØVIK AREA

In the Gjøvik area several occurrences of galene are known to occur in the Vangsås Formation (Fig. 3 and Bjørlykke 1979). The formation is divided into the Vardal Sandstone Member and the overlying Ringsaker Quartzite Member. The Vardal Sandstone is 160 metres thick and consists of arkoses and feldspathic sandstones (Fig. 4), with microcline dominating over plagio-clase. The degree of maturity increases upwards and there is a gradual transi-tion into the Ringsaker Quartzite. Conglomerates occur in the southern part of the area (Fig. 3) and thin out rapidly northwards. Red beds are observed
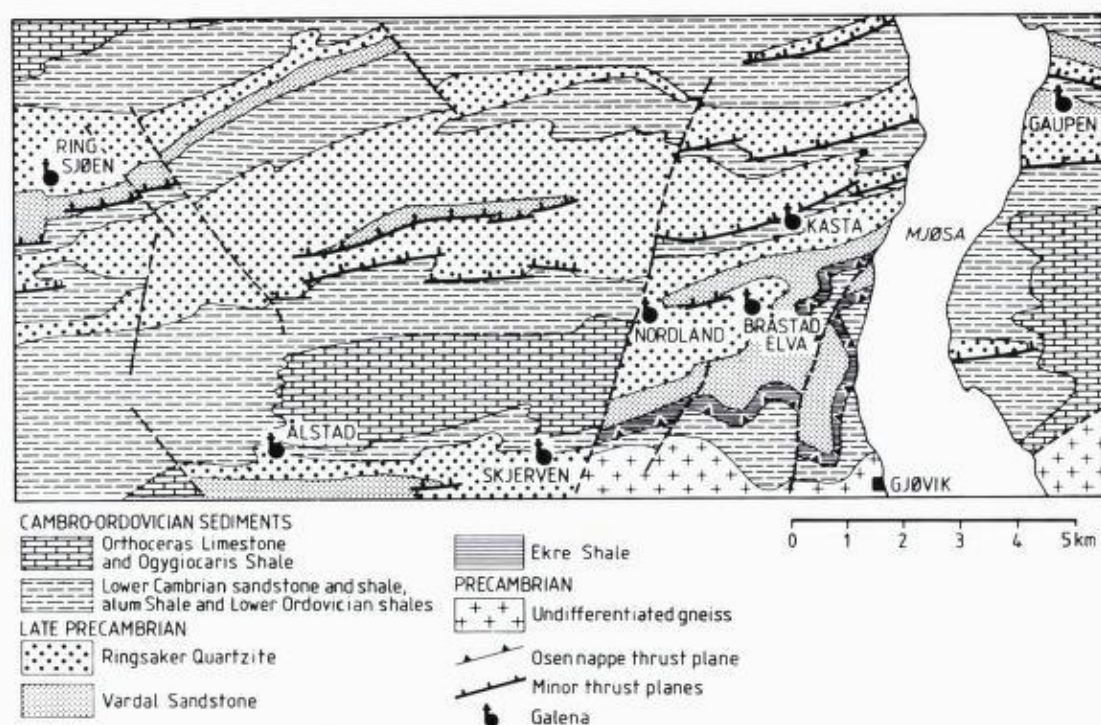

CAMBRO-ORDOVICIAN SEDIMENTS
- Orthoceras Limestone and Ogygiocaris Shale
- Lower Cambrian sandstone and shale, alum Shale and Lower Ordovician shales
- Ekre Shale

LATE PRECAMBRIAN
- Ringsaker Quartzite
- Vardal Sandstone

PRECAMBRIAN
- Undifferentiated gneiss
- Osen nappe thrust plane
- Minor thrust planes
- Galena

Fig. 3: Geological map of the Gjøvik Area.

in a few places in the lowermost part of the Vardal Sandstones. Thin beds of phosphorites (A. Bjørlykke 1979) indicate a marine origin for at least parts of the Vardal sandstone, which earlier had been interpreted as entirely fluvial (K. Bjørlykke et al. 1976). The Ringsaker Quartzite is 50–80 metres thick. The lower half is a fine- to medium-grained quartz sandstone which is locally rich in altered feldspar and with a sericitic matrix. The upper half is a medium- to coarse-grained quartzite, often with a blue colour caused by a thin film of carbonaceous material enveloping quartz grains. The uppermost part of the Ringsaker Quartzite contains *Scolithus* burrows (Skjeseth 1963), which indicate a shallow-marine environment considered typical for lowermost Lower Cambrian strata (Vidal 1981).

In the Gjøvik area the galena occurs only in the orthoquartzite and mainly as cement often with poikiloblastic texture. Some galena was remobilized during the Silurian nappe movement and fills small cracks and joints in the orthoquartzite. An erosional hiatus beneath the fossiliferous Lower Cambrian strata is marked by a 0.2–0.5 m thick conglomerate consisting of rounded fragments of the underlying Ringsaker Quartzite. The conglomerate is overlain in places by impure limestone followed by sandstones and green shales. The sub-Middle Cambrian break is marked by a conglomerate with pebbles of dark quartzites and phosphorites, overlain by black shales (Alum shale).

During the Silurian the Vangsås Formation and the overlying Cambro-Silurian sediments were thrust towards the south, folded and imbricated.

GALÅA AREA

Galena disseminations in the Galåa area south of Rena were found in the course of a regional geochemistry program (A. Bjørlykke et al. 1973). Middle Cambrian black shales were deposited directly upon weathered Proterozoic basement gneisses. The Osen Nappe, which truncates the autochthonous sequence 10 metres above the basement, consists of the Vangsås Formation and Cambro-Ordovician sediments (Fig. 4).

Because of the imbricated structure of the Osen Nappe it is difficult to find a continuous complete section through the Vangsås Formation. The Vardal Sandstone is approximately 150 m thick. It consists in its lower part of grey and red feldspathic sandstones and arkoses of assumed fluvial origin. The sandstones become more quartzitic in the uppermost part and exhibit a blue-grey colour resulting from an increased organic content. The boundary with the overlying Ringsaker Quertzite is defined by the feldspar content. The Ringsaker Quartzite is approximately 40 m thick and is a white, clean, quartz-cemented quartz-arenite. The quartzite is overlain by shallow-marine fossiliferous fine-grained sandstones and green shales of Early Cambrian age.

The lead mineralization occurs in the blue-grey quartz sandstone of the uppermost part of the Vardal Sandstone both as disseminations and as mobilizations in cracks and joints. Disseminated pyrite occurs frequently also in the grey-to-blue beds of the Vardal Sandstone.
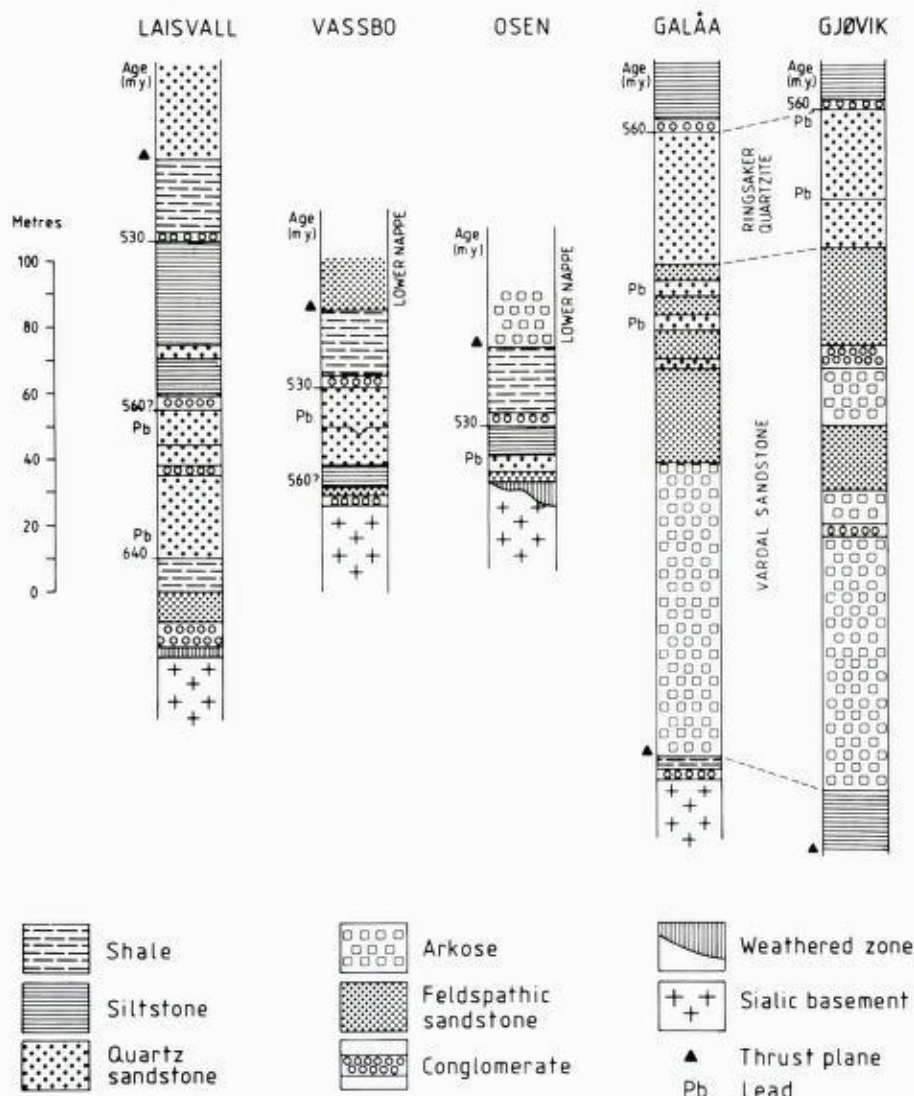
Fig. 4: Lithostratigraphy of five areas of the Baltic Shield containing sandstonelead deposits. Descriptions and bibliographic sources are given in the text.

OSEN AREA

The basement in the Osen area consists mainly of granite with subordinate gneisses of Middle Proterozoic age. The basement forms a peneplain upon which a weathered zone up to ten metres thick was developed. The weathered basement grades upward into a feldspathic sandstone followed by up to 4 m of coarse-grained mineralized quartzite of Early Cambrian age, probably deposited in a beach environment (Høy 1977). It is overlain by 2–3 m of fine-grained, slightly mineralized, dark sandstone of possible tidal origin, which grades into grey, strongly bioturbated siltstones (Nystuen 1969) (Fig. 4).

The Middle Cambrian strata begin with a 0.2 m thick conglomerate containing fragments of shale, quartzite and phosphorite. It is followed by up to 20 m of black shale before the autochthonous sequence is truncated by Caledonian nappes.

LAISVALL

The following data (Fig. 4) are compiled mainly from Rickard et al. (1979), Grip (1967, 1973) and Willdén (1980). The basement in the Laisvall area consists of weathered granites of Proterozoic age. A 1–9 m thick mixtite rests directly on the basement. It is followed by 7–9 m of feldspathic sandstone, with sporadic galena mineralization, overlain by a green-to-grey pebbly shale. This lower part of the sequence is interpreted to be of glacial origin (Rickard et al. 1979) and to have an age of about 654 ± 7 m.y. (Pringle 1973, Sturt et al. 1975).

The glacial sediments are followed by a 40–45 m thick sandstone sequence, which is divided into lower, middle and upper units. The lower unit is up to 25 m thick and consists of a well sorted, medium-grained quartzite with intercalated green shale beds. These are often brecciated or show liquefaction structures. The middle sandstone starts with a conglomerate that contains fragments of the underlying sandstone and truncates the liquefaction structures in the underlying beds. The middle sandstone is 7 m thick and has a more clayey matrix than the lower sandstone; channel structures are also common. The upper sandstone, which starts with a quartzite conglomerate, is 11 m thick with well developed cross-bedding. Fragments of phosphorite occur in the upper part.

The whole sandstone sequence up to the fossiliferous Lower Cambrian (560 Ma) represents a period of approximately 80 million years (Cowie & Cribb 1978); the conglomerate may represent a long period of subaerial exposure. Willdén (1980) has interpreted the lower sandstone, which hosts the main mineralization, to have been deposited in a lagoonal environment. The poorly mineralized middle sandstone was interpreted as a tidal deposit and the well mineralized upper sandstone as deposits formed in tidal channels and on beaches.

Above a thin conglomerate containing fragments of quartzite and phosphorite occurs Lower Cambrian strata, consisting of green shales and siltstones commonly bioturbated and with fossiliferous limestone beds. After a new break in sedimentation between Lower and Middle Cambrian, black shales (alum shale) were deposited in a shallow-marine environment. The sedimentology shows that the Laisvall area was located within a shallow and broad depression surrounded by gently rising areas to the north and south (Willdén 1980). The autochthonous sequence is then truncated by Caledonian thrusts. In the lower nappe, minor lead and zinc mineralization occurs in a blue quartzite which is correlated with the upper sandstone in the autochthonous strata (Willdén 1980).

VASSBO

The following data (Fig. 4) are mainly compiled from Tegengren (1962), Grip (1973), Christoffersen et al. (1979) and Wallin (1982). Basement in the Vassbo area consists of quartz porphyry dated at 1669 ± 38 M.a. (Welin & Lundqvist 1975, Welin 1980), sandstone and diabase dykes. A thin basal conglomerate is overlain by a 1–6 m thick shale of Early Cambrian age, locally with mineralized coarse sandstone beds. The shale is followed by a fine-grained calcite-cemented quartz sandstone, 12–14 m thick, with disseminations of galena in the upper part. A marked erosional disconformity exists between this sandstone and the overlying coarser quartz sandstone. The quartz sandstone, with galena, sphalerite and barite is 7–12 m thick. It contains cross-bedding and ripple-marks, and is interpreted to have been deposited in an open-marine beach environment (Christofferson et al. 1979).

The Middle Cambrian starts with a 0.1 m phosphoritic conglomerate with fragments of quartzite. Some of the fragments contain disseminated galene with a matrix rich in pyrite and minor, possibly remobilized, galena. This is followed by 10–20 metres of black shale before the autochthonus sequence is truncated by Caledonian thrusts.

ORE GEOLOGY

A more detailed description of the ore geology has been published by Rickard et al. (1979), Christofferson et al. (1979) and Bjørlykke & Sangster (1981). The ore bodies are blanket-like in shape and often follow the stratification and other sedimentary structures in the host sandstone. In homogenous sandstones galena appears to have nucleated around organic material, forming poikiloblastic spots and heavier concentration around shale fragments.

The ore minerals occur as cement in zones which were the most permeable parts of the quartz sandstone. The original porosity in the Laisvall deposit was probably around 30% (Rickard et al. 1979) but in the most intensely mineralized parts corrosion and replacement of the detrial grains can be seen. Galena and sphalerite are the most important sulphides; accessory minerals include framboidal pyrite, marcasite, bravoite, pyrrhotite and chalcopyrite (Ncube et al. 1978). Although the galena contains small inclusions of native silver, the silver content of the ore is low, ranging between 7 and 21 g/t (Grip 1973). The sphalerite is mostly light-coloured and has an iron content between 1% and 2% and a Cd content of 0.3% (Rickard et al. 1979). Bravoite was found at four different places in Laisvall, but the nickel content in the bravoite-bearing rocks was found to be only 17–41 ppm (Ncube et al. 1978). The non-sulphide cement consists dominantly of quartz, with some calcite, fluorite and barite. The non-quartz cement, including the sulphides, occupies on average about 6% of the rock volume (Rickard et al. 1979).

Isotope Results

The samples were crushed and the sulphides and sulphates separated at the Geological Survey of Norway. The analytical work was performed at

Geochemisches Institut der Universität Göttingen. The error limit is generally within 0.1‰ for the sulphides and 0.3 ‰ for the sulpates (Nielsen & Sperling 1973).

The results of the sulphur isotope analysis of galena, pyrite and barite from the sandstone-lead deposits in Southern Norway and from Laisvall and Vassbo in Sweden are listed in Table 1. The samples are characterized by a large variation in the sulphur isotope composition of the galena and most of them are isotopically heavy.

Table 1. Sulphur isotope analyses.

No.	Deposit	$\delta^{34}S$	No.	Deposit	$\delta^{34}S$
	GALENA SAMPLES				
1	Ringsjøen, Gjøvik	22,3	16	Osen	22,3
2		− 0,1	17		20,0
3		25,7	18		20,2
4		17,8	19		19,8
5		25,6	20		20,8
24		14,2	21		18,4
25		13,7	22		18,0
26		14,4	23		20,7
27	Ålstad, Gjøvik	12,9	47		18,0
28		12,2	48		16,7
29		11,8	49		17,2
44	Skjerven, Gjøvik	17,7	101		18,7
45		14,2	102/105	Middle Cambrian	
46		14,5		black shale	0,5
30	Kasta, Gjøvik	21,0	103/109		21,4
31		17,7			
32		17,1		PYRITE SAMPLES	
42	Nordland, Gjøvik	14,2			
43		15,3	116	Galåa	28,5
33	Tjerne, Gjøvik	18,2	117		14,9
34		14,6	118		28,5
35		16,8	115/119		31,6
38	Vassbo ore zone	18,6	126	Vassbo	18,4
39		18,5	128		18,0
40		10,2	102/105	Osen–Black shale	51,2
41		13,7	103/104		16,0
36	Laisvall ore zone	20,1	106	Sub-middle Cambrian	
37		19,9		conglomerate	−20,5
6	Galåa	22,9	107	Lower Cambrian	
7		19,7		siltstone	−25,6
8		22,8	110	Middle Cambrian	
9		20,6		black shale	20,8
10		19,8	111		21,5
11		20,8	112		33,5
12		19,3	113	Lower Cambrian	
13		33,4		siltstone	−22,5
14		10,8			
15		37,1		BARITE SAMPLES	
114		21,0	127	Vassbo	20,7
115/119		21,5	134		18,9

A frequency distribution of the $\delta^{34}S$ values in 47 galena samples from Southern Norway is shown in Fig. 5. Except for three samples they all fall between +10 and +26‰ and they have an average $\delta^{34}S$ composition of +18,5‰. The sulphur isotope composition of the sulphides in the Galåa deposit and in the Gjøvik area shows a larger spread than in the Osen deposit (Fig. 5). The average composition in the Gjøvik area is +16.0‰, Osen + 18.3‰ and Galåa +22.5‰ (Fig. 5). Only two galena samples from Laisvall and four from Vassbo were analyzed and the results are within the spread in the data from Southern Norway. In Fig. 5 data published by Rickard et al. (1979) are combined with our data and the average $\delta^{34}S$ composition of galena-sulphur is +22.87‰.

One pyrite-galena pair from Osen and two from Galåa were analyzed (Table 1), and from Laisvall two pairs of sphalerite–galena have been published (Rickard et al., 1979). None of the pairs shows isotopic equilibrium during precipitation. Two samples of barite from Vassbo were analyzed and their sulphur isotope compositions are similar to the average composition of
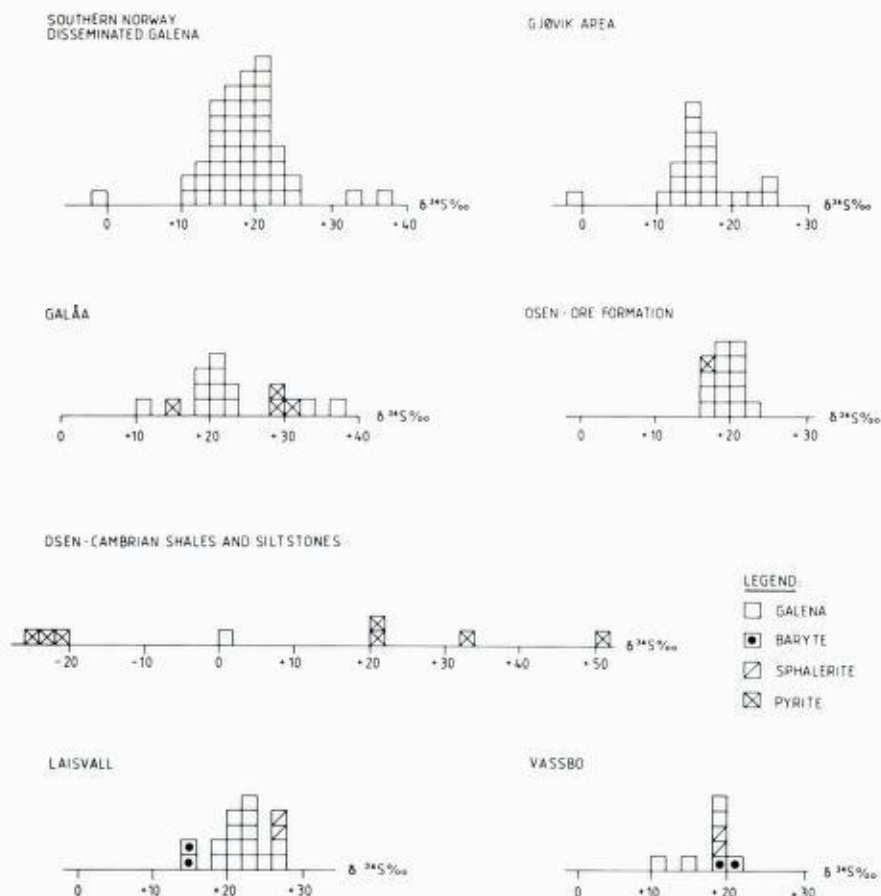

Fig. 5: Sulphur isotopic composition($\delta^{34}S$) in sandstone-lead deposits on the Baltic Shield. The data from Laisvall are partly from Rickard et al. (1979).

the galena. The sulphur isotope composition in barite from Laisvall (Rickard et al. 1979) is 7‰ lighter than the sulphide-sulphur. In Osen. eight samples were taken from above the mineralized zone, from the Lower Cambrian silts-tone and from Middle Cambrian black shales. They show a large variation in sulphur isotope composition, from −26 to +51‰ (Fig. 5).

Discussion

SULPHIDE–SULPHUR

The sulphur isotope study reported here shows that sulphides from the Norwegian occurrences have a lighter average and a larger spread in isotopic composition than those from Laisvall published by Rickard et al. (1979). These authors concluded that the Laisvall data are not inconsistent with those expected for sulphide–sulphur in oil-field waters. Solutions low in base metals with hydrocarbon and reduced sulphur could have been supplied during either the late stages of the Caledonian orogeny (as proposed by Rickard et al. 1979) or, alternatively, somewhat earlier from Late Precambrian rift basins.

The new data reported here from Norwegian sandstone-lead occurrences are consistent with the oil-field water model proposed by Rickard et al. (1979) for the Laisvall deposit in Sweden. However, the data also permit, as an alternative source for the sulphide–sulphur, sea-water sulphate reduced locally by bacteria. Data compiled by Bjørlykke & Sangster (1981) indicate that the sulphur isotope composition of galena in sandstone–lead deposits reflects the depositional environment of the host rocks. For example, deposits in fluvial sandstone, such as Maubach, Mechernich and Freihung in Germany (Jensen 1967) have isotopically light sulphur similar to red-bed copper and sandstone–uranium deposits (Sangster 1976). In contrast, lead deposits in shallow-marine sandstones on the Baltic Shield have an isotopically heavy composition, not unlike that in Mississippi Valley-type deposits.

A sea-water source for the sulphur in Mississippi Valley-type deposits was proposed by Sangster (1976). In comparing various deposits which may have sea-water sulphate as their sulphur source, one must take into account the change in isotopic composition in sea-water with time. During the Late Precambrian and Early Cambrian the sea-water contained isotopically heavy sulphur with a $\delta^{34}S$ composition between +30 and +35‰ (Claypool et al. 1980). The fractionation in sulphur isotope composition between marine sea-water sulphate (+30 and +35‰) and galena in the sandstone-lead deposits in southern Norway (av. = +18.56‰) is about 15 per mil. This is the average fractionation value found by Sangster (1976) for deposits in marine sediments and supports the seawater–sulphate source for sulphide–sulphur in the sandstone–lead deposits.

The seawater–sulphate model can be examined in somewhat more detail by consideration of the local depositional environment in a manner described by Schwarcz & Burnie (1973). The sandstone–lead deposits on the Baltic Shield occur in sandstones deposited in a shallow-marine, partly tidal

environment. According to Schwarcz & Burnie (1973) this environment is a partly closed sulphur system, both with respect to sea-water sulphate and H_2S gas. In a partly closed system such as this, Δ will range between -3 and $+25‰$ ($\Delta = \delta^{34}S_{SO_4^{2-}} - \delta^{34}S_{H_2S}$) and is assumed to be a function of both the nature of the reducing organism and the depositional environment. Most galena samples from southern Norway have isotopic compositions ranging between $+10$ and $+26‰$ (Fig. 5). The seawater–sulphate in Early Cambrian seas had an isotopic composition between $+30$ and $+35$ (Calypool et al. 1980), which gives Δ-values between $+4$ to $+25‰$. These are within the range of Δ-values given by Schwarcz & Burnie (1973) for bacterial seawater–sulphate reduction in a tidal environment.

The data from the ore zone and the overlying sediments in Osen fall into three groups corresponding to the lithostratigraphy. 1) The tidal sandstone has heavy sulphur isotopes, indicating a closed system during sulphide deposition. 2) The overlying strongly bioturbated siltstone and the conglomerate (Fig 4) have a light isotope composition ($-20.5‰$ to $-25.6‰$). The marked change in composition reflects a transition to an open system both for H_2S and SO_4^{2-} possibly due to the bioturbation. The hiatus between Early and Middle Cambrian, which led to the formation of the conglomerate, could also have oxidized previously formed sulphides, changing the SO_4^{2-} in the sediments towards a lighter isotope composition. 3) The sulphide samples from the Middle Cambrian black shale (alum shale) have a heavy isotope composition ($+0.5‰$ to $51.2‰$). Black shale environments can produce sulphide–sulphur of both light and heavy composition, Schwarcz & Burnie (1973) and the heavy isotopes at Osen indicate that the alum shale was deposited in a closed system where the influx of marine sulphate was restricted.

The sulphur isotope data from Galåa and Gjøvik show a larger spread than in the Osen deposits. In Galåa and Gjøvik the mineralizations occur in the Osen Nappe and have been more remobilized than in Osen, which could have affected the sulphur isotope composition. There is also a change in the average sulphur isotope composition from area to area. One reason for this change can be that the ore occurs in sediments of different ages but we have too sparse information on the detailed changes in the composition of the ocean water in Upper Precambrian and Early Cambrian to correlate these two factors.

SULPHATE–SULPHUR

Rickard et al. (1979) showed that the barite–sulphur in Laisvall was 7 per mil lighter than the sulphide–sulphur (Fig. 5). In Vassbo, the isotopic composition of the sulphate ($\delta^{34}S = 20‰$) is $3.6‰$ heavier than the composition of sulphide–sulphur (Fig. 5). Because of the large difference between this value and that of Early Cambrian seawater ($\delta^{34}S = +30$ to $+35‰$), the latter was considered unlikely to have been the source of sulphate in barite. Rickard et al. (1979) found that the sulphate–sulphur had a composition similar to the pyrite in the Alum shale and proposed, therefore, that the sulphate–sulphur source was oxidized synsedimentary sulphides. The data from Osen show,

however, a large spread in the sulphur isotope composition ($-25.6‰$ to $+51.2‰$) of synsedimentary sulphides of Early to Middle Cambrian age. It is therefore difficult to establish a genetic relationship between synsedimentary sulphides of the overlying sediments and sulphates in the ore without a more comprehensive investigation.

The present author regards the similarity in composition of sulphate–sulphur and sulphide–sulphur in the Vassbo deposit to indicate that the source of the sulphate could have been supplied by oxidation of the ore-sulphides in the following manner. According to the groundwater model for the formation of these deposits (Samama 1976, Bjørlykke & Sangster 1981), original precipitation of sulphides within the sandstone would have taken place in a zone of mixing between groundwater carrying metals and barium, and H_2S-bearing marine water. Variations in sea-level and groundwater flow would move this mixing zone back and forth in the sandstone such that any one locality in the sandstone could be alternatively oxidizing, then reducing and back again. These changes in redox potential could cause the originally precipitated sulphides at Vassbo (av. $\delta^{34}S = +16.2‰$) to be oxidized to sulphate of the same isotopic composition. This increase in the sulphate content, combined with the barium in the groundwater, would precipitate barite with a sulphur isotope composition close to that of sulphide–sulphur in the ore as shown in Fig. 5.

No simple paragenesis has been found in the sandstone–lead deposits in Scandinavia. However, Rickard et al. (1979) report a marked tendency for sphalerite to be generally older than galena, which in turn usually precedes the fluorite, barite and calcite. However, the minerals are commonly mutually exclusive and several generations of each mineral exists. Rickard et al. (1979) suggest (p. 1266) «that the mineralization was formed by a series of pulses of ore-bearing solutions of roughly similar composition, which were mainly zinc-rich initially and lead-rich during the later main mineralization period. Late-stage solutions are evidenced by corrosion and silicia replacement of galena.»

The groundwater model, which does not involve pulses of different solutions (Fig. 6), shows in an idealized way the transitional zone between groundwater and marine water within a tidal sandstone. Due to a higher organic content in marine sediments than in continental sediments in Cambrian time, the concentration of H_2S will increase seawards and groundwater with lead and zinc will first precipate galena and then sphalerite. During a period of regression the mixing zone will move seawards resulting in a sequence of precipitation with sphalerite, galena and barite, similar to what has been reported by Rickard et al. (1979).

Conclusion

The new data from the mineralizations at Gjøvik, Osen and Galåa reported here are consistent with a sulphure source from oil-field water proposed by Rickard et al. (1979) for the Laisvall deposit in Sweden. However, the data
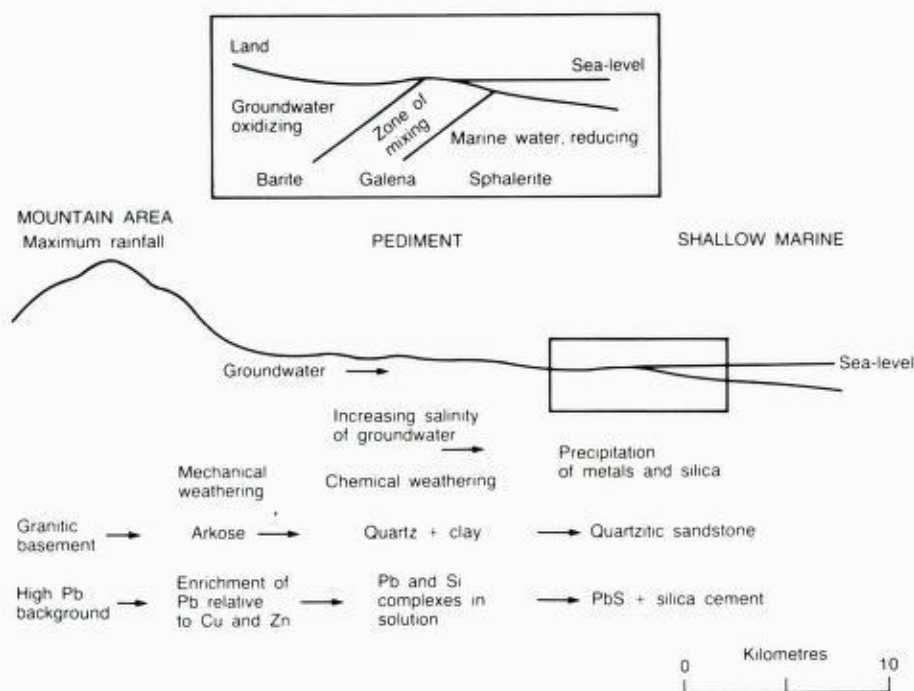
Fig. 6: Schematic representation of the main features in the ground water model for sandstone lead deposits (Modified from Bjørlykke & Sangster 1981).

also permit, as an alternative source for the sulphide–sulphur, sea-water sulphate reduced locally by bacteria. Sulphides from sediments of Early to Middle Cambrian age in Osen show a sulphur isotope stratigraphy reflecting sulphate reduction by bacteria in alternating closed and open systems. In the Vassbo deposit in Sweden sulphate–sulphur has a similar composition to the sulphide, indicating that the sulphur source for the barite could be oxidation of previously formed sulphides.

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