The sandstone-hosted Osen lead deposit, Norway: new Pb isotope evidence for sourcing in the underlying granitoid basement

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The Osen deposit is one of several Pb–Zn deposits in Baltoscandia, hosted in Lower Cambrian sandstone, unconformably overlying a Precambrian granitoid basement and overlain by Caledonian nappes of the Lower Allochthon. In the Osen area, the Palaeoproterozoic Trysil granite (1673 ± 8 Ma) shows evidence of weathering below the unconformity. New Pb isotope data, collected by Laser Ablation Multi-Collector Inductively Coupled Plasma Mass Spectrometry (LA–MC–ICP–MS) on K-feldspar from six samples of the Trysil granite, provide an improved internally consistent model for the age and sourcing of the Osen deposit. Data spread along the published whole-rock errorchron of the Trysil granite form two populations. The least radiogenic of these, defined by a cluster of 10 data points (average $^{206}\text{Pb}/^{204}\text{Pb} = 16.51$ and $^{207}\text{Pb}/^{204}\text{Pb} = 15.37$), is interpreted to represent the initial ratio of the granite. Published isotope data of Pb in galena in the Osen deposit ($20.24 < ^{206}\text{Pb}/^{204}\text{Pb} < 20.49$, $15.85 < ^{207}\text{Pb}/^{204}\text{Pb} < 15.89$) plot on a reference line including this K-feldspar cluster and whole-rock data of the Trysil granite, as it was c. 540 Myr ago. This distribution suggests that the Osen deposit was generated shortly after deposition of the sandstone in the Early Cambrian (c. 541–511 Ma). Lead was released by weathering of the granite basement during development of the sub-Cambrian peneplain. It therefore discards alternative models involving Caledonian events in either Ordovician or Silurian time.

Keywords: Sandstone lead deposits, lead isotopes, Lower Cambrian sandstones, Baltoscandian Shield

Electronic Supplement 1: LA-MC-ICP-MS Pb isotope data

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Introduction

Several sandstone-hosted lead ± zinc deposits occur in Baltoscandia close to the Ediacaran–Cambrian peneplain (Rickard et al., 1979; Bjørlykke & Sangster, 1981; Romer, 1992; Saintilan et al., 2015a). The sandstones are Lower Cambrian in age and represent beach deposits related to the marine transgression over the Precambrian Fennoscandian Shield. Galena and sphalerite, together with barite and fluorite, form the cement in the sandstone. Laisvall is the largest of these sandstone-hosted deposits, with 80 million tons of ore grading 4% Pb (Rickard et al., 1979).

The genesis of these deposits has been explained by the migration of basinal brines during the Caledonian orogeny (Rickard et al., 1979), following the model for the formation of Mississippi Valley-type (MVT) deposits (Leach et al., 2010). A formation related to basement structures has also been proposed by Saintilan et al. (2015a, and references therein). In contrast, Bjørlykke & Sangster (1981) proposed that formation of the deposits was related to chemical weathering of the underlying Precambrian basement.

Bjørlykke & Thorpe (1982) used Pb isotopic data to investigate the source of lead in the Osen deposit as well

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as the age of the lead mineralisation. The Osen deposit was selected because it is small and rests on a relatively homogeneous basement, the Trysil granite. Bjørlykke & Thorpe (1982) concluded that the isotope composition of the galena of the Osen deposit lies on an isochron with an age of c. 520 Ma and an initial ratio corresponding to the calculated lead isotopic composition of the Trysil granite 520 Myr ago. Thus, the isotope data were compatible with a genetic model involving derivation of lead by alteration of the underlying granite basement and transport in groundwater (Samama, 1976; Bjørlykke & Sangster, 1981).

The study by Bjørlykke & Thorpe (1982) was based on U, Th and Pb concentrations and Pb isotope composition of whole-rock samples of the Trysil granite. The initial lead isotope composition of the granite in the Cambrian was calculated. The study was based on relatively few samples of the Trysil granite, the age of which was inferred from lead isotope data.

This paper reports new Laser Ablation Multi-Collector Inductively Coupled Plasma Mass Spectrometry (LA-MC-ICP-MS) analyses of K-feldspar in the Trysil granite. It provides an improved estimate of the initial Pb isotope composition of the granite bedrock and therefore a better estimate of the time when lead was released from the granite.

Geological setting

In the Osen area, the Precambrian basement is overlain by autochthonous Cambrian sandstones and shales. This sequence is cut by the Caledonian Osen–Røa Nappe Complex, which was thrust into place during the Late Silurian to Early Devonian (Figs. 1 & 2) using the Alum shale (Middle to Upper Cambrian) as a décollement surface.

Palaeoproterozoic basement

The Trysil granite is part of the Transscandinavian Igneous Belt (TIB) in southeastern Norway and southern Sweden. The Trysil granite is casually called the ‘tricolor’ granite, as it consists of bluish quartz (25–32%), reddish K-feldspar (40–50%) and greenish plagioclase (15–25%) with some black patches of biotite (2–7%) (Heim et al., 1996). Zircon U–Pb dating has yielded an intrusion age of 1673 ± 8 Ma for the Trysil granite (Heim et al., 1996). This age appears to be representative for a voluminous pulse of felsic magmatism (TIB3) in the Transscandinavian Igneous Belt (Lundqvist & Persson, 1999; Söderlund et al., 2008).

Drillcores from the area of the deposit show alteration of the granite below the Cambrian basal conglomerate, defining the paleosurface. Biotite is commonly the first mineral to alter during chemical weathering of granites (Wedepohl, 1956, 1978) and, in Osen, biotite is altered down to 5 to 10 metres under the paleosurface (Fig. 3). In the first 0.5 to 1 m below the paleosurface, the granite is arkosic in texture. This section is interpreted

Figure 1. Tectonostratigraphic sketch map of SE Norway with the location of the Osen Pb–Zn deposit.

Figure 2. Lithostratigraphy of the Cambrian section in the Osen area.

Figure 3. Thin-section of sample 25 with hematite alteration of biotite. Combined transmitted and reflected light.

as a Cambrian weathering profile of the granite before deposition of the marine Cambrian sediments took place. It is similar to present-day weathering of granite from the Monterey Peninsula, California, which presents different stages of alteration (Goodfellow et al., 2016). The first mineral to alter is biotite: Fe^{2+} is oxidised to Fe^{3+} (possibly by biological processes) and the iron is precipitated as ferrihydrite ($\text{Fe}(\text{OH})_3$) (Fletcher et al., 2006). This reaction results in a volume increase of the rock of c. 4%. This increase will cause increased porosity and permeability in the granite, creating a positive feedback to promote further weathering.

The unweathered Trysil granite contains on average 20 ppm Pb, 49 ppm Zn and 5 ppm Cu (Høy, 1977). Using the increase in the whole-rock $(\text{Al}_2\text{O}_3 + \text{K}_2\text{O}) / (\text{MgO} + \text{Na}_2\text{O})$ ratio as a proxy for the weathering intensity, lead and zinc contents are found to decrease with weathering in the Cambrian paleoweathering zone. This indicates that metals were released from the granite during the Late Precambrian to Early Cambrian peneplain formation.

According to Wedepohl (1978), the Pb content of biotite varies a lot from 10 to 80 ppm and the average uranium content is 8.1 ppm. Old biotite with a high U/Pb ratio may release lead with more radiogenic isotope compositions (Joplin-type or J-type; Doe & Zartmann, 1979) than the lead in the feldspar. This type of signature is typically observed in sediments deposited on a much older basement (Doe & Zartmann, 1979, p. 45 – continental environments).

Lower Cambrian sandstone and shale

The autochthonous sequence of Cambrian sedimentary rocks, sandwiched between the granite basement and the lowermost Caledonian (Osen–Røa) nappe, is 20 to 40 m thick (Fig. 2; Høy, 1977). It consists of the Lower Cambrian Ringstrand Formation and the Middle Cambrian Alum Shale Formation.

In the Osen area, the Ringstrand Formation consists of a fining-upward sequence that can be subdivided into a lowermost sandstone unit, successively overlain by dark, fine-grained sandstone and green siltstone. It is part of sequences LC 2–2 and LC 2–3 in the Lower Cambrian stratigraphy defined by Nielsen & Schovsbo (2011, 2015; Vergalian–Rausvian Baltoscandian stage, c. 541–511 Ma). Between the Ringstrand and Alum Shale formations there is a hiatus covering the upper part of the Lower Cambrian which corresponds to the Hawke Bay Event (Nielsen & Schovsbo, 2015).

Basal sandstone: The transition from granite to the overlying sandstone is gradual in most places. Moving upwards from unweathered to weathered granite, the orientation of the mica becomes more horizontal and the contents of feldspar and mica decrease. The basal arkose is less than 1 m thick. The arkosic sandstone grades into

a 1 to 4 m-thick layer of coarse-grained, blue, quartzitic to feldspathic sandstone, which hosts the ore. The latter unit is cemented by quartz, but pressure solution between primary quartz grains is uncommon. Illite and amorphous carbon occur in the matrix.

The ore assemblage includes galena, sphalerite, quartz, barite, fluorite and calcite, forming a cement in the sandstone. In sulphide-rich volumes, dissolution of primary quartz grains is commonly observed. The sulphur isotope composition variation of the galena varies between +16 and +23‰, consistent with a Cambrian marine source of sulphur with a restricted supply of sulphate (Bjørlykke, 1983).

Dark fine-grained sandstone: The basal sandstone becomes finer-grained upwards and grades into a 2 to 4 m-thick unit of dark fine-grained sandstone. This unit contains thin interbeds of conglomerate and green shale. Both vertical and horizontal burrows are present. Ripple marks, cross-laminations and ball-and-pillow structures have been observed (Nystuen, 1969). Fragments of fossils (1–10 mm) from the conglomerate have been identified as *Hyolithes* sp. and *Torellella laevigata* (Nystuen, 1969). The conglomerate also contains rounded discoidal fragments of fossiliferous dolomite. A weak dissemination of fine-grained pyrite and galena occurs in the sandstone, and some clusters of the same minerals occur in the conglomerate.

Green siltstone: The dark sandstone grades into a 1 to 4 m-thick unit of green siltstone and shale. The primary bedding in this unit is disrupted by a heavy bioturbation, but 5 to 10 mm-thick, coarse-grained, generally more calcitic beds can still be seen. Large nodules of pyrite are common.

The Lower Cambrian sequence is interpreted to have been deposited in a marine transgressive cycle. Deposition of the basal sandstone probably took place in a beach environment. The dark, fine-grained sandstone unit was probably deposited with several small breaks in sedimentation (Nystuen, 1969). The overlying green siltstone and shale may have been deposited in a subtidal environment.

Middle Cambrian black shale

After a hiatus, the Middle Cambrian sedimentary sequence starts with a 20 to 30 cm-thick conglomerate containing fragments of sandstone and shale that are locally phosphatic. A dark grey to black shale (Alum shales) with nodules of carbonate and pyrite rests immediately on top of the conglomerate. It was deposited in a relatively shallow-marine environment. The autochthonous sequence is interrupted 10 to 30 m from the base of the black shales by the Osen–Røa Nappe, made up of Lower Cambrian sandstones (Vangsås Formation).

Analytical methods

Analyses of the Pb isotope composition were performed in thin-sections on K-feldspar from the Trysil granite (Table 1). The thin-sections were specially prepared for this purpose with a thickness of 60 to 100 μm . Pb isotopes were measured in situ using a NWR193 ArF excimer laser ablation system (ESI) coupled to a Nu Plasma II multi-collector ICP-MS (Nu Instruments) at the Vegacenter facility at the Swedish Museum of Natural History in Stockholm. Samples and secondary reference material (K-feldspar from the Shap granite; Tyrell et al., 2006) were ablated for 35 s/spot with a spot size of 100

$\mu\text{m} \times 100 \mu\text{m}$ (square aperture), a laser frequency of 25 Hz and fluence of 5 J/cm². All isotopes from m/z 200 to m/z 208 were measured in static mode on Faraday collectors. ²⁰⁴Pb was corrected for a possible interference by ²⁰⁴Hg. NIST612 was measured as a primary standard (Baker et al., 2004) to determine mass fractionation (spot size 120 μm , line scans, 40 s). NIST 610 served as an additional secondary standard (spot size 45 μm). Instrument parameters are listed in Table 1, samples in Table 2 and results in Table 3. This protocol yielded an average 2 sigma analytical uncertainty of c. 0.5% on ²⁰⁶Pb/²⁰⁴Pb. Both NIST 610 and Shap granite K-feldspar reproduced their literature values within analytical uncertainty showing that mass fractionation was corrected effectively (Table 3).

Table 1. LA-MC-ICP-MS instrument parameters for analysis of K-feldspar.

Mass spectrometer	Nu plasma (II) MC-ICP-MS
Cooling gas flow rate	13 L/min
Aux gas flow rate	0.86 L/min
Mass resolution	low
Cones	common Ni cones
Torch	glass
Laser ablation	ESI NWR193 ArF eximer based laser ablation system
Ar flow rate (Mix Gas)	0.9 L/min
He flow rate	0.3 L/min
Ablation	
Frequency	25 Hz
Spotsize (Samples)	100 $\mu\text{m} \times 100 \mu\text{m}$
Spotsize (NIST612)	120 μm (linescan 200 μm long)
Spotsize (NIST610)	45 μm
Spotsize (Shap)	100 $\mu\text{m} \times 100 \mu\text{m}$
Fluence	5 J/cm ²
Data collection	
Washout time	30 s
Ablation time	35 s
Integration	0.4 s

Samples and results

Six samples of the Trysil granite underlying the galena mineralisation were selected from drillcores in the Osen area (Table 1). A total of 46 analyses of the Pb isotope composition of K-feldspar were collected (Table 3; Fig. 4). Zones of clearly weathered granite were avoided in the selection process. However, at the microscopic level, biotite and some plagioclase were found to be variably altered. The K-feldspar (microcline) seems more resistant to weathering. The volume increase of the rock attributed to the weathering process may, however, have resulted in formation of minor cracks in feldspar and quartz. When placing the analysis spots, optically visible cracks were avoided. However, it cannot be ruled out that some cracks were hit during the analysis.

The data show a significant spread of the ²⁰⁶Pb/²⁰⁴Pb composition, ranging from 16.44 to 18.96 (Fig. 4A), around the previously calculated isochron defined by whole-rock data in ²⁰⁶Pb/²⁰⁴Pb vs. ²⁰⁷Pb/²⁰⁴Pb space (Fig. 4A). The new data define two main clusters, A and B (Fig. 4A). The less radiogenic cluster A (average ²⁰⁶Pb/²⁰⁴Pb = 16.51, ²⁰⁷Pb/²⁰⁴Pb = 15.37) plots close to the calculated initial ratio of the Trysil granite (²⁰⁶Pb/²⁰⁴Pb = 16.14, ²⁰⁷Pb/²⁰⁴Pb = 15.38; Fig. 3) extracted previously from regression of whole-rock data in ²³⁸U/²⁰⁴Pb vs. ²⁰⁶Pb/²⁰⁴Pb

Table 2. Sampling of the Trysil granite underlying the Osen Pb-Zr deposit, along with descriptions of the glendonites found in each horizon.

Sample ID	NGU ID	Drillcore	Depth (m)	Zone	UTM X	UTM Y	Lithology
20	136520	BH5/70	74	32 V	655100	6799300	Granite
22	136522	BH5/70	83	32 V	655100	6799300	Granite
23	136523	BH5/70	83.5	32 V	655100	6799300	Granite
24	136524	BH2/73	19.4	32 V	652800	6799200	Granite
25	136525	BH2/73	24.7	32 V	652800	6799200	Granite
26	136526	BH2/73	28.3	32 V	652800	6799200	Granite

Table 3. LA-MC-ICP-MS Pb isotope data on K-feldspar from the Trysil granite in Osen and reference material.

Sample	Run Nr.	Grain / spot	Sampling time (sec)	$^{206}\text{Pb}/^{204}\text{Pb}$	2SE	Propagated 2SE	$^{207}\text{Pb}/^{204}\text{Pb}$	2SE	Propagated 2SE	$^{208}\text{Pb}/^{204}\text{Pb}$	2SE	Propagated 2SE	$^{208}\text{Pb}/^{206}\text{Pb}$	2SE	Propagated 2SE	^{204}Pb (V)		
20	1	1	14.8	16.44	0.08	0.08	15.35	0.07	0.08	35.70	0.17	0.18	0.9359	0.0025	0.0025	2.1763	0.0086	0.0052
20	1	2	11.7	16.52	0.09	0.10	15.40	0.09	0.09	35.89	0.21	0.22	0.9308	0.0014	0.0014	2.1674	0.0044	0.0055
20	1	3	15.8	16.53	0.14	0.14	15.25	0.13	0.14	35.69	0.31	0.31	0.9215	0.0023	0.0023	2.1556	0.0032	0.0020
20	1	6	16.4	16.66	0.16	0.16	15.44	0.12	0.13	36.02	0.33	0.34	0.9233	0.0035	0.0035	2.1586	0.0070	0.0069
20	1	7	22.8	16.48	0.08	0.08	15.41	0.07	0.07	35.86	0.17	0.18	0.9350	0.0009	0.0009	2.1718	0.0025	0.0049
20	1	8	19.2	16.49	0.05	0.06	15.40	0.04	0.05	35.82	0.10	0.11	0.9336	0.0009	0.0009	2.1719	0.0029	0.0087
20	1	9	21.4	16.60	0.14	0.14	15.44	0.13	0.14	36.01	0.31	0.31	0.9295	0.0011	0.0011	2.1681	0.0022	0.0029
22	1	Areal-2	31.8	18.49	0.11	0.12	15.68	0.10	0.10	38.43	0.24	0.25	0.84816	0.00058	0.00059	2.0790	0.0010	0.0020
22	1	Areal-3	29.3	18.29	0.13	0.13	15.50	0.11	0.11	38.01	0.27	0.27	0.84791	0.00054	0.00055	2.0786	0.0010	0.0022
22	1	Areal-4	22.7	18.24	0.16	0.16	15.44	0.13	0.14	37.88	0.33	0.33	0.84627	0.00059	0.00060	2.0765	0.0010	0.0021
22	1	Areal-5	22.7	18.55	0.11	0.11	15.71	0.09	0.10	38.51	0.22	0.23	0.84690	0.00048	0.00049	2.0761	0.0008	0.0023
22	1	Areal-6	21.4	18.37	0.15	0.15	15.58	0.13	0.13	38.20	0.32	0.32	0.84740	0.00066	0.00066	2.0778	0.0012	0.0023
22	1	Areal-7	24.3	18.45	0.12	0.12	15.63	0.10	0.11	38.36	0.24	0.25	0.84807	0.00049	0.00050	2.0794	0.0008	0.0024
22	1	Area2-2	27.1	18.45	0.14	0.15	15.62	0.12	0.12	38.30	0.30	0.30	0.84698	0.00066	0.00067	2.0764	0.0011	0.0020
22	1	Area2-3	25.5	18.39	0.15	0.15	15.54	0.12	0.12	38.18	0.31	0.32	0.84610	0.00078	0.00078	2.0754	0.0013	0.0023
22	1	Area2-4	21.2	18.53	0.17	0.17	15.53	0.12	0.12	38.22	0.31	0.32	0.8403	0.0036	0.0036	2.0640	0.0067	0.0022
23	1	1	10.4	16.50	0.17	0.18	15.35	0.17	0.17	35.84	0.36	0.37	0.9301	0.0038	0.0038	2.1598	0.0091	0.0035
23	1	2	21.7	16.53	0.14	0.14	15.40	0.13	0.13	35.87	0.31	0.31	0.9328	0.0014	0.0014	2.1679	0.0046	0.0037
23	1	3	22.7	16.54	0.12	0.12	15.32	0.11	0.11	35.71	0.26	0.26	0.9256	0.0019	0.0019	2.1567	0.0038	0.0028
23	1	4	7.9	16.92	0.19	0.19	15.44	0.14	0.14	36.33	0.34	0.34	0.9122	0.0033	0.0033	2.1390	0.0064	0.0024
23	1	5	29.0	18.33	0.10	0.10	15.50	0.08	0.09	38.06	0.21	0.22	0.84667	0.00058	0.00059	2.0775	0.0010	0.0022
23	1	6	17.0	16.47	0.13	0.13	15.35	0.14	0.14	35.83	0.32	0.33	0.9302	0.0020	0.0020	2.1702	0.0050	0.0026
23	1	8	28.4	18.34	0.10	0.11	15.55	0.09	0.10	38.15	0.22	0.23	0.84756	0.00048	0.00049	2.0784	0.0007	0.0025
23	1	9	31.5	18.69	0.09	0.10	15.83	0.08	0.09	38.83	0.20	0.21	0.84724	0.00044	0.00046	2.0773	0.0008	0.0027
23	1	10	32.8	18.44	0.08	0.08	15.52	0.06	0.06	37.50	0.15	0.16	0.8423	0.0010	0.0010	2.0345	0.0028	0.0054
23	1	12	25.5	16.66	0.14	0.14	15.47	0.13	0.14	36.16	0.31	0.32	0.9264	0.0015	0.0015	2.1635	0.0026	0.0025
24	2	1	18.2	16.89	0.12	0.12	15.47	0.11	0.12	36.01	0.25	0.26	0.9142	0.0011	0.0011	2.1311	0.0019	0.0025
24	2	2	10.2	18.23	0.22	0.22	15.42	0.19	0.20	37.75	0.47	0.48	0.8485	0.0010	0.0010	2.0767	0.0016	0.0022
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(continued page 7)

Table 3. (continued from page 6)

Sample	Run Nr.	Grain / spot	Sampling time (sec)	$^{206}\text{Pb}/^{204}\text{Pb}$	2SE	Propagated $^{207}\text{Pb}/^{204}\text{Pb}$ 2SE	$^{208}\text{Pb}/^{204}\text{Pb}$	2SE	Propagated $^{207}\text{Pb}/^{206}\text{Pb}$ 2SE	$^{208}\text{Pb}/^{206}\text{Pb}$	2SE	Propagated $^{208}\text{Pb}/^{206}\text{Pb}$ 2SE	2SE	Propagated ^{20}Pb (V) 2SE	
24	2	3	14.2	18.25	0.17	0.17	15.46	0.15	0.15	37.92	0.35	0.35	0.0064	0.0013	0.0021
24	2	4	30.8	18.49	0.14	0.15	15.62	0.12	0.13	38.36	0.30	0.30	0.0069	0.0013	0.0020
24	2	6	9.3	18.32	0.28	0.28	15.52	0.24	0.24	38.04	0.58	0.59	0.0014	0.0023	0.0020
24	2	9	7.1	17.13	0.18	0.18	15.54	0.14	0.14	36.34	0.35	0.35	0.0028	0.0076	0.0047
24	2	10	15.6	16.97	0.08	0.08	15.430	0.061	0.065	36.08	0.17	0.18	0.0010	0.0024	0.0045
24	2	12	20.5	16.81	0.13	0.13	15.44	0.12	0.12	35.98	0.28	0.28	0.0008	0.0014	0.0020
24	2	13	16.5	17.08	0.15	0.15	15.46	0.15	0.15	36.39	0.31	0.32	0.0019	0.0032	0.0021
25	2	1	16.5	18.38	0.12	0.12	15.64	0.10	0.10	37.09	0.24	0.25	0.00084	0.0015	0.0030
25	2	2	18.7	18.83	0.09	0.10	15.70	0.08	0.08	37.47	0.19	0.20	0.00050	0.0011	0.0032
25	2	3	16.9	18.66	0.10	0.10	15.58	0.08	0.09	37.21	0.19	0.20	0.00077	0.0019	0.0034
25	2	4	12.0	18.96	0.11	0.12	15.60	0.09	0.10	37.54	0.23	0.24	0.00093	0.0034	0.0037
25	2	5	27.1	18.69	0.07	0.08	15.71	0.06	0.06	37.42	0.14	0.15	0.00039	0.0013	0.0041
25	2	6	9.8	18.90	0.07	0.08	15.70	0.07	0.07	37.60	0.20	0.21	0.0015	0.0046	0.0053
26	2	Area1-5	32.5	18.28	0.15	0.16	15.58	0.11	0.12	37.10	0.29	0.29	0.0039	0.0086	0.0023
26	2	Area1-7	16.0	17.99	0.16	0.16	15.35	0.13	0.13	36.86	0.31	0.31	0.0011	0.0055	0.0022
26	2	Area2-1	32.9	17.69	0.20	0.20	15.50	0.12	0.12	36.95	0.33	0.34	0.0045	0.0071	0.0020
26	2	Area2-2	27.6	17.11	0.06	0.07	15.41	0.05	0.06	36.35	0.13	0.14	0.00063	0.0017	0.0038
26	2	Area2-3	13.3	17.48	0.15	0.16	15.63	0.14	0.14	37.00	0.32	0.33	0.00080	0.0019	0.0026
NIST610	1	1	28.4	17.049	0.009	0.027	15.506	0.008	0.024	36.963	0.021	0.063	0.00009	0.00048	0.029
NIST610	1	2	28.8	17.053	0.009	0.027	15.509	0.008	0.023	36.967	0.019	0.062	0.00009	0.00048	0.029
NIST610	1	3	28.8	17.051	0.010	0.027	15.510	0.009	0.024	36.968	0.020	0.063	0.00007	0.00047	0.029
NIST610	1	4	26.4	17.053	0.011	0.028	15.508	0.010	0.024	36.963	0.024	0.064	0.00009	0.00048	0.029
NIST610	1	5	28.8	17.055	0.010	0.027	15.511	0.009	0.024	36.970	0.021	0.063	0.00009	0.00050	0.030
NIST610	1	6	27.2	17.051	0.009	0.027	15.506	0.008	0.024	36.958	0.020	0.063	0.00010	0.00049	0.029
NIST610	1	7	26.0	17.034	0.010	0.027	15.493	0.009	0.024	36.926	0.023	0.064	0.00009	0.00050	0.029
NIST610	1	8	26.0	17.055	0.011	0.028	15.512	0.010	0.024	36.975	0.024	0.064	0.00007	0.00049	0.028
NIST610	1	9	26.4	17.048	0.010	0.027	15.502	0.010	0.024	36.948	0.024	0.064	0.00009	0.00050	0.027
NIST610	2	1	29.8	17.051	0.008	0.024	15.511	0.007	0.023	36.978	0.018	0.057	0.00009	0.00052	0.030

(continued page 8)

Table 3. (continued from page 7)

Sample	Run Nr.	Grain / spot	Sampling time (sec)	$^{206}\text{Pb}/^{204}\text{Pb}$	2SE	Propagated 2SE	$^{207}\text{Pb}/^{204}\text{Pb}$	2SE	Propagated 2SE	$^{208}\text{Pb}/^{206}\text{Pb}$	2SE	Propagated 2SE	$^{207}\text{Pb}/^{206}\text{Pb}$	2SE	Propagated 2SE	$^{208}\text{Pb}/^{206}\text{Pb}$	2SE	Propagated 2SE	^{209}Pb (V)
NIST610	2	2	29.8	17.049	0.010	0.025	15.508	0.009	0.024	36.969	0.022	0.058	0.90950	0.00010	0.00015	2.16826	0.00025	0.00053	0.030
NIST610	2	3	29.8	17.051	0.008	0.024	15.511	0.007	0.023	36.978	0.018	0.057	0.90963	0.00009	0.00015	2.16864	0.00021	0.00052	0.030
NIST610	2	4	29.8	17.058	0.009	0.024	15.518	0.007	0.023	36.997	0.018	0.057	0.90966	0.00008	0.00014	2.16893	0.00020	0.00051	0.028
NIST610	2	5	29.8	17.060	0.010	0.025	15.516	0.009	0.024	36.988	0.021	0.058	0.90953	0.00009	0.00014	2.16819	0.00021	0.00051	0.029
NIST610	2	6	29.8	17.060	0.011	0.025	15.520	0.009	0.024	36.982	0.022	0.058	0.90949	0.00009	0.00015	2.16801	0.00018	0.00050	0.028
NIST610	2	7	29.8	17.041	0.009	0.025	15.499	0.009	0.024	36.951	0.021	0.057	0.90946	0.00008	0.00014	2.16827	0.00018	0.00050	0.029
KfsShapGr	1	1	30.9	18.186	0.039	0.048	15.594	0.032	0.039	38.106	0.081	0.100	0.85742	0.00023	0.00023	2.09533	0.00050	0.00065	0.006
KfsShapGr	1	2	25.8	18.172	0.022	0.035	15.584	0.018	0.029	38.075	0.045	0.076	0.85747	0.00018	0.00018	2.09469	0.00051	0.00066	0.014
KfsShapGr	1	3	30.8	18.164	0.017	0.032	15.578	0.014	0.026	38.058	0.035	0.071	0.85767	0.00011	0.00011	2.09563	0.00032	0.00052	0.014
KfsShapGr	1	4	34.4	18.164	0.015	0.031	15.576	0.013	0.026	38.057	0.030	0.068	0.85773	0.00013	0.00013	2.09525	0.00031	0.00052	0.018
KfsShapGr	1	5	27.2	18.172	0.016	0.031	15.579	0.013	0.026	38.063	0.028	0.068	0.85712	0.00017	0.00017	2.09386	0.00044	0.00060	0.017
KfsShapGr	1	6	34.3	18.158	0.014	0.030	15.566	0.012	0.025	38.027	0.030	0.068	0.85711	0.00013	0.00013	2.09375	0.00044	0.00061	0.017
KfsShapGr	1	7	33.3	18.174	0.019	0.033	15.580	0.016	0.027	38.054	0.039	0.073	0.85718	0.00012	0.00012	2.09369	0.00035	0.00054	0.017
KfsShapGr	1	8	25.0	18.171	0.024	0.036	15.563	0.021	0.030	38.030	0.052	0.080	0.85621	0.00019	0.00019	2.09297	0.00036	0.00055	0.015
KfsShapGr	1	9	20.6	18.177	0.015	0.031	15.582	0.013	0.026	38.065	0.032	0.069	0.85707	0.00015	0.00015	2.09421	0.00038	0.00057	0.017
KfsShapGr	1	10	32.6	18.173	0.015	0.031	15.574	0.012	0.025	38.053	0.030	0.068	0.85710	0.00014	0.00014	2.09430	0.00038	0.00056	0.017
KfsShapGr	2	1	21.1	18.179	0.021	0.032	15.591	0.017	0.028	38.105	0.041	0.069	0.85779	0.00020	0.00023	2.09585	0.00058	0.00074	0.017
KfsShapGr	2	2	31.0	18.201	0.017	0.030	15.602	0.014	0.026	38.127	0.035	0.066	0.85709	0.00015	0.00018	2.09431	0.00038	0.00059	0.015
KfsShapGr	2	3	30.8	18.238	0.022	0.033	15.595	0.014	0.026	38.110	0.035	0.065	0.85549	0.00043	0.00044	2.09070	0.00110	0.00120	0.016
KfsShapGr	2	4	19.1	18.202	0.020	0.032	15.607	0.017	0.028	38.131	0.043	0.070	0.85760	0.00022	0.00024	2.09509	0.00082	0.00094	0.018
KfsShapGr	2	5	27.8	18.183	0.019	0.031	15.597	0.017	0.028	38.103	0.041	0.069	0.85765	0.00015	0.00018	2.09554	0.00041	0.00061	0.015
KfsShapGr	2	6	30.8	18.203	0.017	0.030	15.601	0.014	0.027	38.123	0.035	0.066	0.85707	0.00013	0.00017	2.09412	0.00029	0.00054	0.016

Figure 4. Pb isotope data and a model for the genesis of the Osen Pb–Zn deposit. (A) LA–MC–ICP–MS data on K-feldspar from six samples of the Trysil granite, together with whole-rock data published by Bjørlykke & Thorpe (1982) and the initial ratio of the Trysil granite calculated by Bjørlykke & Thorpe (1982). (B) Galena of the Osen deposit compared with data of the Trysil granite. Galena of the Osen deposit plots on the isochron defined by whole-rock and K-feldspar of the Trysil granite 540 Myr ago, along a growth curve with a μ value of 18. The lead sequestered in the Osen deposit can be derived from weathering of the Trysil granite at the Precambrian–Cambrian boundary. Explanation in text. Two sigma errors on the $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratio obtained by TIMS by Bjørlykke & Thorpe (1982) on whole-rock and sulphide samples are 0.069 and 0.079%, respectively. They are smaller than the symbols on the figure.

and $^{238}\text{U}/^{204}\text{Pb}$ vs $^{207}\text{Pb}/^{204}\text{Pb}$ spaces (Bjørlykke & Thorpe, 1982). This cluster includes all analytical data from sample 20, but also data from samples 23 and 24. The second, more radiogenic cluster B is close to the isotope ratio of one of the whole-rock samples of weathered granite ($^{206}\text{Pb}/^{204}\text{Pb} = 19.44$) and underlying unweathered whole-rock samples ($15.78 < ^{207}\text{Pb}/^{204}\text{Pb} < 16.28$; $20.14 < ^{206}\text{Pb}/^{204}\text{Pb} < 25.26$). It includes analytical data from all samples except sample 20.

Discussion

We wanted to test if the new Pb isotope data on K-feldspar of the Trysil granite support the interpretation of the genesis of the Osen lead deposit proposed by Bjørlykke & Thorpe (1982), involving sourcing of Pb in the Trysil granite basement. The least radiogenic composition of K-feldspar ($^{206}\text{Pb}/^{204}\text{Pb} = 16.44$; Fig. 4A) plots within uncertainty on the isochron defined by analytical data of unweathered whole-rock granite samples in $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ space (Fig. 4A), close to the initial ratio calculated previously ($^{206}\text{Pb}/^{204}\text{Pb} = 16.14$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.38$; Bjørlykke & Thorpe, 1982). The small difference between the less radiogenic K-feldspar data points ($^{206}\text{Pb}/^{204}\text{Pb} = 16.44$) and the calculated initial ratio from the whole-rock isochron ($^{206}\text{Pb}/^{204}\text{Pb} = 16.14$) means either that the K-feldspar contains some U ($^{238}\text{U}/^{204}\text{Pb} > 0$) or that the calculated initial ratio was over-corrected.

In Fig. 4B, the average value of the 10 least radiogenic K-feldspar data points ($^{206}\text{Pb}/^{204}\text{Pb} = 16.51$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.37$) are considered representative for the initial composition of the Trysil granite basement. The whole-rock data together with these 10 data points yield an errorchron with an age of 1657 ± 47 – 120 Ma (robust regression), equivalent to the zircon age of 1673 ± 8 Ma for the Trysil granite (Heim et al., 1996). The Pb isotope ratio of galena of the Osen deposit ($20.24 < ^{206}\text{Pb}/^{204}\text{Pb} < 20.49$, $15.85 < ^{207}\text{Pb}/^{204}\text{Pb} < 15.89$) plots on a reference line corresponding to the whole-rock + K-feldspar errorchron of the Trysil granite, as it was 540 Myr ago (i.e., rotated around the initial composition defined by K-feldspar). The age of c. 540 Ma corresponds to the base of the Cambrian (541 ± 1 Ma; Cohen et al., 2013) and the start of deposition of the Ringstrand Formation (Vergalian–Rausvian stage, c. 541–511 Ma), as estimated by stratigraphic correlation and biostratigraphic methods (see above; Fig. 2). The galena data plot on a growth curve emanating from the K-feldspar composition with a realistic μ value ($^{238}\text{U}/^{204}\text{Pb}$) of 18, in the range of the measured whole-rock samples ($14 < \mu < 33$) (Fig. 4B). Therefore, the galena of the Osen deposit was possibly formed from Pb derived from the Trysil granite c. 540 Myr ago. The Pb isotope composition of galena is invariable after it crystallised, as a result of its extremely low μ value.

This study confirms that the Trysil granite was a probable source for lead to form the Osen deposit at c. 540 Ma, in Early Cambrian time (Fig. 4B). The chemical weathering of the Precambrian basement probably started in the Ediacaran after the Neoproterozoic glaciations and continued until the marine transgression in the Early Cambrian. The good fit for an age of c. 540 Ma indicates that mineralisation probably took place during the diagenesis of the sandstone. However, based on the lead isotope data alone it is difficult to exclude hydrothermal processes and for a period the lead may have been adsorbed on other minerals with low μ values such as kaolinite.

Both weathering and albitisation may release lead from a granite to an ore-forming fluid. In a first stage, weathering is selectively affecting minerals with relatively high μ values such as biotite, allanite and uranium oxides (Fletcher et al., 2006; Goodfellow et al., 2016), while albitisation affects feldspars to form albite, which has less space in the lattice to accommodate lead (Wedepohl, 1978). In SEDEX deposits, the interaction between highly saline water and feldspar-bearing sandstone typically results in mobilisation of non-radiogenic lead from the K-feldspar (Emsbo et al., 2016). This results in a non-radiogenic signature of the lead–zinc deposits, usually with high barium contents, which also may be released from the K-feldspar. In the sandstone-hosted Osen deposit, the radiogenic composition of lead in the galena, compared to K-feldspar in the Trysil granite, supports the model of weathering of the Trysil granite as the first step in the ore-forming process. The radiogenic signature for K-feldspar in cluster B relative to cluster A (Fig. 4A) supports this interpretation. The considerable isotopic difference between the initial rock lead (reflected by the least radiogenic feldspars) and ore lead is probably also related to the weathering of biotite in the granite. During the weathering of biotite, increased permeability and porosity of the granite allowed migration of radiogenic lead generated in the biotite to move in microfractures to other phases including K-feldspar.

The details related to transport of metals from the site of weathering to the precipitation of sulphide in the host sandstone are still largely unknown. However, the proposed age of c. 540 Ma for the release of lead and the sourcing of Pb in the underlying Trysil granite excludes alternative genetic models that advocate a temporal relationship between ore formation and the later stages of Caledonian orogenic history. These include transport of metal-bearing solutions via Caledonian (or pre-Caledonian) faults and sourcing of metals in hot basinal brines from the foredeep of the Caledonian orogenic wedge that were transported in front of the Caledonian nappes (Rickard et al., 1979, 1981, Saintilan et al. 2015b). The relationship of the sandstone-hosted Pb–Zn deposits to structural elements in the basement, such as faults and shear zones, was noted by Bjørlykke et al. (1991), Romer (1992), Billström et al. (2012) and Saintilan et

al. (2015a). The continent Baltica is suggested by some workers to have collided with the continent Arctica during Ediacaran to Early Cambrian time in Finnmark, northern Norway, and northern Russia, thus creating the Timanide orogen (Andresen et al., 2014). This collision may have resulted in faulting and lead–zinc vein formation as a far-field tectonic response farther to the south on Baltoscandia (Billström et al. 2012, Saintilan et al., 2015b).

Conclusions

The timing of the mineralisation process is one of the most important parameters in the understanding of the formation of an ore deposit or a deposit type. New Pb isotope data on K-feldspar from the Palaeoproterozoic Trysil granite, combined with published whole-rock and ore lead data, have led to an internally consistent and more robust model for the genesis of the sandstone-hosted Pb–Zn deposit in Osen. The data suggest that galena in the Osen deposit was generated at c. 540 Ma, shortly after the sandstone deposition in the Early Cambrian, sourced from Pb released by weathering of the granite basement during the development of the sub-Cambrian peneplain. The data therefore exclude alternative models involving Caledonian events in either Ordovician or Silurian time.

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